The 2021 ECFA Detector Research and Development Roadmap

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THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

**The European Committee for Future Accelerators
Detector R&D Roadmap Process Group**

European Strategy Update

ECFA
European Committee for Future Accelerators

The 2021 ECFA Detector Research and Development Roadmap

Prepared by the Detector R&D Roadmap Process Group of the European Committee for Future Accelerators

Published:	21.10.2021
References:	ECFA/RC/21/510
	CERN-ESU-017
DOI:	10.17181/CERN.XDPL.W2EX
ISBN online:	978-92-9083-614-8
ISBN paperback:	978-92-9083-615-5

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Introduction

The centrality of experimentation to the scientific method which has led to the discoveries that underpin our current understanding of the Universe, and the technological wonders which have flowed from this understanding, cannot be overstated. To appropriately test our current level of understanding requires very high accuracy instrumentation. The degree of confirmation that can be assigned to any hypothesis is determined both by the agreement between theoretical prediction and measurements and the level of precision achievable in each. Enabling future particle physics experiments to achieve the most accurate measurements possible is the fundamental target of all the proposed detector developments outlined in this report.

The European Strategy of Particle Physics is reviewed and updated every five to ten years with the most recent one concluded by CERN Council adopting the latest set of recommendations [Ch0-1] in June 2020. It provides an ambitious vision of the experimental programme for the future spanning many decades. Amongst the many recommendations, one requirement listed is: "organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields". The purpose of this Roadmap more specifically should be to "identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics programme in the near and long term". The particle physics programme mentioned here is taken to consist of the projects listed in the Deliberation Document of the European Particle Physics Strategy Update (EPPSU) [Ch0-2] as either *"High-priority future initiatives"* or *"Other essential scientific activities for particle physics"*. The different priorities of the physics projects themselves is not a topic for this document, but the relative importance of proposed detector R&D activities to these projects is the main aspect that will be discussed. A grouped distillation of the EPPSU mentioned facilities/areas is listed below.

- Detector improvements required for full exploitation of the HL-LHC (R&D still needed for the next LHC Long Shutdown, LS3, upgrades and for experiment upgrades beyond then) including studies of flavour physics and quark-gluon plasma (where the latter topic also interfaces with nuclear physics);
- R&D for long baseline neutrino detectors (including aspects targeting astro-particle physics measurements) and supporting projects such as those at the CERN Neutrino Platform;

- Technology developments needed for detectors at e^+e^- Higgs-EW-Top factories in all possible accelerator manifestations including instantaneous luminosities at 91.2 GeV of up to $5\times10^{36}\,\mathrm{cm^{-2}s^{-1}}$ and energies up to the TeV range;

- The long-term R&D programme for detectors at a future 100 TeV hadron collider with integrated luminosities targeted up to $30\,\mathrm{ab^{-1}}$ and 1000 multiple interactions for 25 ns bunch crossing interval;

- Specific long-term detector technology R&D requirements of a muon collider operating at 10 TeV and with a luminosity of the order of $10^{35}\,\mathrm{cm^{-2}s^{-1}}$;

- Detector developments for accelerator-based studies of rare processes, DM candidates and high precision measurements (including strong interaction physics) at both storage rings and fixed target facilities, interfacing also with atomic and nuclear physics;

- R&D for optimal exploitation of dedicated collider experiments studying the partonic structure of the proton and nuclei as well as interface areas with nuclear physics;

- The very broad detector R&D areas for non-accelerator-based experiments, including dark matter searches (including axion searches), reactor neutrino experiments and rare decay processes, also considering neutrino observatories and other interface areas with astro-particle physics.

To create a time-ordered technology requirements driven R&D roadmap, focused on capabilities not currently achievable, ECFA set up the structure shown in Figure 1. One of the main routes for the community to shape the Roadmap has been through the six technology facing Task Forces (1-6) and three cross-cutting Task Forces (7-9) shown in the figure. These Task Forces are also composed of experts from the community covering the key sub-topics in the relevant technology areas including two convenors per Task Force. The Task Force convenors join the Chair, Scientific Secretary, ECFA appointed Coordinators and (ex-officio) representative from the Laboratories Directors Group (LDG), present ECFA Chair and previous ECFA Chair to make up the Detector R&D Roadmap Panel. Close contact is maintained with the LDG in particular, as their charge includes the development of the corresponding Roadmap for a coordinated and intensified programme of Particle Accelerator R&D including exploration of new technologies. This Accelerator R&D Roadmap is to be developed in parallel and on a similar timescale to the Detector R&D Roadmap.

The EPPSU report requires the Panel to take into account progress with emerging technologies in adjacent fields, which is here provided through the Advisory Panel with Other Disciplines (APOD), composed of the Chairs or Directors of the corresponding organisations. APPEC, ESA, LEAPS, LENS and NuPECC[1] have provided expert contacts by Task Force area (as appropriate) within their organisations. The Roadmap

[1] APPEC: Astro-Particle Physics European Consortium; ESA: European Space Agency; LEAPS: League of European Accelerator-based Photon Sources; LENS: League of advanced European Neutron Sources and NuPECC: Nuclear Physics European Collaboration Committee

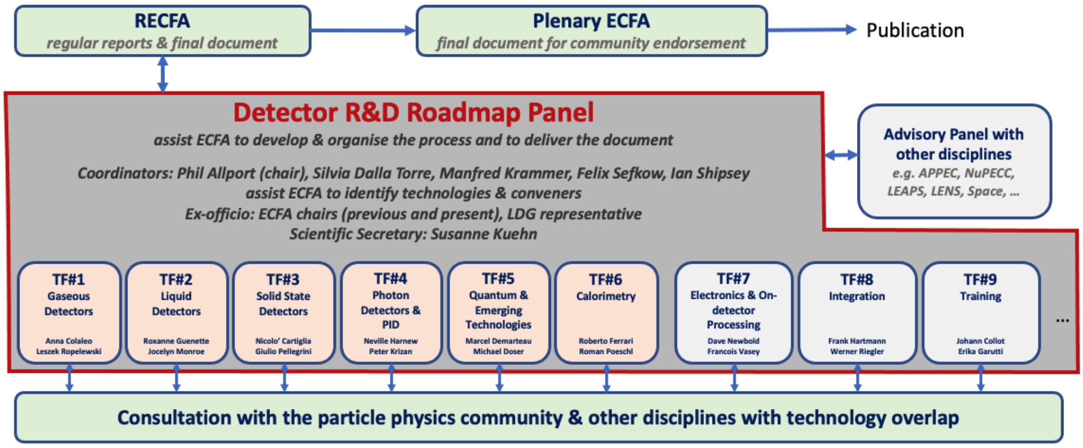

Figure 1: ECFA Detector R&D Roadmap Panel Organisation.

Panel Chair or representative reports progress through Restricted ECFA (RECFA) and thence to the full Committee which is also kept fully informed by the ECFA Chair. To assist the process, ECFA has provided a list by country of National Contacts who are also consulted directly by the Task Forces. This report is developed with and submitted for endorsement by ECFA.

Figure 2 illustrates the process and timeline whereby this report is prepared. The different stages are shown in three blocks. The process started in May 2020 with the Coordinators team confirmed by ECFA. The Panel composition was completed by September and the organisational aspects were concluded by the end of that year. The first phase of input was through two days containing twelve presentations from leading scientists representing the eight facilities/areas listed above (for more details see [Ch0-3]). Their brief was to emphasise unmet detector R&D needs in a context that extends decades into the future, given the very long lead-times that some developments will inevitably require. These presenters have also agreed to continue as the primary contacts of the Panel and Task Forces for material in their area of expertise. Following these, the Task Forces were mainly occupied with collecting further inputs through surveys distributed largely through the National Contacts; consultation with the contacts provided by APOD[2] and (also taking advantage of these) preparation of the corresponding day-long symposia discussed below.

Throughout the process, all the materials used to build the Roadmap have been publicly available through webpages [Ch0-3] that have been widely advertised within the community. Information on the nine topical Open Symposia (each devoted to a specific technology area or cross-cutting activity) was distributed at a national level through ECFA and the National Contacts; via APOD and using a large number of particle physics R&D related mailing lists. In compiling material for the Detector R&D

[2]ECFA provided a list of contacts by country, while APPEC, ESA, LEAPS, LENS and NuPECC have all provided expert contacts by Task Force area.

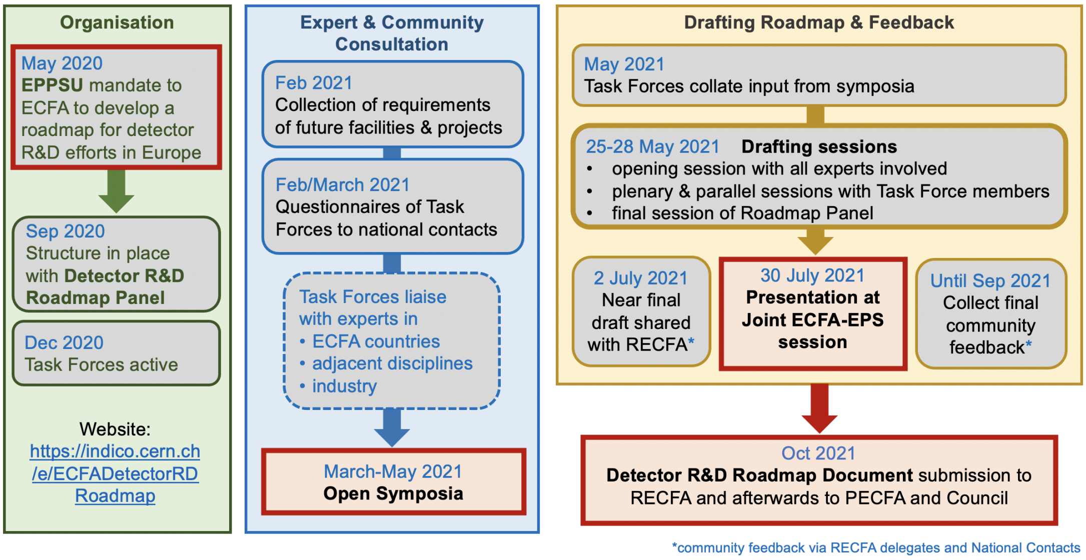

Figure 2: Timeline of the ECFA Detector R&D Roadmap process.

Roadmap, a group of 70 leading instrumentation scientists have both contributed their own expertise and been very active in organising this broad community consultation. The level of participation of the experimental physics community is reflected in the 1359 registrations for the symposia. More details on the level of engagement by Task Force topic can also be found at Reference [Ch0-3].

Following the last symposium, an intensive period of collating the inputs followed, including those from the expert presentations at the symposia, community feedback and the Input Session speakers, to structure the material both in terms of facility/area requirements but also by the sub-topics within each Task Force. For the six technology Task Forces in particular, the information has been first grouped by sub-technology area and then relevance to different current, planned or potential experiments evaluated along with the associated timeline for these. The driving principle has been to bring out synergies and stress interconnections between developments of similar technologies needed at different times by different programmes. In this context, for projects without fully defined schedules, the policy has been adopted to work in terms of the "earliest technically feasible start date" such that were the most optimistic scenario to be realised, the detector technology readiness could not become the limiting factor.

In the following chapters each Task Force (apart from Task Force 9 Training), has further sub-divided their technology area into broad sub-topics and taken the list of eight facilities/areas to help define the most pressing requirements as a function of time when needed (or could be needed where this is not yet defined). In addition, the Task Forces were asked to consider the following additional aspects when putting together their symposium agenda and seeking further community feedback.

- Facilities needed for detector evaluation, including test beams[3] and different types of irradiation sources, along with the advanced instrumentation required for these;
- Infrastructures facilitating detector developments, including technological workshops and laboratories, as well as tools for the development of software and electronics;
- Networking structures in order to ensure collaborative environments, to help in the education and training, for cross-fertilisation between different technological communities, and in view of relations with industry;
- Overlaps with neighbouring fields and key specifications required for exploitation in other application areas;
- Opportunities for industrial partnership and technical developments needed for potential commercialisation.

The individual sections relating to different detector technologies in the document reflect the programme defined by first ensuring that the EPPSU identified *"High-priority future initiatives"* should not be potentially delayed by lack of availability of the required detector capabilities and also that the *"Other essential scientific activities for particle physics"* should not be compromised. As one looks further ahead, the required specifications could be matched by more than one development from current capabilities and the discussions are intended to reflect that, while focusing on the most promising options as viewed today. It is also accepted that serendipity has historically played an important role and that capabilities not widely emphasised even five years ago can now be regarded as highly desirable or essential to achieving the physics goals driving the updated particle physics strategy. It is not possible to foresee all the different ways current detector research activities may evolve to enable future experimental programmes but the need for greater coherence and coordination across Europe (and more widely) in many areas has come out clearly in discussions at the symposia. The Roadmap as presented (just as the European Particle Physics Strategy itself) is a snapshot of the perception of many of the leading experts at a particular time, and must itself also be subject to updating in the light of further developments. Nevertheless, it would also be a dereliction of the Roadmap Panel's obligations not to provide guidance on what are currently viewed as the most urgent topics to address if the future experimental programme is not to be compromised.

Detector technology development is a necessary but hardly sufficient basis for future progress in experimental particle physics. Talented and committed people are really the core requirement. They need to be enthused, engaged, educated, empowered and employed. The scientists, engineers and technicians who will build the future facilities need to be carefully nurtured and incentivised by appropriate and rewarding career opportunities. Without a constant infusion of bright individuals with a wealth of new

[3] These could be coupled with some of the demonstrators discussed in the corresponding Accelerator R&D Roadmap document.

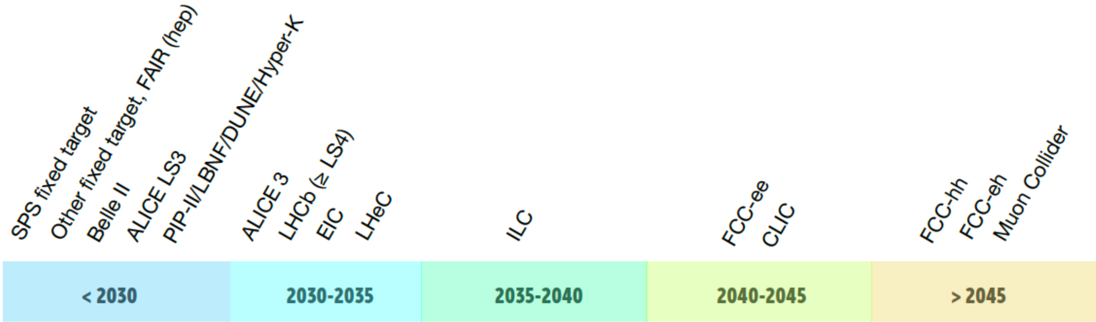

Figure 3: Large Accelerator Based Facility/Experiment Earliest Feasible Start Dates.

ideas and the drive to realise these, the field of detector R&D for particle physics would wither and die. It has become evident in the process of compiling this Roadmap that many at early stages of their careers have a real passion for wholehearted engagement in the instrumentation aspects of particle physics, if only a number of real and perceived obstacles could be overcome and some negative attitudes of those who are able to shape their longer-term career prospects could be addressed. Recommendations in the following chapters and in the conclusions also reflect the all-important human aspects of ensuring a healthy future for the particle physics detector R&D activities which will be essential to allowing the ambitious envisaged future experimental programme to be realised.

Figure 3 shows an indicative future timeline for future collider and larger accelerator facilities, while Figure 4 shows that for non-accelerator and smaller accelerator experiments. Although the Roadmaps for both detector and accelerator R&D are focused on deliverables over the next five to ten years, they can only be developed and prioritised with some knowledge of the target dates for the final facilities. On the other hand, the projects shown in the diagrams are at differing stages of definition, approval and technical maturity. The dates shown in the diagram therefore have low precision, and are intended to represent the earliest 'feasible start date' (where a schedule is not already defined), taking into account the necessary steps of approval, development and construction for machine and civil engineering. They do not constitute any form of plan or recommendation, and indeed several options presented are mutually exclusive. Furthermore, the projects mentioned here are limited to those mentioned in the EPPSU, although it should be noted that detector R&D for other possible future facilities is usually aligned with that for programmes listed in Figure 3. For example, there are large overlaps and synergies between the R&D for the proposed CEPC in China and FCC-ee and in some cases also to the proposed experiments at either the ILC or CLIC. The timelines – and potentially the scope – of the projects will naturally change depending on future strategic decisions. The objective of the Roadmaps is to ensure that: (a) the basic R&D phase is not the limiting step, i.e. that R&D is started sufficiently early and prioritised correctly to meet the needs of the long-term European particle physics programme in its global context; and (b) that the outcomes of the R&D programme are able to provide the necessary information on the feasibility and cost of future deliver-

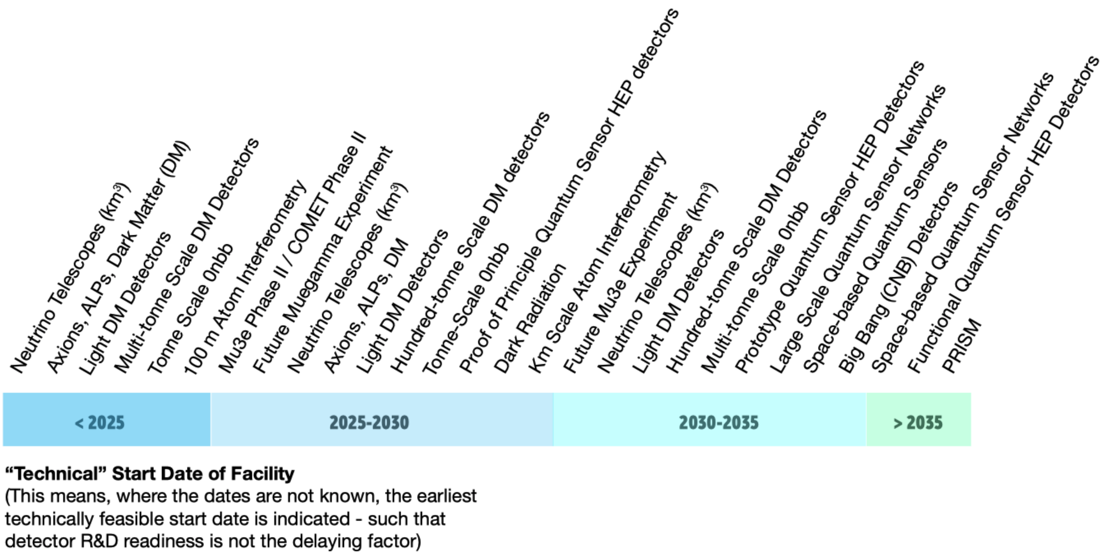

Figure 4: (Representative) Smaller Accelerator and Non-Accelerator Based Experiments Start Dates (*not intended to be at all an exhaustive list*).

ables to allow such decisions to be made. In Figure 4 the information for a variety of smaller accelerator and non-accelerator based experiments is presented, where possible, grouped in the overarching physics themes they address. For each of the relevant Task Forces, a set of detector R&D aspects are identified which are required if the physics programmes of experiments at these facilities are not to be compromised.

In the ECFA Detector R&D Roadmap the focus has been on facilities targeting the properties and interactions of fundamental particles (including those that are undiscovered but theoretically motivated). It is appreciated that a number of particles increasingly play the role of cosmic messengers for phenomena happening far beyond our own galaxy which provides some of the exciting science opportunities in the neighbouring field of astro-particle physics, but the demanding detector requirements specific to this area are not generally within the scope of this document.

Throughout the following chapters, these figures inform the development of the Detector R&D Roadmap with a view to set concrete target timelines for the readiness of the recommended R&D thematic programmes emerging in each Task Force and summarised in Chapter 11. As the list of EPPSU facilities/areas shows, there are also many R&D requirements for upgrades to ongoing experiments or new experiments at existing facilities. It also discusses a wealth of future particle physics detector developments requiring R&D on highly specialised and advanced technologies at smaller accelerator and non-accelerator based experiments which are also described in the relevant sections.

The common introductory figures at the start of the following chapters are designed to capture where there are strong needs for new R&D activities in support of these programmes. The aim is not to provide an exhaustive list of all the running or future particle physics or particle physics related experiments, but to try to draw attention to major areas of unmet detector requirements which may benefit from more general (rather than with high specificity to a single experiment) R&D programmes.

The introductory figures ("Detector Readiness Matrices") intend to be a graphical representation focusing only on where significant R&D is required beyond incremental improvements to current capabilities. The colour coding is linked not to the intensity of the required effort but to the potential impact on the intended physics programme at the experiment. In some cases, absence of the proposed R&D would compromise the main motivation for the experiment as a whole (red, largest dot). In other cases, the R&D is required to ensure that many of the physics goals can be met (orange, large dot); or is desirable to enhance the physics reach and therefore gain maximum benefit from the investment in the facility (yellow, medium dot). In addition, in some cases the needs will be met from current R&D activities (green, small dot) while in others no further R&D is required or it is not relevant (blank). The tables should only be taken as a crude and imperfect summary of the much more detailed discussions in the text of each chapter but hopefully they illustrate how R&D needs are expected to broadly evolve with time.

It will be seen that in each chapter, the corresponding Task Forces have identified a number of recommendations particular to their technology area, also taking account of the community inputs they have received, and each provided a list of Detector R&D Themes (DRDTs) and Detector Community Themes (DCTs) which capture a number of the most pressing aspects of their R&D requirements. These are collated in the Conclusions (Chapter 11) along with a number of the most urgent related recommendations. Topics which have come up multiple times as being of more general significance to the community are also discussed in Chapter 10, "General Observations and Considerations". From these, a number of high level proposals and recommendations, based on the Panel's deliberations, are also offered for consideration in Chapter 11.

Finally, Appendix A contains a glossary of the most commonly used acronyms in the various sections; Appendix B lists those who have participated directly in the drafting of this document; while Appendix C acknowledges the many other contributors and provides further information on the Input Sessions, Symposia and the contact list for the Advisory Panel with Other Disciplines (APOD).

References Introduction

[Ch0-1] https://europeanstrategy.cern.

[Ch0-2] The European Strategy Group, *Deliberation document on the 2020 Update of the European Strategy for Particle Physics*, CERN-ESU-014, 2020. https://cds.cern.ch/record/2720131.

[Ch0-3] https://indico.cern.ch/e/ECFADetectorRDRoadmap.

Chapter 1

Gaseous Detectors

1.1 Introduction

Gaseous Detectors (GDs) have been pivotal to the history of nuclear and, later, particle physics since the use of the first Geiger counters (dating back to 1908) and have represented the first approach to fine spatial resolution with the introduction of the MultiWire Proportional Chamber (MWPC) in 1968. Their role in particle physics experiments remains central, as testified by their use in the trigger and muon systems of all major LHC experiments (ALICE, ATLAS, CMS, LHCb) largely based on extended GD sets; while novel concepts within the same experiments are being developed for the next LHC data taking periods. The ongoing upgrades include the ALICE TPC with Gas Electron Multiplier (GEM) readout [Ch1-1]; the ATLAS muon system making use of Micro-mesh gaseous structure (Micromegas) [Ch1-2], small Thin Gap Chambers (sTGC) and Resistive Plate Chambers (RPC) [Ch1-3]; and the CMS muon system, where the endcaps are being instrumented with GEMs [Ch1-4] and improved RPCs [Ch1-5]. Large GD arrays, such as RPCs, have been widely used in large-scale experiments (including the ultra-high energy cosmic ray observatories [Ch1-6]), that demand low cost detector units able to operate reliably and cover large areas, with high efficiency and low power consumption, even in outdoor environments and with minimal maintenance.

The explanation of this persistent success is related to the main characteristics of GDs, namely the capability to cost-effectively instrument large areas, low material budget, operation in the presence of magnetic fields and radiation hardness; while their spatial and time resolution, along with high-rate capability performance, are continuously improving thanks to a world-wide community dedicated to R&D in this field. No other detector technology is providing a similar diversity of uses. The rich panorama of up-to-date GDs makes them adequate for a variety of applications in fundamental research domains and beyond, in spite of the operational complexity posed by the needs of high voltage and gas supplies. The portfolio of novel ideas promises innovative approaches and improved performance, while the experimental set-ups at the major future collider facilities as well as several future research programmes in the nuclear, astro-particle, neutrino and rare-event areas all require the use of GDs.

The main activity areas corresponding to the major drivers from future facilities, which will be analysed in this chapter, can be effectively summarised in the set of Detector Research and Development Themes listed below.

DRDT 1.1 - Improve time and spatial resolution for gaseous detectors with long-term stability.

DRDT 1.2 - Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different readout schemes.

DRDT 1.3 - Develop environmentally friendly gaseous detectors for very large areas with high-rate capability.

DRTD 1.4 - Achieve high sensitivity in both low and high-pressure TPCs.

The R&D needs for these areas are categorised schematically versus time in Figure 1.1. Based on these it can be seen that the R&D programmes for DRDT 1.1, DRDT 1.2 and DRDT 1.3 are linked to deliverables for multiple programmes in each of the half decades listed in Figure 3 and Figure 4 of the previous chapter up to the time of the FCC-ee; with DRDT 1.1 and DRDT 1.3 needed also for the FCC-hh/muon collider era. This is illustrated in Figure 11.1 with explanation of the diagram in the caption and corresponding text. As also discussed in Chapter 2, R&D for even longer-term facilities addressing topics in the nuclear, astro-particle, neutrino and rare-event areas will certainly be needed beyond the timelines shown in Figure 11.1 but it is not sensible today to attach dates to such further future projects.

1.2 Main drivers from the facilities

1.2.1 Muon systems

GDs will remain the primary choice for muon tracking and triggering at future facilities whenever cost-effective, large-area coverage with low material budget and high detection efficiency is required. Moreover, muon systems are often designed to provide a precise momentum measurement, usually in combination with an inner tracker. The use of fast gas mixtures, together with an optimisation of the geometry and the electric fields, has led to different design GDs (e.g. RPC, Cathode Strip Chambers (CSC), TGC, GEM) for trigger and bunch-crossing tagging in the major LHC experiments (ATLAS, CMS, ALICE and LHCb). Precision nanosecond-level timing also helps to mitigate pile-up effects and to reduce uncorrelated beam-induced backgrounds, while improving the sensitivity for heavy long-lived particle searches (e.g. slow muon-like particles with $\beta < 0.9$).

Moving from LHC to HL-LHC, the currently installed GDs in ATLAS [Ch1-3] and CMS [Ch1-7] (i.e. RPC, CSC, Drift Tubes, TGC) will remain in most of spectrometer

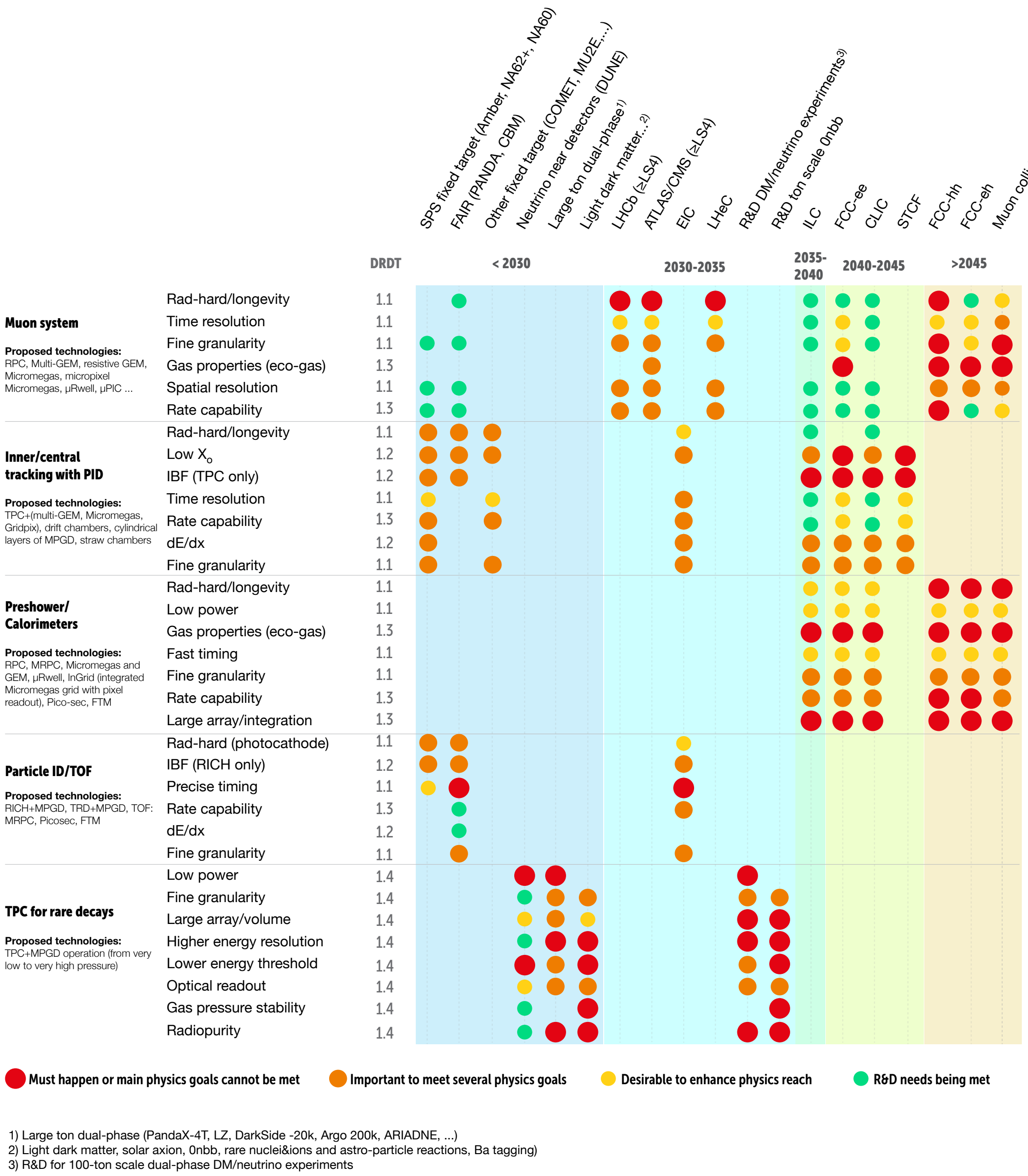

Figure 1.1: Schematic timeline of categories of experiments employing GDs together with DRDTs and R&D tasks. The colour coding is linked not to the intensity of the required effort but to the potential impact on the physics programme of the experiment: Must happen or main physics goals cannot be met (red, largest dot); Important to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); No further R&D required or not applicable (blank).

areas for muon tracking and triggering. Their performance, radiation hardness, and longevity have been demonstrated for a wide range of operating conditions at different irradiation facilities. Some detectors will undergo major electronics upgrades to cope with higher trigger rates and bandwidth requirements (e.g. triggerless DAQ readout in ALICE and LHCb). Other upgrades, targeting LHC running from 2022 (Run 3) and beyond, are the addition of new muon stations, at different pseudo-rapidities, with improved rate capability, spatial and timing resolution. These will complement existing GDs to ensure redundant tracking, triggering and momentum determination and significantly decrease L1 muon trigger rates.

In particular, new RPCs with smaller gap size (1 vs 2 mm), High Pressure Laminate (HPL) electrodes with reduced resistivity, and the latest generation of front-end electronics ASICs (noise $< 4000\,\mathrm{e}^-$) will be installed in the ATLAS Muon Barrel spectrometer during LS3 together with a new small diameter (15 vs 30 mm) Muon Drift Tubes (sMDT) [Ch1-8]. Similarly, new double gap RPC with smaller gap size (1.4 vs. 2 mm) and reduced electrode resistivity will start operation in the CMS Muon endcap for the LHC Run 4 (the beginning of HL-LHC running).

There have been major Micro-Pattern Gaseous Detectors (MPGD) developments for ATLAS and CMS muon system upgrades (from Run 3 onwards), towards establishing technology goals, and addressing engineering and integration challenges. A big step in the direction of large-scale applications has been obtained with both improved conceptual consolidation and industrial plus cost-effective manufacturing of MPGDs by developing new fabrication techniques: resistive Micromegas (to suppress destructive sparks in hadron environments) and single-mask with self-stretching GEM techniques (to enable production of large-size foils and significantly reduce detector assembly time). Scaling up of MPGDs to very large single unit detectors of $\mathcal{O}(\mathrm{m}^2)$, has facilitated their use in LHC upgrades: Micromegas in combination with sTGC will instrument an area of $\mathcal{O}(1000\,\mathrm{m}^2)$ in the ATLAS New Small Wheel [Ch1-9], while GEMs will equip the stations GE1/1 and GE2/1 to complement CSC in the CMS Muon endcaps [Ch1-10]. Exploiting Micromegas, GEM, and Micro-Resistive WELL (μ-RWELL) ability to measure both the position and arrival time of the charge deposited in the drift gap, a novel μ-TPC concept has been developed; it permits achieving nearly constant spatial resolution over a wide range of particle incident angles and allows 3D-track reconstruction with a single MPGD layer [Ch1-11].

For HL-LHC operation from 2025 onwards, the CMS muon system (ME0 station) [Ch1-12], based on GEMs with high granularity and spatial segmentation, will be installed during LS3 to ensure efficient matching of muon stubs and offline pixel tracks at large pseudorapidities. Several solutions (μ-RWELL) [Ch1-13], Micro Pixel Chamber (μ-PIC) [Ch1-14] and small-pad resistive Micromegas [Ch1-15]) were initially considered for the very forward muon tagger in the ATLAS Phase II Upgrade Muon TDR proposal [Ch1-2]. Here, the main challenges are discharge protection and miniaturisation of readout elements [Ch1-16], [Ch1-17], which can profit from the ongoing developments on Diamond-Like Carbon technology [Ch1-18], [Ch1-19]. The μ-RWELL approach is also considered as one of the tracker options in LHCb beyond LS4 [Ch1-20]. GDs are also proposed for the future CBM [Ch1-21] and PANDA experiments [Ch1-22] at the

FAIR facility. A GEM-based muon tracker with zigzag readout strips is foreseen at NA60+ [Ch1-23]. Zigzag strips can cover a readout area with fewer strips than regular straight ones while maintaining good spatial resolution ($\sim 100\,\mu$m) and rate capability ($10\,$kHz/cm^2). Addressing the short-term R&D needs for the existing muon systems beyond 2023 will require improvement of operation procedures to guarantee their longevity and stable, discharge-free, operation at high rates, and mitigation strategies for the use of greenhouse gases when it becomes mandatory (DRDT 1.3).

Muon systems at future e^+e^- colliders (ILC, FCC-ee, CLIC, SCTF) or LHeC do not pose significant challenges in terms of particle fluxes and radiation environment. The IDEA detector layout concept at FCC-ee will require operation at rates up to $10\,$kHz/cm^2, spatial resolution of $\sim 60 - 80\,\mu$m and a time resolution of 5-7 ns, with the total integrated charge $< 100\,$mC/cm^2. Currently available technologies (RPC, sMDT, MPGD) can be used to instrument large-area $\mathcal{O}(1000\,\mathrm{m}^2)$ FCC-ee muon detectors. The ILC muon system/tail catcher technologies can include RPC or MPGD, as for Hadron Calorimetry (HCAL). Some engineering challenges are related to the operation in the high magnetic flux return (up to several Tesla). Generally, background rates in LHeC muon detector, which is based on the updated design of ATLAS Phase II Muon spectrometer, are lower than in *pp* colliders.

The muon tracking and triggering at a future hadron collider, such as FCC-hh, also requires large area coverage ($\sim 3000\,\mathrm{m}^2$), while particle rates do not exceed $0.5\,$kHz/cm^2 in the barrel and below $500\,$kHz/cm^2 in most of the endcaps. The existing technologies for HL-LHC (MPGD, RPC, sMDT, sTGC) are adequate in most of these muon spectrometer areas. However, major R&D would still be needed for the very forward endcap region at a radius below 1 m.

In a multi-TeV muon collider, the Beam Induced Background (BIB), due to muon decays, dominates in the endcap region, reaching a maximum flux of $\mathcal{O}(\mathrm{MHz/cm}^2)$. Based on the CLIC detector concept [Ch1-24], [Ch1-25], the muon system will be based on instrumented iron yoke plates with the option to use gaseous detectors in either or both of the barrel and endcap. A new generation of fast-timing GDs based on glass RPC, Multi-Gap RPC (MRPC), or fast timing MPGD (FTM) [Ch1-26], [Ch1-27] and PICOSEC [Ch1-28] are being developed, with a goal to achieve timing resolution of $\mathcal{O}(100/\mathrm{ps})$ and to reject off-time BIB hits. The main challenges at future facilities, particularly beyond 2030, include large area coverage with precision timing information (DRDT 1.1) to ensure correct track-event association, and the ability to cope with large particle fluxes using environmentally friendly gas mixtures (DRDT 1.3). Figure 1.2 summarises the main facilities, the proposed technologies to address the main challenges, and the most stringent conditions expected in muon systems.

1.2.2 Inner and central tracking with particle identification capability

The general requirement for central tracking with GDs are to ensure high-rate capability and excellent spatial resolution for precision momentum measurement and particle identification (PID) with a minimal material budget and lightweight mechanical support structures (DRDT 1.2). Straw tubes, drift chambers, planar or cylindrical MPGDs also

Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm² Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm² (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA):** Max. rate: 10 kHz/cm² Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm²
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm² ($\theta<8^0$) < 2 kHz/cm² (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm²
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR):** Max rate: <500 kHz/cm² Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10^{13} neq/cm²/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm² Spatial resolution = 50 μm Angular resolution = 70 μrad (η=0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

Figure 1.2: Main drivers for the Muon Systems at future facilities. The most stringent requirements for the future R&D activities are quoted in the last column.

using μ-TPC mode (Section 1.2.1), and TPCs with MPGD readout are widely employed.

Straw trackers

The technique of self-supporting straw tubes with thin anode wire and an aluminised Mylar cathode wall offers a combination of short drift time, low mass, and high spatial resolution tracking by using long (a few meters) and small diameter (< 1 cm) straws, arranged in planar layers and mounted in a hexagonal array. Innovative straw detectors are foreseen at both future storage rings and fixed target facilities.

One example of the large-scale straw detector is the ATLAS Transition Radiation Tracker, based on 4 mm diameter tubes and $\sim 250,000$ straws. The state-of-the-art NA62 straw tracker, with a tube diameter of 9.8 mm and a wall thickness of 36 μm, leading to material budget of $\sim 0.045\%$ X/X_0, operates directly in the experiment's vacuum tank at rates up to 40 kHz/cm (500 kHz/straw), and requires ageing resistance up to ~ 1 C/cm/wire [Ch1-29]. NA62 has developed new construction techniques of ultrasonic welding to close the straw (and to keep them straight and withstand the vacuum pressure without breaking) - an important breakthrough for future experiments. The straw detector in the PANDA experiment at FAIR will be based on the 10 mm diameter and 1.5 m length tubes, made of a 27 μm thick Mylar foil, allowing to reduce detector thickness to $\sim 1.2\%$ X/X_0 (where 2/3 comes from tube walls and 1/3 from the gas), and to achieve spatial resolution of ~ 150 μm. A straw tracker has also been proposed for the NA62 upgrade, where a four times higher beam intensity is expected. This work has synergies with R&D for COMET Phase-II [Ch1-30] at JPARC and Mu2e-II [Ch1-31] at Fermilab, where the goal is to develop Mylar thin-walled (8 μm), narrow-gauge (less than 5 mm) straw tubes using the ultrasonic welding technique. This will allow decreasing the material budget to $X/X_0 \sim 0.02\%$ per tube. The smaller diameter will lead to a reduction of the drift time and improvement in the trailing-edge time resolution from currently 30 ns to an ultimate goal of ~ 6 ns (per straw) and 1 ns (per track).

Planar and cylindrical MPGDs
Due to the variety of geometries and flexible operating parameters, MPGDs fulfil the most stringent experimental constraints imposed by future nuclear, hadron physics experiments, and heavy ion facilities, i.e. Electron-Ion Collider (EIC), offering intrinsic high-rate capability ($\sim 10^6$ Hz/mm^2), spatial resolution (down to 30 μm), multi-particle resolution ($\sim 500\,\mu$m), and superior radiation hardness [Ch1-32]. Although normally used as planar detectors, GEM, Micromegas, and μ-RWELL can be bent to form cylindrically curved ultra-light inner tracking systems, without support and cooling structures, as implemented in KLOE-2, BESS-III, ASACUSA, MINOS, CMD-3, and proposed for the EIC and SCTF.

At the EIC [Ch4-2], all proposed detector concepts feature some form of large area MPGDs for barrel and forward tracking. Light-material planar Micromegas, μ-RWELL or GEMs, are the main options for forward tracking to achieve a momentum resolution of $\sigma(p_T)/p_T \sim 0.1\ \% \times p_T \bigoplus 2\%$ with a material budget of $X/X_0 \leq 5\%$. Disk realisation with Cr-GEM foils is proposed where the Cu electrodes are reduced to the mere adhesive Cr-film with 50% less material compared to standard GEMs [Ch1-33]. Spatial resolution of 100 μm can be reached with a reduced number of readout channels thanks to a zigzag pad layout. Vigorous R&D is also needed for EIC barrel tracking, where multi-layer cylindrical MPGDs (Micromegas, GEM, or μ-RWELL) or a TPC with MPGD readout and an additional external cylindrical MPGD layer are being considered. The TPC approach has an advantage of high density of space points per track, which enables ionisation loss measurement for PID (DRDT 1.2); however, the TPC is slower and more challenging than MPGD-based tracking at rates $\mathcal{O}$(kHz/cm^2).

The requirements for central tracking at high luminosity future lepton colliders favour an ultra-light tracker to fully exploit the cleanliness of the e^+e^- environment for precision electroweak physics, and for flavour physics, where the average charged particle momenta (few MeV to few GeV) are in a range over which the multiple scattering contribution to the momentum resolution is significant. The main technologies for tracking at "Higgs Factories" are: Drift Chambers (FCC-ee, CePC) and TPC with MPGD readout (ILC, CePC). The SCTF tracking system will comprise of Inner Tracker (TPC or cylindrical MPGDs) and a drift chamber [Ch1-34].

Drift chambers. DAFNE's KLOE drift chamber [Ch1-35] and the recent version of it developed for the MEG2 experiment [Ch1-36] are the precursors of the next generation of ultralight weight central trackers for the future e^+e^-colliders [Ch1-37]. The IDEA drift chamber at FCC-ee is based on a high granularity, low mass cylindrical drift chamber, coaxial to the 2 T solenoid field, which is expected to operate at a maximum rate of ~ 25 kHz/cm^2, with spatial (time) resolution $< 100\,\mu$m (~ 1 ns) in a very light gas mixture (He/iC$_4$ H$_{10}$). Particle separation is foreseen using a cluster counting technique at a dE/dx $< 3\%$ level and momentum resolution of $\sigma(p_T)/p_T \sim 0.40\%$ is required at

100 GeV/c. Main peculiarities of the drift chamber IDEA are its high transparency, in terms of radiation lengths, which leads to minimal multiple scattering and secondary interactions; the material budget in barrel (endcap) regions is designed to be equivalent to $\sim 1.6\% X_0$ ($\sim 5\% X_0$).

Since the main contribution in terms of radiation length is related to tungsten wires, high transparency can be achieved thanks to a novel approach for the wiring and assembly procedures, stemming from the original ancestor KLOE drift chamber, and recently culminating in the construction of the MEG2 drift chamber. The main R&D is related to new wire materials: in particular carbon monofilaments obtained through high-power impulse magnetron sputtering techniques. The proposed drift chamber at SCTF will consist of O(100 k) thin wires, instrumented with new readout electronics implementing the cluster counting technique. The requirement for a maximum rate of $1\,\mathrm{kHz/cm^2}$ is less stringent than for drift chamber at FCC-ee, however, spatial ($< 100\,\mu$m), momentum ($\sigma_p/p \sim 0.38\%$ at 1 GeV) and dE/dx ($\sim 7.5\%$) resolutions, and radiation hardness (~ 1 C/cm) will be challenging.

Conventionally, drift chambers have been operated with hydrocarbon-based mixtures, which are not reliable for long-term, high-rate operation [Ch1-38], [Ch1-39]. A dedicated R&D is necessary to find an alternative hydrocarbon-free mixture adapted to the desired performance at future colliders.

Time Projection Chamber (TPC)

The "ultimate" drift chamber is the TPC concept, which provides 3D precision tracking with low material budget and enables PID through dE/dx measurement or cluster counting dN_{cl}/dx techniques; examples are continuous or pulsed mode (depending on beam structure) operation in magnetic fields that ranges from 0.5 T (ALICE) to 3.5 T (ILC). An important major innovation is related to the replacement of MWPC with MPGD for the TPC endplate readout, which allows greater geometrical design freedom, and offers many advantages: reduced pad-angle, track-angle, and negligible $E \times B$ track distortion effects, narrower pad response function, and intrinsic suppression of Ion Back Flow (IBF) [Ch1-40]. The use of Micromegas with resistive layers allows spark protection and further pad response function tuning. The upgraded ALICE TPC with GEM readout, which will operate from LHC Run 3 onwards, and T2K Near Detector TPC based on Micromegas represent the state-of-the-art in TPC technology.

Large TPC R&D efforts are ongoing within the LCTPC collaboration [Ch1-41]. The required ILC TPC performance in a 3.5 T field (with material budget below $10\% X_0$) is a momentum resolution $\Delta(1/p) < 10^{-4}\,\mathrm{GeV^{-1}}$, corresponding to a single-hit transverse (longitudinal) resolution better than $100\,\mu$m (1 mm) over more than 200 3D-space points and a dE/dx resolution superior to 5% [Ch1-42], [Ch1-43]. Three MPGD approaches are pursued for the ILC TPC: GEM, Micromegas, and GridPix. The GEM option is based either on a triple-GEM stack with a standard chemically etched thin-foil Cu-kapton-Cu sandwich or double-GEM with Liquid Crystal Polymer GEMs [Ch1-44]. Development of innovative encapsulated resistive anode Micromegas, based on a bulk technology and a Diamond-Like Carbon thin layer sputtered on a $50\,\mu$m thick insulator sheet [Ch1-45], [Ch1-46], profits from R&D synergies between the ILC TPC and the

T2K-II Near Detector TPC. A real breakthrough towards a pixel TPC is the development of an endplate with a 160 GridPix detectors (each $\sim 2\,\mathrm{cm}^2$), corresponding to 10.5 million pixels, and read-out with the RD51 Scalable Readout System [Ch1-47]. One of the main TPC limitations is the field distortions in the drift volume coming from the space charge of ions due to the IBF process. MPGD-based readout allows suppression of IBF values to $\sim 5 \times 10^{-2}$ ($\sim 2 \times 10^{-3}$) in multi-GEM (Micromegas) and to below 1% in a cascaded GEM-Micromegas structure, originally developed to suppress sparks. The ILC beam bunch structure allows the implementation of a TPC gating scheme, based on large-aperture GEMs with honeycomb-shaped holes, while keeping high electron transparency [Ch1-48].

Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	MPGD	High spatial resolution, high rate/occupancy, radiation hardness, low mass	**LHCb option:** replace Scintillating Fibre tracker Spatial resolution:70 µm bending plane
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	TPC+(multi-GEM, Micromegas, GridPix), Drift Chambers, Cylindrical layers of MPGD	Ultra-lightweight inner or central tracker, high spatial resolution, high rate/occupancy, radiation hardness, low mass, transparency, cluster counting, TPC continuous mode at high rate, (IBF x Gain) ~1	**Inner tracker (SCTF)** Fluxes: ≥10 kHz $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ Time resolution: 1 ns X/X0 = 1% Spatial resolution: ~100 µm **Central tracker (CepC)** Max. rate: >100 kHz/cm^2 Spatial resolution: ~100 µm Time resolution: ~ 100 ns dE/dx: <5% Particle separation with cluster counting at 2% level
Rare processes, atomic and nuclear physics (SPS Kaons: K^+ Phase, K-Phase, Mu2eII/COMET-II, ELENA)	TPC, straw tubes	High spatial resolution, occupancy, fast/precise timing, radiation hardness, low mass, Gd-deposited MPGD detectors	Max rate = 500 kHz/straw **(Mu2e II)**: Thinner straw material: 8 µm X/X0 ~ 0.02% per layer, X/X0 ~ 1% total **(COMET+)**: Diameter = 4.8 mm Trailing time resolution = 1 ns per track
Hadron and nuclear physics (EIC, AMBER, PANDA and CMB@FAIR, PRES MAINZ, NA60+	Micromegas, GEM, µ-RWELL, straw tubes	High spatial resolution, good timing, radiation hardness , tolerance to magnetic field	**(EIC)** Max rate = 100 kHz/cm^2 Spatial resolution ~50 µm X/X0 = 5% dE/dx=12%, continuos running

Figure 1.3: Main drivers for the Inner and Central tracking at future facilities. The most stringent requirements for the future R&D activities are quoted in the last column.

The TPC at CepC has been inspired by the ILC-TPC development. Contrary to ILC, Z-pole running at CepC luminosity of $\sim 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, does not allow gating mode TPC operation. In this situation, GridPix is an attractive option, which provides the high granularity needed to resolve individual electron clusters and to determine energy loss by the cluster counting technique, rather than by measuring the charge, with a precision of better than 3 %. Baseline candidates for an inner tracker at the SCTF are cylindrical MPGD or TPC readout with GEM, Micromegas, or GridPix. Inspired by the PANDA-TPC development[1], the latter aims to achieve transverse (longitudinal) spatial resolution in a 1 T field of about $50 - 100\,\mu$m ($\sim 300\,\mu$m), depending on the drift path. Figure 1.3 summarises the main facilities, the proposed technologies to address the main challenges, and the most stringent conditions expected in tracking systems.

[1]The PANDA-TPC has been abandoned in favour of a straw-tube tracker.

1.2.3 Calorimetry

R&D in particle-flow calorimetry is a major "paradigm shift" for high-resolution imaging calorimeters, which was originally an e^+e^- linear collider driven effort, but nowadays is highly relevant for HL-LHC upgrades and future facilities (see Chapter 6). Particle-flow hadronic calorimeters with alternating layers of absorbers and sampling elements, based on GDs, are considered for ILC, FCC-ee, EIC, FCC-hh and muon collider [Ch1-49].

The main differences between circular and linear e^+e^- colliders reside in the readout timing and the power pulsing, which if possible enables a larger effective density of the calorimeter and more compact particle showers. GD-based calorimeters with a typical cell size of $\mathcal{O}(1\,\text{cm}^2)$, together with a large number of sampling layers ($\approx$50 to contain hadronic showers) imply a very large channel count ($\mathcal{O}$(10k) per m^2). This requires thin gas layers, which might affect signal amplification and timing resolution, and embedded electronics integrated in a very compact system. Moreover, production of high planarity, large-area PCBs for MPGDs and mechanical fabrication issues of very thin High Pressure Laminate RPCs represent additional challenges. Single-stage structures, based on RPC, resistive-plate WELL (RPWELL) and Micromegas also require a very uniform resistivity, gas gap thickness (down to micron level), and well-modelled gas distribution inside the detector volume in order to guarantee uniform response in terms of signal efficiency, rate capability and timing resolution. Last, but not least, hermetic calorimeters are usually extended down to small polar angles where beamstrahlung particles deposit several MGy of dose per year. Therefore, radiation hard gaseous detectors are needed.

Facility	Technologies	Challenges	Most challenging requirements at experiment
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC,/SCTF)	RPC, Micromegas and GEM, µ-RWELL, GridPix, PICOSEC, FTM	High granularity, excellent hit timing, large area detectors, stabiliy, uniform response, eco-gases	**(ILC)** Max. rate:1 kHz/cm² Granularity (~1 cm²) Radiation hardness: no Jet Energy resolution: 3-4 % Power-pulsing, self-triggering readout
Muon collider	RPC, Micromegas and GEM, µ-RWELL, GridPix, PICOSEC, FTM	High granularity, radiation hardness, excellent hit timing, stabiliy, uniform response, eco-gases	Granularity (~1cm²) Fat jet identification Time resolution= O(100ps) Energy resolution =(5%)/sqrt(E) for fat-jet High radiation hardness
Hadron physics (EIC)	RPC, Micromegas and GEM, µ-RWELL, GridPix, PICOSEC, FTM	High granularity, radiation hardness, excellent hit timing, stabiliy, uniform response, eco-gases	**(EIC option)** DHCAL

Figure 1.4: Main drivers for Calorimeters at future facilities. The most stringent requirements for the future R&D activities are quoted in the last column.

Digital or semi-digital hadronic calorimeters, based on one- or two-bits ADC [Ch1-50], were advanced within the CALICE collaboration [Ch1-51]. In a semi-digital hadronic calorimeter, the energy measurement relies on the approximate linear relationship between the particle energy and the number of associated hits and requires sampling elements with high detection efficiency and a low pad hit multiplicity per traversing particle. Glass RPC [Ch1-52], GEM, RPWELL [Ch1-53] and Micromegas [Ch1-54] have been studied as potential sensing elements for the ILC Semi-Digital Hadronic Calorimeter. Larger area RPC prototypes were subsequently built to verify the scalability of the fabrication process and to address engineering challenges. Ultra-fast picosecond-timing information with technologies like MRPC, PICOSEC and FTM can be used to resolve the development of hadron showers, resulting in a smaller "confusion term" and to improve jet energy resolution in hadronic calorimeters. The main challenges of the future R&D in the GD-based calorimetry is to ensure a uniform response over the large detector area (DRDT 1.1), and operation with eco-friendly gas mixtures (DRDT 1.3). Figure 1.4 summarises the main facilities, the proposed technologies to address the main challenges, and the most stringent conditions expected for calorimetry.

1.2.4 Photon detection

Gaseous photon detectors have been developed as single photon sensors for one of the most effective approaches to high-momentum particle identification, namely by Ring Imaging Čerenkov (CHerenkov) Counters (RICHs) with gas as the radiator medium (see Chapter 4). The driving considerations for this approach are the main features that characterise the GDs: cost-effectiveness, very low material budget and minimal sensitivity to magnetic fields. At future colliders, when particle identification is needed, as at the EIC or e^+e^- factories, gaseous RICH based systems are the only possible options for PID at high momentum. This is particularly an issue at high pseudorapidity where PID is required for particles at high laboratory momenta.

Three generations of gaseous photon detectors have been developed [Ch1-55]: the GDs with converting vapours included in the gas mixture, open geometry MWPC with solid state CsI-photocathodes, and MPGD-based detectors with CsI-photocathodes. This historical development matches the need to provide progressively better solutions to the challenging requirements in this field, namely: (i) to reduce the photon feedback generated in the multiplication process which leads to spurious signals; (ii) to reduce the IBF rate because the ion bombardment destroys the proportional chamber and limits the lifetime of the detector (R&D line in common with TPC needs, DRDT 1.2) and (iii) to improve the detector performance in term of spatial and time resolution, along with fast response in order to open the way to high rate capabilities and precision measurements (DRDT 1.1).

MPGD-based photon detectors have been pioneered with the Hadron Blind Detector of the PHENIX experiment [Ch1-56]. Three layers of GEMs with a CsI layer as photoconverter were operated in a threshold Čerenkov counting mode. MPGDs are now in operation for single photon detection in the COMPASS RICH where a hybrid architecture formed by two THGEM layers is adopted [Ch1-57]. The first layer is coated with a CsI film, and a Micromegas acts as a third amplification stage. A quintuple GEM detector is considered for the photon detection at the EIC in a windowless RICH configuration [Ch1-58]. This new generation of gaseous photon detectors represents a major step forwards with respect to all three specific challenges: the intrinsic properties of MPGDs match the improved performance requirement (iii); a multi-layer GEM or THGEM architecture has no optical transparency and, therefore, removes photon feedback (i); IBF is reduced to a few percent because a significant fraction of ions are trapped in the intermediate layers (ii). Dedicated geometries derived from the GEM technology adding extra electrodes and, therefore, increasing the operation complexity, such as in the double micromesh arrangement, in the Micro Hole and Strip Plate (MHSP) [Ch1-59] and in the COBRA [Ch1-60] design, allow for IBF reduction down to O(10^{-4}). In spite of this progress, the residual IBF poses limitations to photocathode durability and to the selection of photoconverting materials. CsI, with sizeable quantum efficiency (QE) only in the far UV region, has been used as a photocathode material because of its relatively high work function, which makes it more robust than others commonly used in vacuum-based detectors. In fact, CsI photocathodes, exposed to atmospheres with oxygen and water vapour contamination at a few ppm level, are robust at low integrated IBF and can preserve their QE over periods of years with a modest decrease. The use in GDs of solid state photoconverters in the visible range is desirable, even if challenging due to their fragility and chemical reactivity. Nevertheless, it is being pursued, even if maturity for adoption in an experiment is far from being accomplished. Novel, more robust photon converters are urgently needed. A systematic study of the hydrogenated nano-diamond powder photocathodes coupled to MPGD-based photon detectors is ongoing [Ch1-61]. The initial studies indicate its compatibility with gaseous atmospheres, reduced chemical reactivity and limited ageing by ion bombardment. Diamond-Like Carbon has also been proposed as a photoconverter candidate.

Nowadays, gaseous photon detectors are not restricted to Čerenkov counters. They are proposed for cryogenic noble liquid detectors in rare-event experiments (QUAX (Section 1.2.6) and are able to detect the luminescent light produced by the multiplication processes in the gas (Section 1.3.1). They can provide fine time resolution response by detecting the Čerenkov light produced by ionising particles in compact radiators thanks to the intrinsic isochronism of the produced Čerenkov radiation (Section 1.3.1).

Facility	Technologies	Challenges	Most challenging requirements at experiment
Hadron and nuclear physics (EIC, AMBER, PANDA and CMB@FAIR)	**Gaseous-RICH** with MPGD-based photon detector **TRD** with GEM or GridPix	- **RICH:** Compact, single photon detection, high gain, fine spatial and time resolution, eco-friendly gas radiator, high pressure; limited IBF, novel photoconverters - **TRD:** cluster counting technique, heavy gas for X-ray absorption, TRD photon -dE/dx separation.	**(EIC-gaseous RICH)** 1 meter of radiator gas High-gain: 10^5 - 10^6 Spatial resolution: O(1mm pitch) Time resolution (even with small signals) $\lesssim$ 1n Tolerance to magnetic field (1.5 - 3 T) Rad-hardness up to 10^{11} neq/cm^2 option: High Pressure-Rich: Ar @ 3.5 bar **(EIC-TRD)** compactness 10^{-2} rejection in 20-30 cm improved MIP/x-ray identification
Higgs-EW-Top Factories (ee) (FCC-ee/CepC)	**Gaseous-RICH** with MPGD-based photon detector	- **RICH:** Compact, single photon detection, high gain, fine spatial and time resolution, eco-friendly gas radiator, high pressure, limited IBF, novel photoconverters	**(Gaseous-RICH):** High-gain: 10^5 - 10^6 Spatial resolution O(1mm pitch) Time resolution (even with small signals) $\lesssim$ 1ns

Figure 1.5: Main drivers for the RICH and TRD. The most stringent requirements for the future R&D activities are quoted in the last column.

Transition Radiation Detectors (TRDs) offer electron identification at high momenta, by detecting soft X-rays. Traditionally, MWPCs and straw tubes (with Xe-based mixtures) have been used within various accelerator-based experiments. Ongoing R&D activities in the context of preparatory studies for the experiment at EIC are dedicated to establishing GEM detectors as active elements in a TRD counter [Ch1-62], with the capability to provide tracking information. The option of a GridPix detector as the TRD active elements is also considered [Ch1-63]. A summary of the main challenges and proposed technologies at facilities for photon detection by GDs is presented in Figure 1.5.

1.2.5 Time of Flight Systems

Time of Flight (TOF) systems based on GDs are complementary to other PID techniques at low momenta in accelerator-based experiments, such as Čerenkov counters or energy loss dE/dx measurements. The identification of charged particles with momenta larger than 1 GeV/c, by means of measuring their TOF, requires a very good time resolution and a long flight path. Large TOF systems in use today typically achieve $\mathcal{O}(100\,\mathrm{ps})$ resolution. Ongoing R&D aims to improve this significantly. Refining of time resolution leads either to the same discrimination power at higher momentum or to a more compact systems (reduced time of flight) at the same momentum range.

Gaseous TOF systems are currently based on MRPC technology. The existing ALICE TOF detector, covering an area of $\sim 150\,\mathrm{m}^2$, has proved to be robust, stable and reliable and achieved a time resolution of ~ 60 ps [Ch1-64]. Another fundamental MRPC parameter is the rate capability. For example, the large-area TOF in the CBM experiment at FAIR is designed to operate at particle fluxes up to $30\,\mathrm{kHz/cm}^2$ with a time resolution of ~ 80 ps [Ch1-65]. Other TOF systems, based on MRPCs, include eTOF wall for the CEE experiment at HIRFL-CSR and the TOF detector in the SoLID experiment at JLAB. R&D has to continue towards an ultimate time resolution of ≤ 20 ps. This can be achieved by reducing the thickness of the gas gaps $\mathcal{O}(100\,\mu\mathrm{m})$ and by increasing the number of gaps (up to order of tens) to maintain a high efficiency. In addition, time resolution below $15 - 20$ ps is comparable to the avalanche jitter level, requiring novel very low noise front-end electronics. A rate capability up to $100\,\mathrm{kHz/cm}^2$, necessary for systems in high radiation environments, could be achieved by thinner (better signal induction), low resistive electrodes (order of $10^7\,\Omega\,\mathrm{m}$). MRPCs are currently studied in order to fulfil these requirements thanks to low resistivity, radiation hard ceramic electrodes [Ch1-66], [Ch1-67].

Facility	Technologies	Challenges	Most challenging requirements at experiment
Hadron and nuclear physics (CMB@FAIR, SOLID@JLAB, CEE@HIRFL-CSR)	MRPC, MPGD with precise timing (PICOSEC, FTM)	Rate capability, radiation hardness, large area detectors, new material, eco-gas, thinner structures, FEE, system time distribution	**(CMB)** Max Rate = 30 kHz/cm² Full system time resolution < 80 ps Occupancy < 5% Full system area = 120 m² ~100.000 channels, low power electronics

Figure 1.6: Main drivers for the TOF system. The most stringent requirements for the future R&D activities are quoted in the last column.

The front-end electronics needs to be improved with fast low-power amplification and continuous read-out. MPGD technologies for precision timing are FTM [Ch1-26], [Ch1-27] and PICOSEC [Ch1-28] with a goal to reach $\sigma(\mathrm{MIP}) \sim 25$ ps. Here the R&D is focused on scaling up to large area detectors which requires, in particular, to identify less expensive materials (radiators for PICOSEC) and very precise mechanical stability and uniformity ($\lesssim 10\,\mu\mathrm{m}$ flatness over $10 \times 10\,\mathrm{cm}^2$). Radiation-hard photocathodes (CsI) are also needed for the anticipated particle fluxes. The main challenge for future R&D is to be able to keep uniform response, in terms of high rate capability and time resolution (DRDT 1.1), over a large TOF detector area while operating with eco-friendly gases (DRDT 1.3). Figure 1.6 summarises the main challenges and proposed technologies at facilities using GD-based TOF systems.

1.2.6 TPCs for rare event searches

Gaseous TPCs are commonly used in rare event searches. Depending on the experimental needs one can vary the density of the gas to determine the track magnification or demagnification. Achieving high sensitivity in both low and high pressure TPCs, with differing readouts depending on the application, is a milestone for low-background rare event experiments (DRDT 1.4). Typically MPGD are used for the TPC amplification stage. Contrary to condensed phases, gaseous TPCs allow full 3D reconstruction of the nuclei recoils through elastic scattering together with the flexibility of choosing gas targets and operating pressures over a wide range. In particular, information about the direction of the nucleus can be obtained down to some 10's of keV (potentially allowing extraction of the apparent WIMP "wind" direction due to Earth's motion) for operation well below atmospheric pressure (20-130 mbar).

The most popular technique for direct detection of WIMP Dark Matter in the 100 GeV − TeV mass range is to observe low energy nuclear recoils ($\mathcal{O}$(1 - 100 keV)) using different types of physical signals: ionisation electron charge (e.g. MIMAC [Ch1-68], NEWAGE [Ch1-69]) and negative ions at 20-40 mbar (e.g DRIFT [Ch1-70]). Recent experiments focus on the operation at near-atmospheric or even high pressure. In fact, electron ionisation and optically based readout at 1 bar in CYGNUS [Ch1-71] will allow exploration of WIMP masses below 15 GeV using He/CF_4/SF_6 based TPC. Operation at 1-10 bar in Ar or Ne mixtures are considered at TREX-DM [Ch1-72] and with the NEWS-G spherical detector [Ch1-73], using solely radio-pure materials (μBq/cm^2) and purified light gases in order to achieve a low energy threshold ($\lesssim$ 1 keV) for low mass WIMP (0.1-10 GeV) searches.

Going down into the WIMP MeV-mass range, the MIGDAL experiment uses 14.1 MeV neutrons at a rate of 10^{10} Hz on a target gas (CF_4) at low pressure ($<$ 100 mbar) to detect visible MIGDAL [Ch1-74] electron tracks. Here the scintillation light from the electron multiplication in CF_4 is captured by a camera, while the amplified charge is collected at the indium tin oxide anode.

Solar axions conversions into low-energy $\mathcal{O}$(keV) photons can be detected in large TPC volumes operated inside strong magnetic fields. The future IAXO [Ch1-75], [Ch1-76] observatory, with an improvement of $\mathcal{O}$(1-1.5) of magnitude in sensitivity to g_α^γ with respect to the CAST [Ch1-77], aims to explore a range of axion masses up to 0.25 eV. It will be equipped with a 6 T magnet able to focus signal photons into $\approx 0.2\,\mathrm{cm}^2$ spots imaged by ultra-low-background "Microbulk" Micromegas, operating at atmospheric pressure.

In the field of low energy nuclear reactions, the next-generation active target multipurpose experiments will study very rare nuclear processes in inverse kinematics induced by low-intensity exotic beams. The TPC with an active target and a THGEM-Micromegas pad plane at the NSCL [Ch1-78] can operate under a 2 T magnetic field

Facility	Technologies	Challenges	Most challenging requirements at experiment
WIMP search (DRIFT, MIMAC, CYGNUS, MIGDAL, TREX-DM)	-TPC w/ MWPC/MPGD at 20-130 mbar, charge readout -TPC w/ MPGD at 66 mb/1 bar, charge and optical readout -TPC w/ MPGD at 1-10 bar, charge readout	High granularity, high gain, low background, very low noise level and fast electronics, self trigger capability, gas optimization	**(CYGNUS)** Gain = O(10^6) Spatial resolution = O(100 µm) Energy Threshold = 2 keVee Energy Resolution = 20% at 5.9 keVee Optical readout He:SF_6 or He:CF_4 at P = 1 bar
Solar axion helioscope (IAXO)	-TPC w/ pixelated Micromegas, GridPix, charge readout	High granularity, low background, radiopure electronics, self-trigger capability	High efficiency in ROI (0-10 keV) Spat. res = O(100 µm) Background: 10^{-7} c/keV/cm2 /s Xe at P = 1 bar B = 6 T
Low energy nuclear physics general purpose active target (AT-TPC, ACTAR)	-TPC+MM at 0.05- 3 bar, charge readout	Electronics with large dynamic range and flexible configuration. self-trigger capability, high pressure MPGD	(AT-TPC) B = 2 T P = 0.05-1 bar 3D-layout Generic target gases (H2, He, Ar, CO2. . .)
Neutrino physics and Neutrino-less double beta decay (DUNE-ND, NEXT, PANDAX-II)	-TPC+SiPM+PM: electroluminescence readout, -TPC+MM: charge readout	low background, energy resolution and topological rejection factors, scale to large volume, transparency and long drifting distance, high pressure, Ba++ tagging	**(NEXT)** P = 5-15 bar 3D-reconstruction of tracks through SiPM plane Energy resolution < 1% Ba++tagging
Neutrinos and DM search (Dune, DarkSide-20k, Argo, PandaX-4T, LZ, ARIADNE, Darwin)	- Dual-Phase TPC+MPGD	Large volume (uniform and stability response), ultra-low background, energy resolution, low energy thresholds, high granularity, charge extraction from liquid to gas, background rejection by prompt scintillation light -S1/ signal from the charge -S2 optimisation; Xenon and Argon storage and recuperation techniques	**(Darwin)** - 200 t x yr exposure - Drift/diameter: 2.6 m / 2.6 m - LXe Mass: 40 t - Particle discrimination by S1/S2 - Low-energy threshold of ~1 keVnr - Robust electrode design (up to 50kV) - Ultra-low intrinsic radioactivity materials - 222Rn: factor 100 reduction - (α,n) neutrons (from PTFE) - >99.98% Electron Recoil rejection at 30% Nuclear Recoil efficiency - High light yield (QE) ~ 8 PE/keV **(Darkside-20k /Argo)** - 200 t x yr exposure /Argo = 3000 t x yr) - Drift/diameter: 3.5 m / 3.5 m - LAr Mass: 51.7 t /Argo - 350 t - Particle discrimination by S1/S2 and pulse shape. - Low-energy threshold of ~0.5 keVnr - Highlander scintillation yield ~40 PE/KeV - Membrane cryostat like the ProtoDune - Low radioactivity argon in underground CO2 wells (UAr) with an activity 1400 times lower than atmospheric

Figure 1.7: Main drivers for TPCs used in rare event searches. The most stringent requirements for the future R&D activities are quoted in the last column.

and have similar size and complexity compared to TPCs at collider experiments. Gas and pressure (range of 0.1-3 bar) are adjustable to ensure an adequate interaction probability and stopping power, while amplification and electronics should be suitable for potentially relevant reactions. In nuclear astrophysics, the advent of high-intensity γ-ray beams opened a new opportunity to determine the C/O ratio at the end of the helium burning in stars; a low pressure CO_2 gas TPC with an active target and a GEM readout at ELI-NP facility is ideally suited for such studies [Ch1-79]. The most advanced $0\nu\beta\beta$ gaseous TPC is the one built for the NEXT experiment [Ch1-80]. It uses high-pressure enriched ^{136}Xe gas as both the source of the decay and the detection medium, and relies on the electroluminescence effect in order to approach the intrinsic energy resolution of the gas medium. The TPC performs 3D-track reconstruction through a SiPM plane with an energy resolution at $Q_{\beta\beta}$ of 1% FWHM. The aim is to consolidate the technology in view of future experiment stages (100 kg and 1 ton) by studying low-diffusion mixtures (Xe/He, Xe/CH_4). Searches for $0\nu\beta\beta$ decay are also performed with the high-pressure PandaX-III and R2D2 spherical TPCs. The detection of rare processes often requires a dense target (to increase the interaction probability) and good background discrimination. The R&D is focused towards NEXT-1Ton with Ba-tagging, i.e. identification of the ^{136}Ba daughter from ^{136}Xe $0\nu\beta\beta$ decay in tandem with electron energy measurement techniques. It resorts to a coating consisting of a molecule that changes its fluorescent properties after trapping a Ba^{++} ion. The DUNE collaboration is exploring a pressurised (10 bar) Ar-based TPC for its Near Detector to characterise precisely the ν-beam energy and constrain nuclear effects in ν-Ar interactions with much lower momentum threshold for particle detection, compared to the adjacent LAr Near Detector. Dual-phase detectors, based on gaseous TPC with a noble liquid, allow combined high resolution tracking (MPGD for amplification and charge readout) with good calorimetric response (electroluminescent signal) and a T0 signal for a trigger using primary scintillation. Large dual-phase multi-ton experiments, either based on LAr (Dune FD [Ch1-81], ARIADNE [Ch1-82], DarkSide-20k and an ultimate ARGO [Ch1-83]) or LXe (PandaX-4T [Ch1-84], LZ [Ch1-85] towards DARWIN [Ch1-86], [Ch1-87]) are under consideration for detection of complex neutrino and WIMP interactions. In noble element detectors, the target mixture or doping with other elements can influence detector sensitivity and response (e.g. wavelength shifting and time-profile compression), enable optical readout of scintillation light or negative ion charge transport, and improve detector stability by quenching, etc. The proof of concept for this is successfully progressing in small size systems. The main R&D challenges are related to scaling up in dimensions and complexity to the future experiments (see in particular Chapter 2). Figure 1.7 summarises the main challenges and proposed technologies in rare event search experiments.

1.3 Recommendations

1.3.1 Key technologies

Gaseous detectors offer a diversity of technologies to meet the challenges posed by future facilities in various applications, as described in the previous sections, thanks to the specific advantages that each GD concept provides. Future R&D should focus on pushing the detector performance limits by overcoming the related technological challenges. In several cases, the limitations are well understood, and R&D lines clearly defined, in others, fully novel approaches are needed to meet the requirements.

For MPGDs, the main challenges remain large area, high rate, precise timing capabilities (PICOSEC [Ch1-28], FTM [Ch1-26], [Ch1-27]), and stable discharge-free operation. They are addressed by developing resistive electrodes and exploring novel materials, amplifying structures, and detector architectures. Precise assembly at an industrial scale and integration of large area detector systems are additional items to be faced.

The focus for RPCs, MRPCs stays with the improvement of high-rate and precise timing capabilities, uniform detector response, and mechanical compactness. Exploration of novel materials [Ch1-88], [Ch1-89], [Ch1-90], [Ch1-91] and readout patterns, development of low noise electronics [Ch1-92], [Ch1-93], optimisation of gas mixtures, including eco-friendly ones, and mechanical designs [Ch1-94] are the main future R&D lines.

Requirements for straw tubes include extended length and smaller diameter, low material budget, and operation in a highly challenging radiation environment. Primary efforts will focus on ultra-thin wall development, long and thin wire handling, precise mechanics, innovative designs, and over-pressure for vacuum operation. Additionally classical ageing issues should not be neglected.

Large volume drift chamber operation with a reduced material budget in a high-rate environment requires searches for new wire materials and wiring procedures to increase the detector granularity and optimisation of gas mixtures to mitigate classical ageing effects. The application of cluster counting techniques, one of the motivation behind the future adoption of this approach, requires the development of dedicated electronics.

IBF remains the main challenge for TPC applications in future facilities. The goal is to minimise IBF while preserving good energy and spatial resolution, uniformity of response, stable operation, and low material budget. Exploration of novel readout sensor architectures and amplifying elements, including hybrid solutions with pixel ASICs (e.g. GridPix), are the main directions in this domain.

IBF minimisation is also one of the recipes to extend the photocathode lifetime in gaseous photodetectors in RICH and PICOSEC, with a similar approach to the described above and an additional challenge of high gain stable operation. An alternative solution is the development of robust photocathodes by exploration of novel materials and photoconverter protection. The development of dedicated low noise electronics coping with high input capacitance and large dynamic range requirements are also essential in the future.

TPCs for rare event searches represent a specific class of applications probing fundamental physics with the properties of the gas molecules used for ionisation, charge transfer and amplification, or light emission. Those applications have additional requirements like radio-purity and ultra low noise electronics. In addition, they explore core topics in detector physics, i.e. different amplifying structure designs for high/low-pressure stable operation, ions as charge carriers to mitigate charge diffusion or gas electroluminescence for optical readout, with potential for many novel applications.

1.3.2 Common challenges

To meet objectives as described in the DRDTs (Chapter 1.1) and to overcome common challenges, new developments and novel approaches will be necessary. For many GDs, the problem of greenhouse gases, widely used nowadays for detector operation, could become a fundamental limitation; the European Commission regulations [Ch1-95] require a substantial reduction of these emissions. The total amount of the most important flourinated gases that are sold in the EU should be drastically reduced by 2030, their prices could go up and future availability is unknown. Therefore, reduction of the use of flourinated gases is fundamental for future GD applications. Flourinated gases will be banned in the new installations where alternatives are available, and emission from existing facilities needs to be minimised by checks, optimisations, and recovery systems. Currently the most effective strategy to reduce greenhouse gases' emissions is gas recirculation in large detectors [Ch1-96]. This leads to the optimisation of gas consumption at the expense of operational complexity, with possible pressure and flow fluctuations requiring improved control and monitoring. The creation and accumulation of impurities, especially in F-based mixtures, requires gas purification techniques and could potentially affect long-term detector operation depending on luminosity and the recirculation fraction. Gas recuperation systems, even if very challenging, could permit the most valuable component to be extracted, stored, and re-used, according to the quality of recuperated gas. Unfortunately, gas leaks could make less effective this strategy for already installed gas systems [Ch1-97]. Possible alternatives to greenhouse gases ($C_2H_2F_4, SF_6, CF_4$) should remain the principal focus of the future R&D [Ch1-98], [Ch1-99], [Ch1-100]. New eco-friendly liquids/gases have been developed for industry [Ch1-101], [Ch1-102] as refrigerants and HV insulating medium. The ionisation and transport properties in these mixtures are not yet well known in high electric fields and should be simulated and measured. Performance studies of several eco-friendly mixtures for GDs are essential, together with a better understanding of the impurities creation under large irradiation fluences and their long-term ageing effects on GD performance [Ch1-103], [Ch1-104].

Muon System	Inner and Central tracking	Calorimetry	Photon detection	TOF	Rare decays
• Radiation hardness and stability of large area up to integrated charges of hundreds of C/cm2: - aging issues and discharges; • Operation in a stable and efficient manner with incident particle flows up to ~10 MHz/cm2: - miniaturisation of readout elements needed to keep occupancy low • Manufacturing, on an industrial scale, large detectors at low cost, by means of a process of technological transfer to the industry and identifies processes transferable to industries • Identification of eco-friendly gas mixture and mitigation of the issue related to the operation with high WGP gas mixture: - gas tightness;gas recuperation system;accessibility for repairing • Study of resistive materials (RPC and MPGD): - higher gain in a single multiplication layer, with a remarkable advantage for assembly, mass production and cost - new material and production techniques for resistive layers for increasing the rate capability • Thinner layers and mechanical precision over large area	**Drift chambers** • High rate, unique volume, high granularity, low mass • Hydrocarbon-free mixture for long-term and high-rate operation • Prove the cluster counting principle with the related electronics • Mechanics: new wiring procedure, new wire materials • Integration: accessibility for repairing **TPC** • R&D on detector sensors to suppress the IBF ratio • Optimize IBF together with energy resolution • Gain optimization: IBF, discharge stability • Uniformity of the response of the sensors • Gas mixture: stability, drift velocity, ion mobility, aging • Influence of Magnetic field on IBF • High spatial resolution • Very low material budget (few %) • Mechanics: thickness minimization but robust for precise electrical properties for stable drift velocity • Integration: cooling of electronics **Straw chambers** • Ultra-long and thin film tubes • "Smart" designs: self-stabilized straw module, compensating relaxation • Small diameter for faster timing, less occupancy, high rate capability • Reduced drift time, hit leading times and trailing time resolutions, with dedicated R&D on the electronics • PID by dE/dx with "standard" time readout and time-over-threshold • 4D-measurement: 3D-space and (offline) track time • Over-pressurized tubes in vacuum: control the leakage rate to maintain the shape	• Uniformity of the response of the large area and dynamic energy range • Optimization of weights for different thresholds in digital calorimeters • Rate capability in detectors based on resistive materials: resistivity uniformity, discharge issue at high rate and in large area detector • R&D on sub-ns in active elements: resolution stables over wide range of fluxes • Gas homogeneity and stable over time • Eco-friendly gas mixture for RPC • Stability of the gas gain: fast monitoring of gas mixture and environmental conditions • Mechanics: - large area needed to avoid dead zone: limitation on size and planarity of PCB is an issue - multi-gap with ultra-thin modules: very thin layer of glass and HPL electrodes, gas gap thickness uniformity few micron	• Preserve the photocathode efficiency by IBF and more robust photoconverters • Gas radiator: alternative to CF4 • Gas tightness • Very low noise when coupling large capacitance • Large dynamic range of the FEE • Separate the TR radiation and the ionization process • In TRD use of cluster counting technique and improve it by means of a InGrid	• Uniform rate capability and time resolution over large detector area • New material for high rate (low resistivity, radiation hardness) - uniform gas distribution - thinner structures: mechanical stability and uniformity • Eco-gas mixture • Electronics: Low noise, fast rise time, sensitive to small charge • Possibly optical readout • Precise clock distribution and synchronization over large area	• Radio-purity of the materials • Low background • High granularity • For large volume detectors: transparency over large distance • Pressure stability and control • Electronics with large dynamic range and flexible configuration. • Self-trigger capability • Low noise electronics • Fast electronics • Optical readout

Figure 1.8: Summary of the R&D challenges for different applications.

Large GD systems in future facilities will face integration challenges and the requirement for easy accessibility and replaceability in complex installations. The main challenges include gas tightness, overpressure operation and electronics cooling. In addition, engineering effort to ensure precision assembly of a large scale detector components will be needed.

Ageing phenomena constitute one of the most complex and serious potential problems which could limit or severely impair the use of gaseous detectors in unprecedented harsh radiation environments and lead to operational instabilities [Ch1-38], [Ch1-39], [Ch1-105], [Ch1-106], [Ch1-107]. To guarantee reliable and long-term operation in extreme conditions for large area detectors using different technologies (resistive Micromegas, μ-RWELL, GEM, THGEM, FTM, RPC, MRPC, sMDT, sTGC, straws tubes, et), further research on classical ageing effects and discharge suppression and mitigation is mandatory [Ch1-108], [Ch1-109], [Ch1-12], [Ch1-110]. Such studies should include fundamental gas properties and materials R&D, exploration of novel technologies, new architectures and amplifying structures.

Gaseous detectors require dedicated front-end electronics development, both discrete and ASICs, focused on specific applications and technologies, while addressing diverse requirements such as: fast timing, TPC readout, large input capacitance, low noise, cluster counting, input discharge protection, cross-talk reduction, large pixel size, compactness, low power consumption and detector integration [Ch1-111]. At the same time, alternative and hybrid readout methods should be explored to grow the potential applications portfolio: optical readout with imaging sensors; hybrid (optical with electronic) readout and direct readout with pixelated ASICs (intensified TPX3Cam, GridPix, GEMPix). A summary of the main R&D topics needed for the different applications is shown in Figure 1.8.

1.3.3 R&D environment and development tools

It is imperative to create a friendly environment to facilitate detectors development and networking activity. Promoting R&D collaborations [Ch1-112], [Ch1-32] focused on detector technologies is very effective for an easy exchange of experience and resources; it allows building of a community with continuity and institutional memory and enhances support of generic R&D, education, and training of younger generation instrumentalists (see Chapter 9). Educational and outreach activities introduce high school students and teachers to research activities in a strong and intense collaboration with academic institutions (e.g. measurements of the cosmic ray radiation in the context of the EEE Project [Ch1-113]).

It is rather fundamental to secure institutional investment and maintenance support of infrastructures for detector development, testing and production laboratories; equipped and maintained tests beam installations (trackers, DAQ, magnets); and production and R&D facilities maintaining access to modern technologies through academia, industry and upgrades of in-house infrastructure (see Chapter 10 and Chapter 11). Support for development and maintenance of the detector development tools, which should include electronics R&D and software for detector physics simulations, is essential. It is common practice to underestimate these important aspects and substantially delay or practically prevent progress in the field. Development tools should be treated in the same way as the essential hardware infrastructure.

Future projects will rely on large scale, industrial production. A suitable model of effective academia-industry collaboration is largely missing. Institutional (or even governmental level) policy to facilitate relations with industry, including mitigation of administrative barriers which often prevent successful technology transfer, is crucial (see Chapter 10).

Supporting applications beyond fundamental research opens possibilities for industry involvement, increases visibility of detector R&D activities with a profound impact on society at large. The specific features of GDs allow for very challenging future applications of scientific, social and industrial interest. Many examples already exist using different concepts: GEMs and THGEM like-structures, Micromegas, RPCs, etc. The high spatial resolution, combined with large sensitive volume, energy resolving and time precision capabilities, enlarges the portfolio of GD applications for other science sectors, such as: Material Science, Energy, Space and Healthcare. Innovative approaches include: Material Science – neutron diffractometers [Ch1-114], energy dispersive x-ray fluorescence and imaging [Ch1-115]; Energy – Tokamak neutron and radioactive waste diagnostics [Ch1-116]; Medical – micro-dosimetry to qualify radiation fields for cancer therapy; 3D-ion beam monitoring and treatment plan verification in hadron therapy [Ch1-117], [Ch1-118]; monitoring of energy released in Intensity-Modulated Radiation Therapy; energy resolved radiography and Positron Emission tomography scanners [Ch1-119], [Ch1-120]; and muon based imaging - geophysics, geology, archaeological heritage [Ch1-121], civil engineering, and nuclear industry [Ch1-122]. Strategies, fostering portability and high detection efficiency, are of major interest to ensure competitiveness and a low level of complexity which facilitate large-scale production. In this context, common R&D efforts dedicated to: gas purification systems and the search for low outgassing materials (which are mandatory for sealed-system operation); improved photon detection efficiency at high gas pressure; compact and/or embedded dedicated readout, DAQ and biasing electronics “all in one”, should be advanced in order to facilitate the adequacy of GDs in applications beyond fundamental research.

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Chapter 2

Liquid Detectors

2.1 Introduction

Liquid detectors today primarily employ target media of water, liquid scintillator, or cryogenic nobles, notably liquid argon (LAr), xenon (LXe) and helium (LHe). The physics applications of these detectors are in the domain of rare event searches, including neutrino physics, dark matter searches and astro-particle experiments.

The basic detection principle is that an interaction (e.g. of a neutrino or dark matter particle) with an atom in the liquid detector target produces final state particles which deposit energy in the liquid. The final state particle is often just the original scattering partner which obtains some measurable kinetic energy. This energy release may be electromagnetic, resulting in ionisation charge, scintillation and/or Čerenkov light, or heat. In water, Čerenkov emission dominates, typically producing $O(10^2)$ photons/MeV deposited in the visible wavelength range, with a characteristic sub-ns time scale. In scintillators, fluorescent molecules and wavelength-shifters produce $\mathcal{O}(10^4)$ photons/MeV in the visible range, with ns to μs time scales. In noble liquids, excited atoms form dimers, which decay on time scales of ns to μs (for LAr and LXe), producing emission in the VUV (at 128 nm and 178 nm respectively), emitting $\mathcal{O}(4\times10^4)$ photons/MeV. At lower energies relevant for dark matter and $0\nu\beta\beta$ searches, the ionisation energy partition < 100 keV depends on the particle species and varies with energy, reaching $\sim 30\%$ for nuclear recoils, and thus the heat partition is an important detection channel. Above the MeV energy deposition scale, relevant for neutrino physics, the ionisation partition dominates.

The detector instrumentation strategy depends on the liquid employed. Water or scintillator targets are typically operated in single-phase detectors, in which a large open volume of liquid target is surrounded by photon sensors. R&D on liquid scintillators is exploring granular segmentation, similarly to solid scintillator detectors. Noble liquid targets are most often operated in time projection chamber (TPC) detectors. The operation principle is that charge produced in the interaction of a primary particle is drifted in an electric field into a charge collection region, which may contain gas in the case of dual-phase TPCs where amplification of the primary charge produces electro-

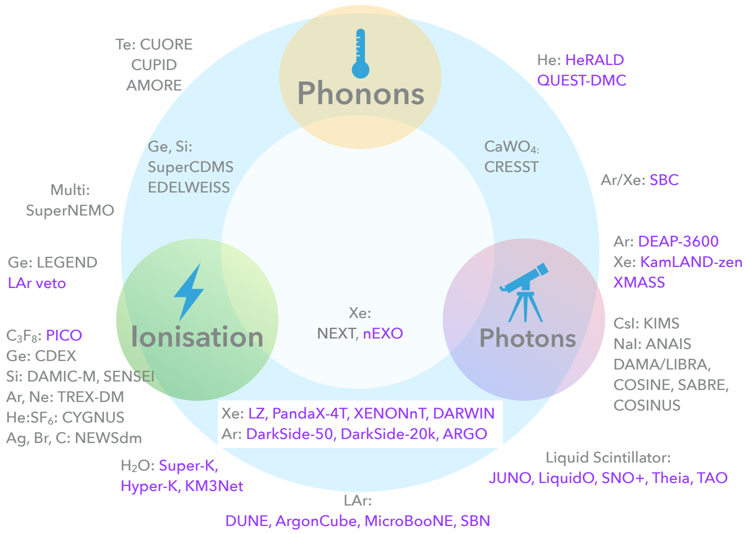

Figure 2.1: Current and near-future experiments addressing the physics drivers for liquid detectors (neutrino physics, neutrino astrophysics, $0\nu\beta\beta$, dark matter), grouped by detection modality, with liquid targets in purple. (Figure modified from L. Baudis, ECFA Plenary Input Session (see Appendix C).)

luminescence, increasing the secondary signal. TPCs are typically instrumented with readout technologies to measure both charge and light (from primary or secondary emission produced in an amplification region). Dark matter experiments that are optimised to detect low-mass dark matter, below the GeV scale, additionally often benefit from instrumenting targets to detect a combination of the ionisation and heat energy partitions. For neutrinoless double beta decay searches, large detectors tend to detect the products of the decaying isotopes with liquid scintillator or with xenon TPCs (where the detector medium is both the source and the detection material). Liquid argon is also used as a veto for large crystal detectors [Ch2-1].

There are several large-scale and many small-scale running and planned experiments exploiting liquid targets. These are shown in Figure 2.1, grouped by energy partition measurement strategy. The major Detector R&D Themes for liquid detectors that have been identified in the framework of this Roadmap include in particular those listed below. It should be noted that R&D should be anticipated for facilities beyond the timelines illustrated in Figure 11.1 but it is not possible today to sensibly suggest dates for such even longer-term programmes requiring liquid detectors.

DRDT 2.1 - Develop readout technology to increase spatial and energy resolution for liquid detectors.
Developments should achieve readout of more highly pixelated detectors with greater photon collection capabilities. Advancing liquid detector readout technologies towards

greater quantum efficiency while still offering much higher granularity is a further objective.

DRDT 2.2 - Advance noise reduction in liquid detectors to lower signal energy thresholds.
The expected performance of future liquid detectors requires R&D to achieve lower sensor and electronics noise, as well as developments to measure simultaneously more components of the energy partition: for example light, charge and heat.

DRDT 2.3 - Improve the material properties of target and detector components in liquid detectors.
The R&D on material properties for liquid detectors aim to improve the emission properties of the target, for example through doping of Xe in Ar, H in Xe, Ne in Xe, Gd in H_20, Xe, Te and Gd in liquid scintillator, and to achieve lower radiogenic backgrounds from the detector components, via target purification, material radioassay, and cryogenic distillation to change isotopic or atomic content.

DRDT 2.4 - Realise liquid detector technologies scalable for integration in large systems.
Dedicated developments should achieve applications of the previous DRDTs in future detectors ten to a hundred times larger compared to the state of the art, and allow coping with increased noise from detectors with sensor areas reaching 10, 100 and ultimately $1000\,\mathrm{m}^2$. This will have to proceed while addressing the step change in complexity, with decade-long construction, in underground or undersea environments, with handling of heat load, value engineering and industrial production.

Current noble liquid detectors are at the one to a hundred tonne scale of active mass, including DEAP-3600, ICARUS, MicroBooNE, ProtoDUNE (LAr), LZ, PandaX, XENONnT, XMASS (LXe) respectively. For the near future, detectors under construction include $\mathcal{O}(100)$ tonne scale LAr TPCs for dark matter in DarkSide-20k and $\mathcal{O}(10)$ kT-scale for neutrino physics in DUNE.

Broad R&D activities are being carried out on the basic properties of the liquid target media, discussed in Section 2.3.1. In addition to tailored doping components, work includes modifying the light emission spectrum and intensity, fast and ultra-fast light components, transparency, radiopurity, and developing novel light detection devices. R&D challenges include drifting charge over large distances in high-purity conditions, the electric rigidity of purified liquid nobles, and removal of electronegative compounds.

R&D directions associated with the realisation of alternative advanced ionisation detection methods (e.g. pixels replacing conventional wire planes), and the integrated collection of (possibly directional) light, over wavelengths ranging from NIR to UV and VUV, as well as charge, are discussed in Section 2.3.2.

R&D challenges associated with this massive scale up in size and complexity from current to near-future detectors is discussed in Section 2.3.3. In addition to widely-distributed small-scale R&D, the CERN Neutrino Platform is a major test facility that has underpinned development and demonstration at the massive scale required for LAr detectors.

R&D on new photodetectors is in common across many applications of liquid detectors, as described in Section 2.3.4, driven by the increasing size and complexity of the detectors and the need of a more "multifaceted" detection of the physics signals.

The key R&D aspects for water Čerenkov experiments, at the 55 kilotonne scale in Super-Kamiokande and the near-future Hyper-Kamiokande (Hyper-K) above the 200 kilotonne scale, are described in Section 2.3.5. Many of the ideas are in common with the liquid scintillator approach employed by experiments such as JUNO, SNO+, Theia and TAO. Technological synergies include target doping (e.g. Gd doping of water, quantum dots doping of scintillators), and the simultaneous detection of Čerenkov and scintillation light.

Synergies with other areas of high energy physics concern the physical properties of the media, for example the use of LAr calorimeters at high-energy colliders (Chapter 6); the detection technologies for charge (in Chapter 1 and Chapter 3) and light (in Chapter 4) produced by particle energy deposition in the target media; and the readout strategies for these signals, using electronics (Chapter 7) as well as quantum technologies (Chapter 5).

2.2 Main drivers from the facilities

Liquid detector development is driven by diverse science areas, of which some are linked to large common facilities, while others are pursued by groupings of individual experiments aiming at a coherent physics sensitivity. The main areas are categorised as: the DUNE programme; the Hyper-K programme; neutrino near detectors; neutrino telescopes; multi-tonne scale dark matter detectors; light dark matter detectors (0.001-10 kg scale); tonne-scale $0\nu\beta\beta$ experiments; and, low-energy scintillator neutrino detectors.

The R&D needs for these areas are categorised schematically as a function of time in Figure 2.2. The associations of DRDTs and R&D tasks are shown in Table 2.1. Note that, as discussed above, it is not practical to extend the horizon beyond 2035 although longer term facilities requiring R&D in liquid detectors should certainly be anticipated.

Long baseline accelerator-neutrino programmes are directly related to accelerator facilities (the FNAL PIP-II accelerator for the neutrino beam to LBNF, JPARC for the T2K and Hyper-Kamiokande neutrino beams and CERN for test beams). The physics drivers for these facilities are the discovery of CP violation in the neutrino sector through oscillation experiments, and the precision measurement of the PMNS matrix parameters. These large neutrino physics facilities also study solar and supernova neutrinos and proton decay; R&D addressing these topics is driven by the detector capabilities needed for new discoveries.

Near detector complexes for these long-baseline programmes measure the un-oscillated neutrino beam fluxes vs. energy and flavour, and provide constraints on neutrino interaction uncertainties, both essential to extract the neutrino oscillation parameters. Near detector complexes often combine several detector technologies, including water

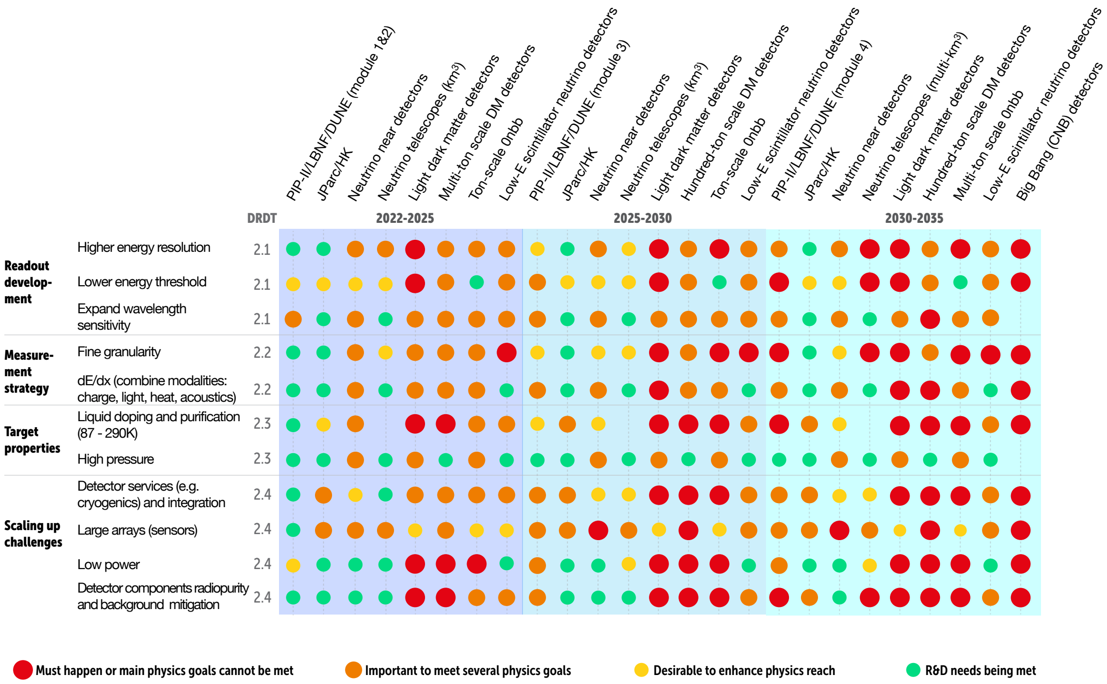

Figure 2.2: Schematic timeline of categories of experiments employing liquid targets together with DRDTs and R&D tasks. The colour coding is linked not to the intensity of the required effort but to the potential impact on the physics programme of the experiment: Must happen or main physics goals cannot be met (red, largest dot); Important to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); No further R&D required or not applicable (blank).

DRDT	DRM (Figure 2.2) Row Numbering
2.1 Readout Development	2.1.1. Higher Energy Resolution 2.1.2. Lower Energy Threshold 2.1.3. Expand wavelength sensitivity
2.2 Measurement Strategy	2.2.1. Fine granularity 2.2.2. dE/dx (combine modalities: charge, light, heat, acoustic)
2.3 Target Properties	2.3.1. Liquid doping and purification 2.3.2. High radiopurity
2.4 Scaling Up Challenges	2.4.1. Detector services & integration 2.4.2. Large arrays (sensors) 2.4.3. Low power 2.4.4. Noise & background mitigation

Table 2.1: Mapping of R&D tasks shown in the rows of Figure 2.2 (the "Detector Readiness Matrix") to the Detector R&D Research Themes (DRDTs) for liquid detectors.

Čerenkov, LAr TPCs instrumented with pixels, high-pressure gaseous Ar TPCs, muon range detectors, electromagnetic calorimeters, etc. These near detector suites aim to characterise completely the final state particles produced in neutrino interactions in the GeV energy range; in addition they offer attractive environments to search for new physics processes.

Dark matter experiments are following two main avenues: (i) large increase in detector scale, to reach the so-called solar neutrino floor for dark matter candidates in the > 1 GeV mass regime, and (ii) new technology directions aiming to study particle dark matter down to the 1 eV scale or to measure new observables, such as direction sensitivity. Models addressed by (i) include not only WIMP dark matter but also high mass asymmetric dark matter, composite states, strongly-interacting massive particles, etc. The mass range addressed by (ii) includes candidates from a broad range of models that invoke either the freeze-in mechanism or non-thermal production, and feebly interacting massive particle candidates (FIMPs). R&D needs for dark matter searches addressing the wave-like dark matter candidate regime, below 1 eV mass, are addressed in Chapter 5.

Both high-mass and low-mass dark matter avenues require substantial technology development in readouts to reach very large areas, to expand wavelength sensitivity of photosensors into the VUV, to scale up target cryogenics and purification systems, to reach ultra-low levels of radioactivity, and to develop new readout technologies, such as quantum sensors, to measure the energy partition components down to the meV energy range in e.g. liquid He detectors.

Double beta decay experiments are driven by the stringent requirements on the background levels, by the need for excellent energy resolution and large increase in detector scale. Detector technologies employ diverse strategies, from liquid Xe or high-pressure Xe gas TPCs to cryogenic bolometers or quantum dots.

2.3 Key technologies

Enabling technologies for next generation liquid detectors have been identified along five main themes, that address either the inherent properties of the liquids themselves or the liquid handling and supporting infrastructures. For low-background experiments, development of supporting infrastructure additionally enables advances in radio-purity of detector materials, including liquid targets.

The global timescale for R&D developments, as illustrated in Figure 2.2, is relatively short compared to e.g. colliding beam experiments. The focused, near-term R&D described here is on a time scale of 5-10 years, and typically associated with existing experimental programmes. On longer timescales, transformative "blue-sky" ideas are being explored to enable new directions for future experiments.

The crucial technology developments needed to enable the next generation experiments in each of the five R&D themes are identified below. In addition, common interests and developments with HEP experiments, and potential collaborations with industrial partners are highlighted.

2.3.1 Liquid Properties of Noble Liquids

The intrinsic properties of liquefied noble gases combine high scintillation yield, high ionisation yield and long electron lifetime, i.e. the fact that the ionisation electrons released remain free to drift across long distances. The possibility of extracting electrons to the gas phase enables reaching very low deposited energy thresholds (DRDT 2.1), since the ionisation signal can be amplified through secondary scintillation or avalanche mechanisms. The key challenges to address the detector R&D themes (DRDTs) above are the following.

Microphysics of liquids
Improved understanding of the liquid microphysics will offer significant advances in detector resolution. For example, exploiting all available signal modalities in noble liquids (charge, light and heat) (DRTD 2.2), could enhance energy resolution and enable lower energy thresholds (DRDT 2.1). The use of dopants to modify the light emission properties is an active area of research, aimed at shifting the intrinsic VUV scintillation into the visible, where photodetectors have higher quantum efficiency. This can enable higher light collection (DRDT 2.1 and DRDT 2.2); building a strong understanding of how the scintillation wavelength spectrum changes when adding dopants to the liquid is needed. Currently, there is a high reliance on signal simulations to inform detector designs and understand physics performance; data-driven models are needed to reduce systematic uncertainties. A coordinated strategy of liquid properties measurements would allow more coherent progress and efficient collaboration within the community.

Light emission/detection
The intrinsic VUV scintillation in LAr (at 128 nm) and LXe (at 178 nm) presents a challenge for efficient light detection. A range of approaches beyond traditional photomultiplier tubes has been proposed to address this, from developing novel photon detectors, including aiming at VUV-sensitivity (DRDT 2.1, described in Section 2.3.4), to using wavelength shifters to modifying the scintillation light spectrum by introducing dopants in the liquid (DRDT 2.3). Other ideas for enhanced light collection exploit sub-dominant emissions, e.g. using the near infra-red light component in LAr to enhance signal discrimination factors (DRDT 2.1 and DRDT 2.2), and the possibility that LXe scintillation light patterns may offer some information on the directionality and the timing of the events via *superradiance*.

High voltages
The scale increase of noble liquid experiments - and more notably dual phase TPCs - is the high voltage needed to establish electron drift over long distances up to ~ 3 m and aiming as large as the 10 m scale. This necessitates power supplies that can deliver higher voltages (DRDT 2.4), new designs for the voltage deliveries (high voltage feedthroughs; also DRDT 2.4) and a much more detailed understanding of the dielectric properties of noble liquids under different conditions (DRDT 2.3). Amplification of a supplied voltage inside the cryostat as in Neutron EDM experiments is an interesting possibility under investigation. Development of new high-voltage schemes offers ample opportunity for collaboration with industry. Detailed models of light emission from high voltage

breakdown are also important for detector design.

Calibration
To enhance physics capabilities, precise detector calibration methods are needed (DRDT 2.1 and DRDT 2.2). New methods are needed to ensure calibration capabilities at larger scales, particularly throughout large volumes. The use of intrinsic or added elements, such as ^{39}Ar or ^{83m}Kr, can be attractive for large-scale calibrations. Nuclear recoil calibration is challenging for large detectors and finding new isotopes and composites with spontaneous neutron emission is an important goal.

2.3.2 Charge Collection in Noble Liquids

Electric charges in noble liquids are generated by ionisation induced by charged particles traversing the medium. The most relevant quantity is the charge density, corresponding for 2.1 (4.0) MeV/cm to about 9000 (26000) electrons/cm for LAr (LXe). Most of this primary charge undergoes recombination. For practical detector implementations, e.g. a 3 mm pitch wire charge collection anode and a 1 kV/cm drifting field, the overall acquired charge corresponds to nearly 20000 electrons for LAr and over 50000 for LXe. The ionisation electrons drift towards the anode at a velocity in the range of about 2 mm/μs for a 1 kV/cm electric field. The electron distribution during the drift experiences charge diffusion, which ultimately impacts on the design granularity of the collecting anode device. The key challenges to address the detector R&D themes (DRDTs) above are the following.

Liquid impurities
Electronegative compounds reduce the net collected charge in an exponential way. The mean electron lifetimes for argon and xenon lie in the range of 1-10 ms for a suitably purified liquid at the level of 1 ppb impurity concentration. Modern technologies allow going well below such a value, strongly reducing the impact of this parameter on the performance of the detectors (Section 2.3.3).

Charge amplification
Charge amplification via several methods has been attempted and eventually exploited to acquire a more robust signal (DRDT 2.1 and DRDT 2.2), which eases requirements on the readout front-end electronics. Charge amplification of up to several orders of magnitude can be attained in the LAr gas phase or in LXe double phase devices [Ch2-2] via electroluminescence. Reaching amplification in the liquid itself is more challenging. A promising technique envisions doping LAr with small percentages of LXe, allowing charge amplification by a factor of a hundred or more [Ch2-3] (DRDT 2.3). Other promising R&D avenues include exploitation of localised electroluminescence, which is under investigation by DARWIN.

Charge readout structures
The “standard” TPC configuration employs planes of wires (with a pitch determined, as discussed above, by charge diffusion) possibly placed in different orientations to allow X-Y plane coordinate reconstruction, while the Z is determined by the measurement of the drift time, assuming accurate knowledge of the drifting field map. The use of wire planes

was brought to maturity by the ICARUS collaboration [Ch2-4] and successfully applied to neutrino physics by the MicroBooNE neutrino experiment at FNAL [Ch2-5]. Recent R&D conducted by the ArgonCube collaboration [Ch2-6] has led to the alternative use of pixel electrodes on PCBs, to directly measure an X-Y coordinate point, virtually eliminating the risk of reconstruction ambiguities, particularly relevant for "high luminosity" applications, such as is the case for a TPC close to a high-intensity neutrino source (as the near detector).

Additional related R&D directions address the stability of the charge amplification (if applied), the high-granularity charge-electroluminescence imaging (mostly in relation to cost and complexity) and, possibly, an integrated, simultaneous readout of light and ionisation charge.

Cryogenic front-end electronics

Electronics are discussed in detail in Chapter 8. Specific to liquid detectors, projective event reconstruction implies a number of readout channels scaling with the number of wires, which can be as long as several meters, sufficient to cover large surfaces even for large-volume, surface-instrumented detectors. Challenges for the cryogenic front-end electronics include heat dissipation and the need of $in - situ$ zero suppression to make manageable handling of the detector readout. Cryogenic optical transmission of signals is foreseen in DUNE and DarkSide-20k, which requires transmission driver and receiver development; this topic could benefit strongly from industrial engagement. Pixel schemes additionally include the requirement of independent front-end channel for each individual pixel, likely operating in cold (even immersed in the cryogenic liquid) with a potentially destructive dissipation heat.

Pixel electronics are being investigated and developed as a priority R&D direction for the five-year R&D timescale by several groups. The LArPiX electronics [Ch2-7] developed in the framework of ArgonCube has proven to be an excellent solution, allowing the operation of a series of increasing size detector prototypes and the full design of the LArTPC of the DUNE near detector [Ch2-8]. Other ideas in development include the option of time-to-charge conversion electronics [Ch2-9], or the integrated CCD readout approach [Ch2-10]. The handling of high bandwidths, the improvement of the S/N ratio, and the reduction of cost/channel will be crucial for envisioning pixel readout for very large-scale applications, such as those mentioned for DUNE.

2.3.3 Purification, Cryogenics, Infrastructure and Integration for Noble Liquids

The large scale of next-generation detectors poses a unique challenge to the development of clean and radio-pure targets.

Purification

To accommodate the long drift distances foreseen by next-generation experiments employing TPCs (DRDT 2.4), an electron lifetime of $> 1\,\mathrm{ms}$ per meter of drift length is required. This is achieved by removal of O_2 and H_2O impurities, usually with standard commercial SAES hot getters, while alternatives are investigated. A disadvantage of the use of hot gas-getters, is a limited system throughput. A new development in this field that is currently under investigation by the XENON collaboration is the removal of electronegative impurities directly from the LXe, which has the advantage of potentially allowing for much higher throughput of the purification system. Further investigation into the optimal getter materials, the optimal amount of getter material, getter regeneration strategies are a benefit to the full community.

Target radiopurity

Target radiopurity of noble liquid targets is primarily of concern for the low-background experiments (DRDT 2.3 and DRDT 2.4). Requirements are diverse and specific, depending on the target. For LAr or LXe dark matter experiments, near absence of impurities like ^{39}Ar, ^{222}Rn, ^{85}Kr is crucial, and prevention and purification of unwanted radioactive isotopes is an important field of R&D. In the case of LAr, sources of underground argon are used and in addition large-scale cryogenic distillation efforts for argon isotope are currently under development within the ARIA project [Ch2-11]. For LXe experiments suppression of events caused by beta or gamma radiation is even more important, due to lack of effective pulse shape discrimination. Through cryogenic distillation ^{85}Kr can be removed to the sub-ppt level, which is sufficient for next-generation dark matter experiments. The focus for R&D is now on removal of ^{222}Rn. As radon continuously emanates from all detector surface, continuous cryogenic distillation is needed, as is now pioneered for the XENONnT experiment.

Cryogenics

Removal of electronegative impurities and establishing sufficiently radio-pure targets (DRDT 2.3 and DRDT 2.4) come at a cost of increasingly complex cryogenic systems (DRDT 2.4). Besides the cooling itself these systems need to facilitate circulation of LAr or LXe to maintain the cleanliness of the liquid targets. R&D into thermodynamic solutions necessitates development of ultra-clean compressors and heat exchangers. Some of the key supporting technologies, like clean hermetically sealed and magnetically driven gas/liquid pumps and vacuum insulation solutions find wider applications. The technologies needs are similar to those of particle accelerators, and detector cooling solutions in high energy physics experiments. This is potentially an area of R&D where the liquid detector community finds a natural synergy with the accelerator-based groups. For different reasons, both communities need clean, non-polluting components in their respective cryogenic and cooling systems. Within the rare event search community –and primarily for experiments using LXe– additional R&D is required to ensure low rates of ^{222}Rn emanation.

Next generation experiments will make the transition from small scale to industrial scale enterprises, requiring high level professional system engineering of not only the core cryogenics systems, but also for auxiliary systems (DRDT 2.4). Extremely pure LAr and LXe are forming a large fraction of the capital cost of rare event searches. LAr and LXe storage components need to be developed for multi-ton experiments and beyond. These developments need seamless integration into the cryogenic environment of the experiment, employing rapid noble liquid recovery systems in case of emergency. Development of the hardware safety systems can benefit from the expertise in accelerator and high-energy physics experiments.

Radioassay
Assessment and control of radioactive background in the construction materials and components can make or break a low-background experiment (DRDT 2.3 and DRDT 2.4). Construction of such experiments is preceded by an extensive screening campaign, usually done in facilities in the low-background environment of an underground lab. In addition, highly specialised radon emanation measurements are performed. An area of R&D is in mitigation of emanation backgrounds by investigating material selection procedures and options for surface treatment in a systematic way. For next generation experiments, ultra-sensitive trace analysis capabilities need to developed for a much larger scale; shared community resources for radioassay would be a clear benefit to both the LAr and LXe communities.

2.3.4 Light Collection in Noble and Other Liquids

Photon detectors used for light collection in noble liquids, water and organic scintillator detectors span PMTs, APDs, Hybrid PMTs, analogue and digital SiPMs.

The main challenges facing near to long-term future experiments are photosensor coverage over huge surfaces (DRDT 2.4), in extreme environments (e.g. underground, undersea and/or at cryogenic temperatures) and with single photon sensitivity (DRDT 2.1 and DRDT 2.2). Long term operation and stability of light collection and sensing technology are crucial as experiments may operate for lifetimes of 10 years or more between detector accesses. The transmission of signals from light collection/sensing technologies presents challenges in numbers of readout channels as well as data volume, since both ns and μs time scales are relevant given the fast and slow emission time constants in noble liquids, and precision measurement of the emission timing distribution is used for particle identification, e.g. [Ch2-12]. This naturally leads towards greater integration within photosensors, for example moving from discrete electronics chains of charge-sensitive preamplifiers or transimpedance amplifiers [Ch2-13], through shaping and ADC/TDC towards fully-integrated photon to digital conversion using embedded digitisation and digital signal processing [Ch2-14]. Radiopurity of light collection, sensing, front end electronics and signal transmission technologies is an essential requirement for dark matter experiments, and also important to lower threshold and backgrounds at low energy in neutrino experiments. The major R&D directions to address these challenges are the following.

Light Collection
Strategies employed to improve light collection efficiency (DRDT 2.1 and DRDT 2.4) include deployment of wavelength-shifting thin films (e.g. TPB, PEN); coating passive detector surfaces with high-reflectivity thin films (such as ESR) or materials (like Teflon); trapping light using dichroic filters to increase the probability that a photon is converted in a smaller photo-sensitive area (e.g. the ARAPUCA concept) [Ch2-15]; and, for silicon detectors, coatings and surface treatment optimisation to decrease the reflectivity at the silicon surface [Ch2-16]. R&D to maximise light collection includes developing large

Experiment	Type	Photon detector	Area (m^2)
nEXO	LXe	SiPMs (FBK [Ch2-18], Hamamatsu [Ch2-19]), digital 3D-SiPM	5
DARWIN	LXe	PMTs, SiPMs or Hybrids (SIGHT, ABALONE)	8
TAO	LSci	FBK SiPMs	10
DarkSide-20k	LAr	SiPMs (FBK NUV-HD triple-dopant)	30
ARGO	LAr	SiPM is baseline option	200
DUNE	LAr	Light guide or trap + SiPM	10-1000

Table 2.2: Area and type of photon detector arrays in use or under consideration in near- to far-future experiments.

scale lamination of 25-50 μm thick polyethylene naphthalate films (PEN) together with enhanced specular reflector (ESR) films; engineering wavelength-shifting bars on PMMA substrate, for optimal matching at LAr temperature (87K); and alternatives such as doping of LAr targets with ppm-1000 pp admixtures of Xe or nanoparticles are under study to shift the VUV emission into the near UV or visible range before a photon reaches the photosensor [Ch2-17].

Photosensitive Area

The active area of near-future experiments is at the $\mathcal{O}(10)$ m^2 scale, whilst further future experiments foresee 100-1000 m^2 active areas, summarised in Table 2.2 (DRDT 2.4). SiPMs are widely used in large-area cryogenic applications. Beyond improvement in quantum efficiency, the main R&D efforts focus on reducing dark current rate, currently at the level of 0.01 Hz/mm^2 [Ch2-20]; reducing channel count through summing SiPM signals in arrays; increasing SNR through front-end electronics design to mitigate the large output capacitance of such arrays; and, timing resolution improvement, most relevant for TOF-PET and TOF-CT. Non-cryogenic experiments are similarly developing detectors composed of arrays of photosensors, such as DOMs in km^3 water/ice detectors, made of 3" mPMTs with 4π angular acceptance, or 2π as planned in Hyper-K [Ch2-21]. Liquid scintillator detectors plan 4π SiPM coverage operated at -50°C in JUNO-TAO [Ch2-22], or 4π ultra-fast LAPPD coverage in the Theia WbLS detector [Ch2-23].

Light detection

New strategies under development to enhance photon detection efficiency include increasing the sensitivity of silicon photosensors in the VUV range and NIR range [Ch2-20], through silicon doping and surface treatment (passivation and ion implantation), and pixel design (e.g. back-side illuminated (BSI) single-photon avalanche diodes [Ch2-24]); increasing the light collection with metalenses [Ch2-25], spectral photon sorting for water Čerenkov and liquid scintillator detectors [Ch2-26]; using color-sensitive sensors (dichroicons) [Ch2-27], and Winston cones together with dichroic filters; photocathode material optimisation for PMTs; and, working towards 10 ps timing resolution for temporal separation of Čerenkov and scintillation light. Light detection R&D in liquid detectors can also find wider applications in medical imaging, e.g. for PET developments using LAr and LXe (DRDT 2.1, DRDT 2.2 and DRDT 2.3).

Integration
As experiments grow in scale, reduction in number of readout channels and cost per channel become increasingly important (DRDT 2.4). Associated R&D includes reducing the DAQ channel cost through digital signal processing within the photosensor itself.

R&D on the 5-year horizon for greater integration include ASIC front-end electronics for PMTs, developing monolithic APD devices, and 3D vertical integration with photon sensing and signal processing electronics within a single silicon device. Specific to SiPMs, strategies under development for greater integration, moving from analog to digital SiPMs, include dedicated ASIC design; 3D-vertical integration R&D; and development of lower-power, larger-area and lower-radioactivity photodetection modules [Ch2-28]. A key challenge here is the need for cooperation with commercial foundries, as well as significant funding and time to develop and package a new device for qualification. Progress in this area needs common sensor or detector development across projects.

For the longer-term future, even greater integration of charge and light readout systems is under development (DRDT 2.1 and DRDT 2.2), via ideas like: making a large fraction of a TPC anode plane surface photo-sensitive; material engineering for pixel readout to collect both charge and UV photons; bubble-assisted liquid hole multipliers in LXe and LAr [Ch2-29]; and fully optical readout of THGEMs using SiPMs, CCDs and Timepix-based cameras [Ch2-10]. "Blue-sky" ideas for fully optical imaging of scintillation light include using segmented photodetectors coupled to coded aperture masks or UV-transparent lenses for 4D event reconstruction; and employing opaque scintillator together with wavelength-shifting fibres read by SiPMs to make calorimeter-TPC drifting light instead of charge [Ch2-30].

2.3.5 Liquid Scintillator and Water Detectors

Large detectors such as Hyper-K [Ch2-31] or JUNO [Ch2-32] take advantage of Čerenkov signals in ultra-pure water (WC) or liquid scintillator (LS). Metal-loaded LS is used in smaller (kT) targets as in the case of SuperK [Ch2-33] and SNO+ [Ch2-34] to search for neutrinoless double beta decay. These techniques are also used with or without Gd-doping in veto detectors as for XENONnT [Ch2-35], LZ [Ch2-36] DARWIN [Ch2-37] and SHiP [Ch2-38]. New ideas that go beyond the current state of the art, entering the demonstration phase, include hybrid Čerenkov/scintillation detectors as in Theia [Ch2-23]; cold LS with SiPM read-out as in TAO [Ch2-22]; opaque LS with fibre read-out as in LiquidO [Ch2-39]; LS doped with quantum dots for $0\nu\beta\beta$ searches as in NuDot [Ch2-40] and LS which becomes wax-like at room temperature.

While the requirements and needs are different depending on the physics goals, the main R&D topics are the following.

Radio-purity
A common requirement for all WC and LS detectors is to achieve sufficiently good radio-purity levels (DRDT 2.3), which is very demanding if the LS is the target of

an ultra low background experiment as for $0\nu\beta\beta$ decay, such as the current leading experiment KamLAND-ZEN [Ch2-41]. The state-of-the-art for water is 10^{-15}g/g U/Th. Any improvement beyond this level would benefit not only the water-based detectors but also LS detectors since they use water to purify the liquid scintillator.

Liquid composition
Liquid composition R&D aims to improve the optical properties of the liquid, the photon detection efficiency, and, closely related, to optimise the coupling of the light emitted to the photosensors (DRDT 2.3). To tune the photon emission spectrum, or wavelength in the liquid, there are proposals of water-based LS with organic micelles suspended in water, or doping with quantum dots. The light emission properties of the liquid are also under investigation to tune the fluorescence times and spectrum. This is particularly relevant for applications in which background is reduced using techniques of pulse shape discrimination, which can be improved by an appropriate choice of the liquid components.

R&D to improve event reconstruction addresses the development of highly transparent target media. This can be achieved either by a Water-based Liquid Scintillator (WbLS) [Ch2-42] or purification of the optically transparent scintillator components. WbLS detectors also offer an excellent capability for metal-loading of the scintillator material. While gadolinium-loading provides enhanced neutron detection, doping with tellurium and other candidate isotopes offers an avenue towards multi-ton $0\nu\beta\beta$ experiments.

The characterisation of the light properties is a key aspect. For instance, measuring the optical attenuation length of these purified liquids (≥ 30 m) requires long-arm setups. Alternatives to these systems based on interferometry of intensity-modulated light pulses in reflective cavities are proposed.

Liquid doping/stratification
R&D for SNO+ has demonstrated the feasibility of loading LS targets with $0\nu\beta\beta$ sensitive dopants; R&D aims to reach loading levels of several percent with increased light output. Another direction for high loading is to operate the LS at low temperatures. R&D on the use of quantum dots is also underway. Related to stratification, there are proposals to explore alternative geometries for large scale LS detectors, for instance the use of dissimilar stratified liquids to separate scintillating and non-scintillating regions without the need of a physical barrier (such as an acrylic or nylon containment vessel). This would also lower detector radioactivity.

Low temperatures
Another promising technique is related to the use of cold organic scintillators. Most liquid scintillators can be cooled down to -50°C which will increase the light yield and reduce the dark noise of SiPMs to an acceptable level. Since thousands of photoelectrons per MeV are collected, it is expected to achieve an energy resolution $< 2\%$ at 1 MeV. For that, it is important to preserve the liquid transparency and chemical stability at these low temperatures.

Opacity
R&D is underway to exploit the opacity, rather than transparency, of the light medium. In an opaque LS detector, light emitted via scintillation remains locally, stochastically confined via an extreme level of light elastic-scattering, typically dominated by Mie and Rayleigh scatterings. The scattering mean-free-path is thus reduced by up to four orders of magnitude (up to order mm) relative to today's technology. In this heavily opaque medium, light displaces barely a few cm's, hence photons must be collected locally via a tight (order ≥ 1 cm) lattice of wavelength-shifting fibres arranged in an axial orientation. This technique aims for topological particle identification in the MeV range, enabling electron-positron discrimination.

Hybrid detectors for event reconstruction
A medium able to separate Čerenkov from scintillation light signals using hybrid optical detectors offers improved capability for vertex reconstruction and background discrimination (DRDT 2.1 and DRDT 2.2). Čerenkov and scintillation signals can be separated based on the relative timing and/or wavelength of the arriving photons as well as the specific topology of Čerenkov rings. Separation by timing is aided by fast (sub-nanosecond) photo sensors (e.g. LAPPDs) or slow scintillating fluors [Ch2-43], wavelength discrimination by colour-sensitive sensors (e.g. dichroicons).

Complex event topologies, including hybrid Čerenkov and scintillation signals, demand the development of new reconstruction techniques including machine-learning and topological reconstruction. The main R&D goals here are the refinement of the current techniques and the realisation of the new concepts at the tonne scale (DRDT 2.4).

2.4 Observations

Expert input at the ECFA Plenary Input Sessions (see Appendix C) made the following observations on community, cross-cutting issues and interactions with neighbouring fields and industry.

2.4.1 Neutrino Oscillation and Astro-particle Neutrino Detectors

Community
The long-baseline neutrino community is growing, costs are increasing, and most funding agencies will be involved in both programmes of LHC and neutrino physics. Global planning and coordination is required. R&D efforts are already playing a role in this. There is significant emphasis on photon detectors, PCB-type readout technologies and related front-end microelectronics to increase detector resolution, for both near and far detectors (like pixels, fine grained detectors, magnetised trackers, wide-angle TPCs, high-pressure gas TPCs) as the field moves from statistical to systematic uncertainty dominated measurements.

For astro-particle neutrino experiments, a global neutrino network (GNN) is envisioned by the community, with greater interaction with particle physics centres, in particular CERN.

Cross-cutting issues
Very complex detector integration and installation plans represent a step-change for the long-baseline neutrino field, with five years of components manufacturing across ~ 30 countries and almost one decade of construction. In both LAr and water Čerenkov programmes the complexity of the detectors in increasing by an order of magnitude, with much bigger far detectors, more diversified near detectors, and more dependencies from industrial projects / initiatives. Proper engineering approaches, both structural and electrical, are becoming more important, in particular as concerns integration and installation underground. This is reflected in DRDT 2.4.

The community has adopted the concept of test beams to test and qualify the performance of what has been built, e.g. the characterisation of ProtoDUNE at CERN and the planned Hyper-K Water Čerenkov Test Experiment.

For astro-particle neutrino experiments, there are overlaps with earth and sea sciences, with potentially relevant measurements for studies of climate change, marine life (e.g. noise pollution), and tsunami warnings. Cross-cutting R&D is exploring more pixelisation of photon detectors for increased resolution, as well as new technologies exploiting radio and acoustic detection of neutrinos.

Interactions
Interactions with industry for the long-baseline programme include membrane cryostat technology. This technology from the liquified natural gas shipping industry has been adopted for very large cryostat vessels ($\sim 13{,}000\,\mathrm{m}^3$). It has been deployed in ProtoDUNE, and in the near term is being deployed in SBND, DarkSide-20k, and DUNE.

For astro-particle neutrino experiments interactions include commercial cabling and civil engineering of $\mathcal{O}(\mathrm{km}^3)$ detectors, which is a major challenge, e.g. in deployment of photosensor arrays from ice surface, or surface vessels (at sea). There is potential for involvement of offshore industry in a future cosmic ray detector on the sea floor.

2.4.2 Dark Matter and $0\nu\beta\beta$ Experiments

Community
Simple extrapolations of existing technologies to larger scales are not sufficient to meet the physics ambition of next-generation dark matter and $0\nu\beta\beta$ detectors. Much of this community is in transition from small scale experiments towards large HEP size experiments, like DARWIN and ARGO.

There is a proliferation of creativity in detection schemes (new sensors, new detector ideas combining heat and ionisation partitions, integration with quantum technologies for readout etc.) in this community, with time scales that can be shorter than most areas of HEP, reflected by DRDT 2.1 and DRDT 2.2. Both incremental and transformative R&D efforts are essential to make progress in dark matter, because the physics parameter space is so large. Shared facilities across experiments are needed, for example for low-background screening and cryogenics facilities to test large scale equipment.

Cross-cutting issues
The main technological challenges across different technologies is upscaling whilst reaching ultra-low backgrounds (DRDT 2.3 and DRDT 2.4). Material science is increasingly important (e.g. surface treatment to reduce backgrounds, cryogenic distillation on huge scale, new insulator or semiconductor target materials for bolometer development) reaching across fields (chemistry, materials science, etc.) Many new R&D efforts aim towards measuring recoil energies down to meV scales, to extend the sensitivity to MeV dark matter masses and below. Technological innovations benefit other fields (e.g. cryogenic distillation and medical isotopes for MRI). The need to keep the engineering/technical expertise at universities for efficient R&D progress is high.

Interactions
Interactions with industry include photosensor development for lower radioactivity (PMTs) and dark count rate (SiPMs); vibration-isolated, cryogen-free dilution refrigerators, large cryogenic systems and cryogenic distillation.

2.5 Recommendations

Motivated by the unmet needs for short, medium and long-term applications of liquid detectors, the following are recommended, addressing both technology and organisation.

- Near-term R&D should facilitate x10 scale increase of dark matter and neutrino experiments over the next decade (DRDT 2.4). Depending on the physics drivers and detector specifics, this requires radiopurity reductions of 10-1000, an $O(10)$ improvement in purification of targets, improvements of TPC pixel charge electronics to reduce heat dissipation and overall cost reduction. Fostering industry-academia collaboration from an early stage is an important requirement at this scale.

- Structural funding instruments are needed to stimulate coherent R&D which can be beyond the reach of relatively small individual experiments, e.g. a programme like AIDA for rare-event search detector development. This aligns with the 2021 APPEC dark matter strategy report recommendations [Ch2-44].

- Community-building is required to develop both science and technology with adjacent fields in:

  - chemistry: to advance understanding/advantages of liquid doping, isotope extraction e.g. barium tagging, cryogenic distillation (DRDT 2.3 and DRDT 2.4);
  - quantum technologies: readout development and also target doping, improvements in quantum efficiency (also relates with materials science) and energy resolution (DRDT 2.1, DRDT 2.2 and DRDT 2.3);
  - optics and photonics: QE improvements, wavelength-shifting, meta-materials developments (DRDT 2.1, DRDT 2.2 and DRDT 2.3);

  - engineering/materials science: liquid purification and radiopurity (DRDT 2.3 and DRDT 2.4);
  - industry: semiconductors (photon detectors, VUV sensitivity, quantum dots) (DRDT 2.1); cryogenic infrastructure (large-scale cryostats from liquid gas industry, vacuum industry) (DRDT 2.4).

- Further future advances should explore how to combine detection of different modalities (DRDT 2.2), for example by:
  - exploring the full light spectrum (from NIR to VUV) and establishing simultaneous Čerenkov-scintillation light detection;
  - readout of electromagnetic and acoustic detection;
  - establishing readout of light and charge in the same device.

- In general, it is important to highlight that both short term and long term R&D are important. In liquid detectors the present well-defined R&D horizon is $\mathcal{O}(5)$ years; beyond this one must open the window to "blue-sky" developments, which could happen on the timescale of $\mathcal{O}(10)$ years from now. This is important not only for technology progress but also for the healthy continuation of this research field.

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Chapter 3

Solid State Detectors

3.1 Introduction

Solid State detectors (SSD) based on semiconductors, and in particular silicon detectors (planar pixels, planar strips, and 3D pixels), are used in almost all particle physics experiments. Since they can be easily segmented using standard photo-lithographic techniques, they can achieve superb position resolution and play a key role in measuring primary and secondary vertices and tracking charged particles. Silicon is also used as an active medium in particle flow calorimeters to associate showers with tracks and then to track showers as they develop in the calorimeter (see Chapter 6). Finally, as discussed in Chapter 4, silicon detectors are fundamental in photonics.

Revolutionary improvements of SSD performance are needed to match the requirements of future experiments. All-silicon trackers are required for future hadron colliders such as FCC-hh and are one of the most competitive option also for e^+e^- Higgs factories. There are commonalities in the possible SSD technological choices since both hadrons and e^+e^- colliders require low mass, low power, high-resolution trackers. Nonetheless, there are also differences since hadron colliders necessitate ultra-fast detectors, enabling 4D-tracking[1], to deal with multiple interactions occurring within a bunch crossing (pile-up). Detectors at FCC-hh must also achieve unprecedented radiation hardness. The highest levels are reached in the forward calorimeters where the total ionising dose and the 1-MeV equivalent neutron fluence rise to values of 5000 MGray and $5 \times 10^{18}\,n_{eq}\,cm^{-2}$. Even in the innermost layer of the barrel vertex detectors the fluences approach $1 \times 10^{18}\,n_{eq}\,cm^{-2}$ after an integrated luminosity of $30\,ab^{-1}$.

After years of R&D, silicon sensors manufactured using mainstream CMOS imaging technologies are now being implemented in several high energy physics (HEP) experiments. CMOS MAPS (Monolithic Active Pixel Sensor) have now been installed in STAR and ALICE; they are planned for other experiments such as CBM, the LHCb tracker, and Mu3e. MAPS technologies are especially suited for applications requiring low-mass and excellent position resolution called for at electron machines.

[1] Reconstructing the trajectory of a charged particle in three spatial dimensions plus time as a fourth dimension.

Future flavour physics experiments will operate in a high-occupancy environment where event reconstruction will be very challenging. The physics programme enabled by the LHCb Upgrade II relies on an efficient and precise vertex detector with real time reconstruction of tracks from all LHC bunch crossings in the software trigger system, which also would highly benefits from having 4D-tracking. The higher occupancy expected in future running will also demand increased detector granularity for the LHCb tracker.

Reduction of material in the region close to the interaction point leading to significant improvements in tracking precision and efficiency at low transverse momentum, is critical to achieving the physics goals of Heavy Ion experiments, such as ALICE, and those planned for the EIC and particularly at future e^+e^- colliders. Better position and timing resolution, and lower power consumption would also benefit the upgrades of Belle and NA62, which will occur during this decade. Devices with $\mathcal{O}(10\,\mathrm{ps})$ timing resolution will be highly desirable for 4D-tracking reconstruction at the foreseen 1000 collision pile-up of the FCC-hh.

One aspect common to most future facilities is the requirement for the front-end electronics to perform very complex tasks, such as those required for 4D-tracking or by the transfer off-chip of very large data volumes. 3D-stacking is therefore a key technological development that needs to be included in future high-performing trackers.

Following these needs, Task Force 3 Solid State Detectors has identified the essential Detector R&D Themes (DRDT) which capture the most critical requirements.

DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.

Developments of Monolithic Active Pixel Sensors (MAPS) should achieve very high spatial resolution and very low mass, aiming to also perform in high fluence environments. To achieve low mass in vertex and tracking detectors, thin and large area sensors will be crucial. For tracking and calorimetry applications MAPS arrays of very large areas, but reduced granularity, are required for which cost and power aspects are critical R&D drivers. Passive CMOS designs are to be explored, as a complement to standard sensors fabricated in dedicated clean room facilities, towards hybrid detector modules where the sensors is bonded to an independent ASIC circuit. Passive CMOS sensors are good candidates for calorimetry applications where position precision and lightness are not major constraints (see Chapter 6). State-of-the-art commercial CMOS imaging sensor (CIS) technology should be explored for suitability in tracking and vertex detectors.

DRDT 3.2 - Develop solid state sensors with 4D-capabilities for tracking and calorimetry.

Understanding of the ultimate limit of precision timing in sensors, with and without internal multiplication, requires extensive research together with the developments to increase radiation tolerance and achieve 100%-fill factors. New semiconductor and technology processes with faster signal development and low noise readout properties should also be investigated.

DRDT 3.3 - Extend capabilities of solid state sensors to operate at extreme fluences.
To evolve the design of solid state sensors to cope with extreme fluences it is essential to measure the properties of silicon and diamond sensors in the fluence range $1 \times 10^{16}\, n_{eq}\, cm^{-2}$ to $5 \times 10^{18}\, n_{eq}\, cm^{-2}$ and to develop simulation models which correspondingly include results from microscopic measurements of point and cluster defects. All technologies will need improved radiation tolerance for use at future hadron collider experiments. Exploration of alternative semiconductors and 2D-materials should already start, having as a target full functionality even after the extreme fluences present in the innermost parts of the detectors. A specific concern to be addressed is the associated activation of all the components in the detector. Exploration is desirable on alternative semiconductors and 2D-materials to further push radiation tolerance.

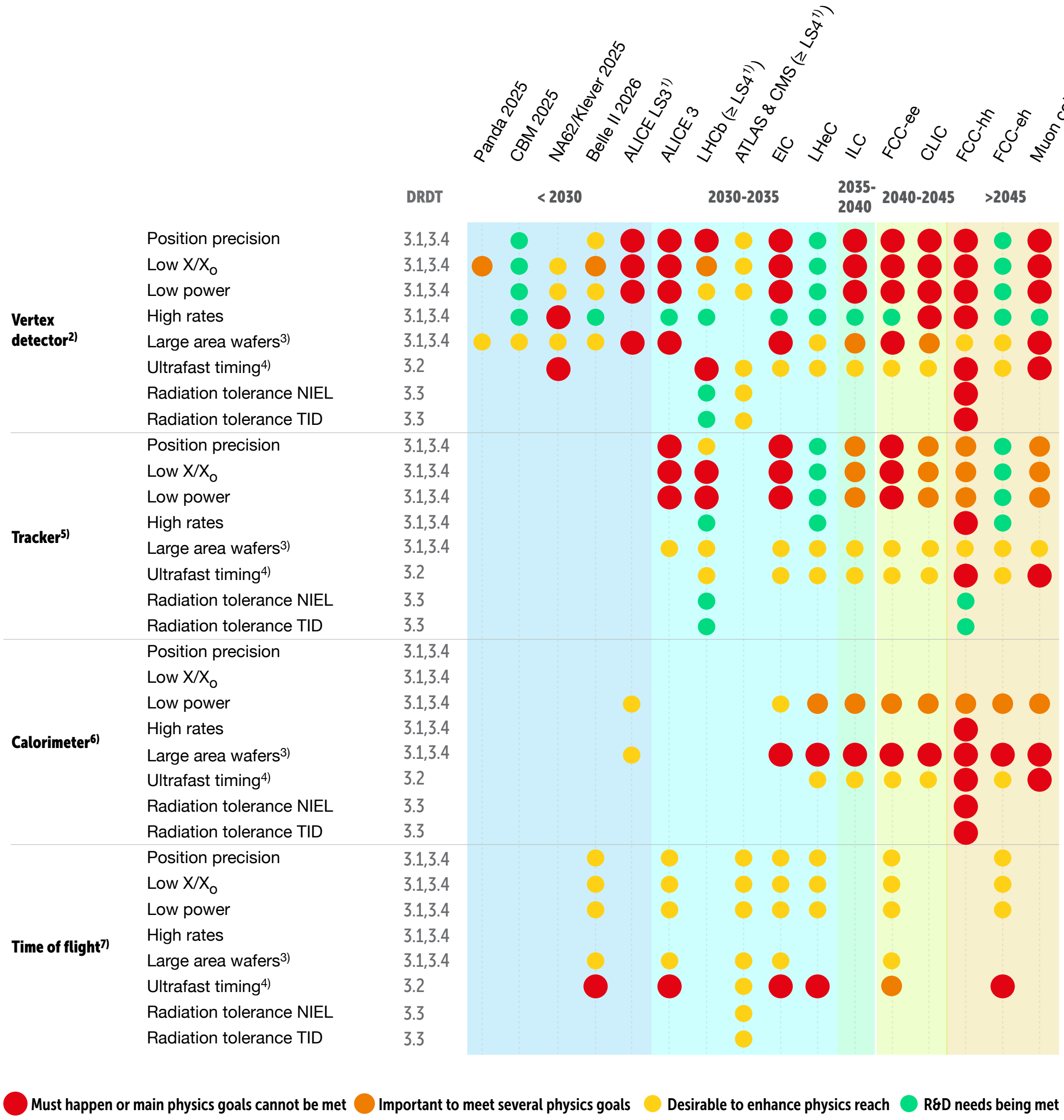
DRDT 3.4 - Develop full 3D-interconnection technologies for solid state devices in particle physics.
3D-interconnection is commercially used, for instance in imaging sensors, to use the most appropriate technology process for the different functionalities of the devices. For particle physics detectors, this process would allow more compact and lighter devices with minimal power consumption. This approach also provides an alternative to the use of finer feature sizes to enable lower pitch and new digital features. An enhanced R&D effort towards building a demonstrator as a starting cornerstone is highly desirable. A demonstrator programme should be established to develop suitable silicon sensors, cost effective and reliable chip-to-wafer and/or wafer-to-wafer bonding technologies and to use these to build multi-layer prototypes with vertically stacking layers of electronics, interconnected by through-silicon vias (TSVs) and integrating silicon photonics capabilities.

The timelines for these R&D themes can be found at Figure 11.1 with explanation in the caption and associated text. R&D on DRDT 3.1, DRDT 3.2, and DRDT 3.4 is needed for multiple facilities listed in Figure 3 and Figure 4 of the Introduction, all the way through to the FCC-hh/muon collider era, as detailed below. For DRDT 3.3 there is fortunately more time to address the two orders of magnitude greater radiation hardness requirements of experiments at the FCC-hh with respect to those at HL-LHC.

3.2 Main drivers from the facilities

Figure 3.1 presents the Detector Readiness Matrix which summarises the requirements for future solid state detectors. The table reports on the horizontal axis the facilities while the vertical axis lists the quantities with the most demanding specifications, such as the spatial and temporal precision, power consumption, material contribution, and radiation tolerance, that must be achieved. The colour coding is explained in the caption.

Figure 3.2 complements Figure 3.1 by showing, in the same format, the required values of the parameters listed on the vertical axis as a function of time (and facility).



1) HL-LHC Long shutdowns: LS3/LS4 2025/2031 (see https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm)
2) LHCb/ATLAS/CMS consider Planar/3D sensors at the time of this document for rates and radiation tolerance. On longer term, pixelated LGADs could be considered for potentially higher timing precision.
3) In trackers, coarser longitudinal granularities could be considered for MAPS. Thorough performance and cost comparison with passive CMOS would be needed. Pixelated LGADs could be considered for potentially higher timing precision.
4) The size of wafers achievable can depend on technology (industrial process) with a general trend to benefits from larger areas.
5) Ultrafast timing refers to ≤100 ps depending on technology and detector purpose.
6) Two options exist for calorimetry: pads O(1) mm pitch with analog readout (applying to all technologies) and particle counting digital with MAPS O(50) μm pitch. LGADs could be considered for potentially higher timing precision.
7) ToF, as compared to 4D-tracking, concerns dedicated layers for very high pile-up, beam induced background or particle identification with highest possible precision. Timing erformance of sensors without amplifcation (MAPS, planar/3D/CMOS passive CMOS) is subject to R&D, while LGADs with amplification are at this stage expected to potentially provide higher precision.

Figure 3.1: Schematic timeline of categories of experiments employing solid state sensors together with DRDTs and R&D tasks. The colour coding is linked not to the intensity of the required effort but to the potential impact on the physics programme of the experiment: Must happen or main physics goals cannot be met (red, largest dot); Important to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); No further R&D required or not applicable (blank).

"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				**< 2030**					**2030-2035**					**2035 - 2040**	**2040-2045**		**> 2045**		
				Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 [1]	ALICE 3	LHCb (≥LS4)[1]	ATLAS/CMS (≥ LS4)[1]	EIC	LHeC	ILC [2]	FCC-ee	CLIC [2]	FCC-hh	FCC-eh	Muon Collider
Vertex Detector[3]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		≃ 5		≲ 5	≃ 3	≲ 3	≲ 10	≲ 15	≲ 3	≃ 5	≲ 3	≲ 3	≲ 3	≃ 7	≃ 5	≲ 5
			X/X_0 (%/layer)	≲ 0.1	≃ 0.5	≃ 0.5	≲ 0.1	≃ 0.05	≃ 0.05	≃ 1		≃ 0.05	≲ 0.1	≃ 0.05	≃ 0.05	≲ 0.2	≃ 1	≲ 0.1	≲ 0.2
			Power (mW/cm^2)		≃ 60			≃ 20	≃ 20			≃ 20		≃ 20	≃ 20	≃ 50			
			Rates (GHz/cm^2)		≃ 0.1	≃ 1	≲ 0.1		≲ 0.1	≃ 6		≲ 0.1	≃ 0.1	≃ 0.05	≃ 0.05	≃ 5	≃ 30	≃ 0.1	
			Wafers area (")[4]					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns)[5]	10		≲ 0.05	100		25	≲ 0.05	≲ 0.05	25	25	500	25	≃ 5	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL ($x 10^{16}$ neq/cm^2)							≃ 6	≃ 2						≃ 10^2		
			Radiation tolerance TID (Grad)							≃ 1	≃ 0.5						≃ 30		
Tracker[6]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)						≃ 6	≃ 5		≃ 6	≃ 6	≃ 6	≃ 6	≃ 7	≃ 10	≃ 6	
			X/X_0 (%/layer)						≃ 1	≃ 1		≃ 1	≃ 1	≃ 1	≃ 1	≃ 1	≲ 2	≃ 1	
			Power (mW/cm^2)						≲ 100	≃ 100		≲ 100		≲ 100	≲ 100	≲ 150			
			Rates (GHz/cm^2)							≃ 0.16									
			Wafers area (")[4]						12			12		12	12	12	12		12
		DRDT 3.2	Timing precision σ_t (ns)[5]						25	≲ 25		25	25	≲ 0.1	≲ 0.1	≲ 0.1	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL ($x 10^{16}$ neq/cm^2)							≃ 0.3							≲ 1		
			Radiation tolerance TID (Grad)							≃ 0.25							≲ 1		
Calorimeter[7]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t (ns)[5]											≲ 0.05	≲ 0.05	≲ 0.05	≲ 0.02		≲ 0.02
		DRDT 3.3	Radiation tolerance NIEL ($x 10^{16}$ neq/cm^2)														≳ 10^2		
			Radiation tolerance TID (Grad)														≃ 50		
Time of Flight[8]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t (ns)[5]				≃ 0.02		≃ 0.02		≲ 0.03	≃ 0.02	≃ 0.02		≲ 0.01		≲ 0.01	≃ 0.02	
		DRDT 3.3	Radiation tolerance NIEL ($x 10^{16}$ neq/cm^2)														≃ 10^2		
			Radiation tolerance TID (Grad)														≃ 30		

Values are indicative of performance targets and of operating conditions relevant to R&D. The latter are reported for the regions most exposed to radiation. Empty cells indicate either that projects are not concerned; or that specifications are already met or not yet fully established, for instance power consumption depends strongly on granularity and digital features that would be finally implemented.

1) LS3/LS4 are scheduled to start in 2025/2031 at the time of this document.

2) Reported rates are within the bunch trains.

3) LHCb/ATLAS/CMS consider Planar/3D sensors at the time of this document for rates and radiation tolerance. Pixelated LGADs could already be considered for NA62/Klever andfor longer term Vertex Detectors for timing precision for high timing precision.

4) The size of wafers achievable can depend on technology (industrial process) with a general trend to benefits from larger areas.

5) Ultrafast timing ≲ 100 ps could be differently achieved by the various technologies.

6) In trackers, coarser longitudinal granularities could be considered for MAPSs. Thorough performance and cost comparison with Passive CMOS would be needed. Pixelated LGADs could be considered for potentially higher timing precision.

7) Two options exist for calorimetry: pads O(1) mm pitch with analog readout (applying to all technologies) and particle counting digital with MAPSs O(50) μm. LGADs could be considered for potentially higher timing precision. DRT 3.1 apply w/o the X/X_0 constraint. DRT 3.4 could achieve higher compactness and be needed for the digital options to integrate full readout within the sensor area.

8) TOF, as compared to 4D-tracking, concerns dedicated layers for very high pile-up, beam induced background or particle identification with highest possible precision. Timing performance of sensors w/o amplifcation (MAPS, planar/3D/CMOS passive CMOS) is subject to R&D, while LGADs w/ amplification are at this stage expected to potentially provide higher precision. DRT 3.1 and DRT 3.4 of Vertex Detector and Tracker apply with less stringent requirement.

Figure 3.2: This matrix complements Figure 3.1 by showing, in the the same format, the required values of the quantities listed on the vertical axis as a function of time (and facility).

The choice to show the evolution of requirements with time reflects that the technologies discussed in the R&D themes are often valid alternatives for these (depending on which combination of properties is most needed) and in the longer term the distinctions between these different pixel approaches will become blurred as 3D-integration allows more sophisticated monolithic solutions.

3.3 Key technologies

3.3.1 CMOS sensors: MAPS and passive CMOS

Silicon sensors manufactured using mainstream CMOS imaging technologies are referred to as MAPS (Monolithic Active Pixel Sensors) [Ch3-1], [Ch3-2], [Ch3-3]. The technology provides very small pitches yielding the best position resolution achieved so far. Furthermore, since the signal readout circuit is integrated into the sensitive element, they minimise multiple scattering, leading to further position and momentum resolution improvements. The radiation tolerance, timing, and efficiency of CMOS MAPS can be improved by applying the same principles that have guided standard sensors' designs in other technologies to achieve faster charge collection.

Recent developments have concentrated on two distinct process implementations for charged particle tracking: (i) MAPS designed with large collection electrodes, which provides the highest radiation tolerance and more uniform sensor timing but exhibits large input capacitance. (ii) MAPS with small collection electrodes yielding reduced capacitance at the amplifier inputs and, therefore, giving lower input noise and potentially faster signals. Traditionally, MAPS have been used in low radiation environments; however, recently, they have been further developed to cope with significant radiation levels through novel device engineering and processing methods. These improvements allow operating the sensors, regardless of large or small electrode designs, fully depleted and with optimised field configurations inside the sensing volume, which is key to reaching timing resolutions below 100 ps and radiation tolerance up to $1\text{-}2\times10^{15}\,\mathrm{n_{eq}\,cm^{-2}}$.

Smaller technology nodes (below the current 100-180 nm) in more advanced technologies or special imaging sensor features will reduce even further the pixel pitch and allow the implementation of digital functionalities necessary to sustain the high particle rates required by several applications. Moreover, with decreasing feature size, increased signal on small collection electrodes will enable precision timing. The lower power consumption will minimise the cooling needs and, therefore, the material in the tracking system. The radiation tolerance is also likely to improve substantially.

Stitching techniques must be developed to provide large area CMOS MAPS sensors, which are vital in minimising a system's material budget and building large area trackers. Large size sensors will require dedicated studies of the readout architecture for power distribution and to reduce consumption in the data transfer over substantially longer paths than achieved so far.

The thickness of the MAPS is the ultimate limit to the device's scattering material, and new designs must allow novel advances in post-processing techniques. Enabling technologies include post-processing techniques based on standard industrial processes adapted or optimised to specific needs. For example, thinning and dicing require optimisation, especially for very thin MAPS, to achieve the maximum sensitive area and implement stress relief to reduce damage.

In summary, to fulfil several and increasingly demanding constraints, the R&D on

MAPS will combine multiple strands that can build on common features, either gradually in time or in parallel, linking also with the further developments in microelectronics discussed in Chapter 7:

- MAPS, in sub-micron node(s) for smaller pixels pitch and stitching process for large area sensors to reach ultimate precision and radiation length in vertex detectors;
- MAPS for small-pixel trackers with radiation-hard cell designs and high hit-rate capability (sufficient charge collection after $1\times10^{15}\,\mathrm{n_{eq}\,cm^{-2}}$ to $1\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ Non-ionsing energy loss (NIEL), single event upsets (SEU) and single event effects (SEE) tolerant and power-optimised logic, concepts for high data volumes handling on a sensor);
- MAPS designs to reach ultimate timing precision in different processes;
- MAPS with reduced granularity and very low power consumption in very large area detectors for tracking and calorimetry applications.

Passive CMOS

The term passive CMOS sensors indicates pixel or strip sensors manufactured using a simplified CMOS process, e.g. with only two metal layers and without any active elements such as transistors. Passive CMOS [Ch3-4] sensors do not contain any active electronics, and they are read-out as standard analogue sensors via wire or bump bonding. Passive CMOS sensors can profit from using CMOS processing lines on large, high-resistivity wafers ($\mathrm{k\Omega\,cm}$), allowing for design improvements and production optimisations with n-well/p-well/metal layers for sensor implantation and biasing. The possibility of Multi-Project Wafers (MPWs) allows for design optimisations with small prototypes (guard rings, implant geometry, ...), limiting the costs. Several studies showed that in terms of breakdown voltage, radiation hardness, and particle detection efficiency, passive CMOS sensors are not of inferior quality with respect to standard silicon sensors. This was proven with pixel sensors up to $1\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ ($>99\%$ efficiency at 400 V bias voltage) [Ch3-5]. The multiple metal layers present in CMOS processes allow new, advantageous variants in the sensor designs and the stitching technique (i.e. composing a larger pattern with more than one small image) allows exceeding reticle size to produce large sensor tiles, such as needed in silicon strip tracking systems.

Several aspects make passive CMOS sensors particularly interesting: (i) they might be cheaper to manufacture in large-scale production since they are manufactured in a CMOS chip technology line, which would be of particular importance for strip applications where the sensors are the cost driver. (ii) Their dependence upon a specific CMOS process is not as important as it is for active sensors or read-out electronics: there are many technology nodes to select from (AMS/TSI [Ch3-6], ESPROS [Ch3-7], IBM [Ch3-8], LFoundry [Ch3-9], TowerJazz [Ch3-10], Toshiba [Ch3-11], XFAB [Ch3-12], ...). (iii) Most design rules are not relevant for the large structures used in a sensor design, for example, the minimum rule set is usually not used. (iv) If one node is not available, porting a design to a new process is simple and can be achieved on a short timescale.

One should note that post-processing is usually required to add the implantation and metallisation as back-plane contact.

The boundary between hybrid and monolithic sensors will become more vague in future developments as even MAPS might require multiple layers. Industrial 3D-integration techniques (see also Chapter 7) promise to integrate multiple specialised wafers with dedicated functions (sensing layer, analogue layer, digital circuit, photonics data transmission) into a single device. The product, a monolithic "sensor" from an assembly point of view, will allow coping with future demands from tracking detectors such as very high hit-rate capability, on-sensor signal processing, data compression, and high-speed data transmission. 3D-integrated imaging sensors currently commercially developed at Sony [Ch3-13] and Samsung [Ch3-14] also allow pitches in the µm range that would enable ultimate spatial resolution for particles entering sensors at different angles.

Feasibility studies on stitched devices will determine the size of the sensors for the future, and whether and to what extent one can profit from wafer-scale integration.

3.3.2 Sensors for 4D-tracking

In the past ten years, silicon sensors moved from being considered sensors with a relatively poor temporal resolution (usually linked to beam bunch spacing) to being the detector of choice in high-precision timing systems. The level of timing accuracy needed by future experiments depends on the targeted applications. Time of Flight (TOF) systems, normally formed by one or two sensor layers, require the best possible accuracy as the time is typically measured in only a single (or at best a few) point(s). Large 4D-tracking systems requiring a good track timing identification might have a relatively lower (50-100 ps) single point accuracy requirement, exploiting the capability of multiple measurements to achieve the required precision on the track. MAPS and passive CMOS sensors are also expected to meet this range of performance. On the other hand, 4D-tracking systems that use the temporal information in their pattern recognition software require a very high single hit timing accuracy, regardless of the number of layers. While calorimeters (see Chapter 6) achieve excellent precision given their very large signals, there is a growing interest in exploring calorimeter timing performances also for MIP particles. They aim at deploying timing performance not only to eliminate collision pile-up and beam induced background but also to be used for greater tracking precision in the detailed reconstruction of particle showers.

Future 4D-trackers will advance from the present state-of-the-art design of timing layers [Ch3-15], [Ch3-16], investigated with IMB-CNM [Ch3-17], FBK [Ch3-18] and Hamamatsu [Ch3-19], a silicon layer that provides precise temporal coordinate but only coarse position, to tracker systems able to concurrently precisely measure the spatial and temporal coordinates. The targeted temporal precision is about 30 ps for the detectors at LHC, 20-30 ps at the EIC collider, and it decreases to about 10 ps for the TOF systems at FCC-ee, other Higgs-EW-Top factories, and FCC-hh. Similar ultimate precision for FCC-hh would be highly desirable for 4D-track reconstruction at the foreseen 1000 multiple interactions per bunch crossing interval.

The primary specifications for these 4D-trackers are typically put in terms of spatial and temporal precision. However, these two requirements do not adequately convey the complexity of the design, as several other parameters are determining the overall architecture: (i) material budget, (ii) power, (iii) rates, (iv) occupancy, (v) area, and (vi) radiation hardness. In addition, the interplay between sensors and electronics in timing applications is particularly important. In this view, a few essential parameters that sensors for 4D-tracking should have, are ample ($> 3\,\mathrm{fC}$) and short (< 200-$300\,\mathrm{ps}$) signal, uniform response, low capacitance[2], very high fill factor, and 100% efficiency. Presently, the two families of sensors that are delivering the best temporal performances are (i) thin, planar Low-Gain Avalanche Diodes (LGADs) [Ch3-20] optimised for timing (also known as Ultra-Fast Silicon Detectors [Ch3-21]) and (ii) 3D with columns [Ch3-22] or trenches [Ch3-23]. The best performances in terms of temporal precision for these sensors are similar, about 20-30 ps. A technology that might deliver excellent performances is BiCMOS MAPS, exploiting the properties of SiGe transistors (low noise and high gain) [Ch3-24]. In the following, a short description of the main characteristics of sensors for 4D-tracking is provided.

- **Radiation levels**: LGADs are proven to work up to about $2{\times}10^{15}\,\mathrm{n_{eq}\,cm^{-2}}$ [Ch3-25], while the 3D detector architecture is intrinsically more radiation-resistant;
- **Large area** detectors, covering areas above 1-2 m^2 can be obtained using LGADs (for example, the CMS timing layer requires 17 m^2 of sensors);
- **Low material budget** LGADs (critically dependent on substrate thickness) and MAPS will deliver the best performances; in 3D sensors the collected charge is proportional to the sensor thickness so they cannot be made very thin;
- **Ultimate temporal precision** might be achieved with thin LGADs, 3D sensors and BiCMOS MAPS;
- **Ultimate spatial precision** requires either small pixels (3D design), or it can be achieved with specialised evolutions of the LGAD concept: inverted LGAD (iLGAD) [Ch3-26], trench-isolated LGAD (TI-LGAD) [Ch3-27], and AC-coupled LGADs (AC-LGAD or RSD) [Ch3-28], [Ch3-29];
- **High fill factor** iLGAD, TI-LGAD, and 3D-column architectures.

The field of silicon sensors for 4D-tracking is very young; therefore, the rate of improvement is quite rapid, and the capabilities of present technologies have not yet been fully exploited. For example, (i) MAPS are presently lagging in performances with respect to hybrid systems. However, this situation might change in the near future. (ii) The radiation hardness of the LGAD design is improving rapidly, and it has more than doubled in the past five years. (iii) The full potentiality of 3D sensors for timing is still to be reached. (iv) The production of BiCMOS MAPS for timing has just started. Independently from each other, both the sensors' radiation resistance and temporal precision will improve in the coming decades.

[2] An important figure of merit is the ratio between generated charge and input capacitance. If the capacitance can be reduced significantly, the required minimum charge can be even lower than 3 fC.

3.3.3 Silicon sensors for extreme fluences environments

Silicon is by far the most studied sensor bulk material at high fluences [Ch3-30], although studies of other materials such as SiC, GaN, and Diamond are also being performed due to the good potential shown so far. The expected behaviour of silicon sensors at high fluences obtained by predictions based on the damage parameters (introduction rate of space charge, trapping probabilities, generations current) measured at low fluences proved to be too pessimistic. Measurements above fluences of a few $\times 10^{15}\,\mathrm{n_{eq}\,cm^{-2}}$ demonstrate that silicon sensors' performance greatly surpass the predictions. The successful operations of thin silicon planar detectors at fluences above $2\times 10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ and silicon 3D detectors above $3\times 10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ have been reported [Ch3-31]. The few measurements available at fluences approaching those at FCC-hh, about 1-2$\times 10^{17}\,\mathrm{n_{eq}\,cm^{-2}}$ [Ch3-32], point to the possible operation of silicon 3D detector even above these radiation levels, maintaining signals around a few thousands of electrons. Although 3D detectors are the most promising technology for high-radiation environments, signals of around 1000 electrons were also observed in planar sensors of standard thickness (about 300 μm) [Ch3-33], with some indications of charge multiplication found in thin sensors [Ch3-34]. The signals (induced currents) at these fluences are very short, only a few 100 ps, and the losses are dominated by the charge trapping.

The changes of silicon properties at extreme fluences are currently poorly known. Reliable measurements of fundamental semiconductor properties such as carrier mobilities, impact ionisation coefficients, the introduction of charged defects, trapping, and generation centres are therefore prerequisites to any detector design. It is crucial that the properties of silicon sensors above fluences of 5-10$\times 10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ are measured and modelled.

The current limitations in exploring the semiconductor properties at extreme fluences are both in terms of the investigation techniques as well as in facilities that would allow the studies and exposure of the sensors to such extreme radiation levels. Any future progress in this field is very closely linked to improvement in both these aspects. The latter particularly depends on access to adequate resources.

The synergies with fusion reactor instrumentation are many and can be fruitfully exploited. The extension of current research lines of the RD50 [Ch3-35] research group and/or the creation of new R&D collaborations is needed to create the necessary resources to explore the extreme fluence frontier. This is particularly true given the associated issue of finding microelectronics solutions able to withstand such an environment, while coping with the heavily reduced signal size and the demands of ever faster timing capabilities (see Chapter 7).

3.3.4 Wide band-gap semiconductors

Wide band-gap (WBG) semiconductors have some attractive properties and also some associated problems. The balance between these benefits and drawbacks will decide how they could be used in future tracking detectors. Whilst a WBG reduces the leakage current, maintaining low noise levels even at high temperatures, it also increases the required electron-hole generation energy. This increase implies that the number of electron-hole pairs generated for the same deposited energy is lower in WBG materials. For instance, the charge generation in SiC is approximately half of that in silicon. However, the substantial reduction of the noise level ensures that the overall signal-to-noise ratio (SNR) for WBG-based detectors is high enough, even after irradiation. In addition, the high breakdown field allows operation at high internal electric fields, minimising the carrier transit time and the trapping probability.

Diamond

In the HEP community, the most studied material among WBG semiconductors is diamond. Diamond sensors have been studied intensively in the past decade [Ch3-36], and many of the initial hurdles have been passed [Ch3-37]. Detector-grade polycrystalline synthetic diamond (pCVDD) is available today with a charge-collection-distance (CCD) of about 400 μm. This level of quality has been achieved in close collaboration with manufacturers. The aim for the next 10 years is to increase the quality of as-grown pCVDD wafers from 400 μm to 500 μm, and at the same time improve the wafer uniformity in terms of CCD from currently 10% to 2% across the wafer. The radiation hardness of diamond has been verified with protons, neutrons, and pions; the damage constants for the different particle types and at different energies have been extracted. Based on these numbers, a rough estimate of the Schubweg[3] at a fluence of 10^{17}cm^{-2} 24 GeV protons gives $\lambda \approx 16\,\mu$m. This would lead to a significant reduction in signal efficiency for MIPs in planar detectors of approximately $\epsilon = \frac{\lambda}{\mathrm{d}} = 3.4\%$ assuming a detector thickness of d=500 μm. A remedy to this problem is the use of 3D electrode geometries [Ch3-38]. In recent years, substantial progress has been achieved in the production of 3D diamond detectors, using a femtosecond laser process to convert diamond into graphite electrodes. The smallest cell size of 3D diamond detectors achieved so far has 50 μm in base length, which is equivalent to an electrode distance of d=35 μm. Smaller cell sizes should be possible, achieving an electrode distance similar to the expected Schubweg of $\lambda = 17\,\mu$m for 10^{17}cm^{-2} 24 GeV protons, yielding good efficiency even at this fluence. The radiation damage of 3D devices has not been extensively studied yet. Still, preliminary results indicate that in a 50 μm cells size 3D detector, the collection efficiency decreases by $5 \pm 10\%$ after irradiation with 3.5×10^{15} cm^{-2} 24 GeV protons, compared to a loss of 45 ± 5 % for a planar diamond device at the same fluence [Ch3-39]. More studies are needed to assess the radiation tolerance of 3D diamond detectors comprehensively. The first 3D diamond detector devices in a collider experiment are planned as small beam condition monitors (BCMs) in the upgraded tracker as part of the ATLAS HL-LHC programme [Ch3-40]. This device will prove the readiness of the technology for small-scale applications on the timescale of the next ten years, and it represents a stepping stone towards larger area applications as needed for the FCC-hh to be developed over the next two decades.

Silicon Carbide

In the past [Ch3-41], SiC radiation detectors were discarded for their use in large-area HEP experiments due to the low quality of the bulk materials produced by manufac-

[3] Schubweg, often identified with the letter λ is defined as the average distance a carrier traverses before being captured.

turers. In addition, the possibility of buying only small-sized (50 mm) wafers was a limiting factor for large productions. Nowadays, the widespread use of SiC in power devices, together with the use of SiC as a substrate for GaN LEDs, has pushed the quality of this material to levels similar to those of silicon. In addition, 150 mm SiC wafers are now standard in the semiconductor industry. The high-quality material required for SiC sensors is typically epitaxially grown by Chemical Vapour Deposition (CVD). Epitaxy allows precise control of thickness, doping, and homogeneity of crystal films. High-purity detector-grade SiC epitaxial layers with a thickness of up to 150 μm have been recently obtained [Ch3-42]. The possibility of using thick substrates and fabricating cylindrical contacts with small electrode distances will also allow the fabrication of innovative SiC radiation detectors. Such a design would enable the sensors to be operated without cooling and to withstand high radiation fluences. The main technological challenges for SiC detectors in the following years are: (i) radiation hardness of high-quality materials, (ii) timing performances (LGAD option), (iii) reliable simulation models, (iv) production, in collaboration with industry, of large-area planar detectors with high yield and (v) explore the possibility of creating cylindrical electrodes (with different techniques such as laser, wet etching, Deep RIE) for extreme fluences.

Innovative 2D-materials
Recently, photo-detectors based on novel materials such as graphene and meta-materials have received a lot of attention. As in other fields, graphene has been a game-changer and, as early as in 2009, its combined outstanding electronic and photonic properties achieved ultra-fast photo-detectors [Ch3-43]. In addition to graphene, other 2D-materials such as the family of transition metal dichalcogenides also exhibit interesting characteristic properties, including a set with (direct) bandgaps. As a related example, MoTe2 has been proven as efficient for radiation detectors [Ch3-44]. It would be of great interest to explore the use of 2D-materials intrinsic properties to test the limits of fast signal collection (ps), high spatial resolution (μm), ultra-thin active membranes (few nm), very high operation rates (higher than 10 Gcycles), and high radiation hardness (Grad or $1\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$).

3.3.5 The future of interconnection technologies

Future 3D- and 4D-trackers will use hybrid and monolithic detectors. Contrary to the monolithic detectors, hybrid detector modules comprise a read-out ASIC and a solid-state sensor produced in two different technologies. The sensor can be of many different types, including passive CMOS, LGAD, planar and 3D silicon, planar and 3D diamond. The interconnection technologies used for the hybrid detector module production are state-of-the-art wafer-level post-processing technologies, including 2D-bumping, back end of line (BEOL) layer deposition, and 3D-integration technologies (see also Chapter 7). The future requirements on a highly flexible wafer-level processing line are:

- Process capabilities for different wafer sizes and sensor material types: 200 mm and 300 mm read-out chip (ROC) wafer produced in 65 nm technology node or below, 150/200/300 mm silicon sensor production wafers, single chip/small size diamond wafers;

- Reduction of overall detector material budget requires cheap and flexible handling concepts or alternative bonding technologies for ultra-thin wafers;
- Reduction of interconnection pitches from standard 50 μm to around 25 μm or even below 20 μm.

In the construction of future tracking detectors, an increased hybridisation processing at the vendor is foreseeable in combination with an associated cost reduction per module. A chip-to-wafer and/or wafer-to-wafer bonding approach can address both aspects. However, both bonding technologies require an optimisation of the chip and the wafer design. A chip-to-wafer assembly with a subsequent chip separation process is only possible if the top chip is smaller than the substrate chip: this is not the case for the current ROC on sensor chip design. The demands brought in by a wafer-to-wafer bonding process are even more complex. ROC and sensor wafers have to match in wafer size and require a matching reticle. If these requirements cannot be guaranteed, wafer bonding using a chip-to-carrier re-configured wafer can be a fall-back.

Independently from the bonding technology used, electrically conductive interconnections must be realised between every read-out cell and sensor pixel of the hybrid module. The very flexible, state-of-the-art bump bonding technology will be available also in the future, using a fast chip-to-wafer placement and parallel solder reflow process. This technology has already been used successfully for interconnection pitches of about 10 μm. Alternative bonding processes using a reduced solder layer thickness, like Transient Liquid Phase Bonding (TLPB) / Solid Liquid Inter-face Diffusion (SLID) can be applied for chip-to-wafer as well as wafer-to-wafer bonding. The metal-metal diffusion bonding and metal-oxide-hybrid bonding processes are working without an additional solder layer. Both technologies require highly planarised, residue- and particle-free bonding surfaces. In addition, the metal-oxide-hybrid bonding processes are patent protected (ZiBond®, DBI®) and are commercially available only under licence [Ch3-45].

New materials are under development to be used for an electrically conductive pixel-to-read-out interconnection. Bonding with anisotropic conductive films (ACF), already used in high volume production in the display manufacturing industry, can be a low-cost interconnection technology option. Future research topics will focus on the availability of ACFs with smaller and densly-packed filling particles, applicable for fine pitch interconnects, and the reliability of this polymeric material for use in high luminosity radiation environments [Ch3-46].

Advanced integration technologies will be required for the assembly of hybrid modules for inner tracking detector layers. 3D-integration technique with TSVs in the read-out electronic chips will be one important approach. Wafers, produced in a via-first or via-middle production, are required in order to reduce expensive post-processing steps. Other integration technologies introduced by the semiconductor and manufacturing industry are using a chiplet-to-active interposer assembly for ultra-high bandwidth communication [Ch3-47]. This concept can be adapted to an advanced hybrid module set-up. In this approach, the interconnection to the thinned read-out electronics chip can be realised either by TSVs to the chip backside or by a BEOL redistribution on the sensor wafer surface. Finally, photonic integration technologies allow even faster communication between chips and modules. Research on integration of photonic ICs, photonic wave-guides on chip and photonic interconnections will have to be carried out in the context of the radiation hardness requirements of future trackers and calorimeters.

3.3.6 Status and evolution of the simulation tools

A variety of commercial, open-source, and custom software is used within the HEP community, often in combination, to solve the various problems associated with the design, optimisation, and operation of radiation sensors. In the case of sensor design and optimisation, Synopsys' [Ch3-48] and Silvaco's [Ch3-49] commercial Technology Computer-Aided Design (TCAD) tools have played a decisive role for years, with the majority of users using Synopsys' tools, probably due to easy access to licenses via Europractice. TCAD was developed primarily for the semiconductor industry and consists mainly of process and device simulators. Process simulations are used to simulate the various fabrication steps of the sensors to obtain realistic doping profiles and structures. These doping profiles are essential for device simulators, allowing solution of the fundamental equations for semiconductor devices considering different physical models and boundary conditions. Since process details are usually confidential, close collaboration with vendors is required to optimise radiation sensors successfully. As tools for the semiconductor industry to develop new technologies, device simulators contain the necessary transport and physics models to design state-of-the-art devices. However, the challenge for radiation sensors lies more in the size of the structure to be simulated and in the implementation of satisfactory models for radiation damage effects resulting from bulk damage and surface damage. Bulk-damage models have been developed with various numbers of "effective trap levels", providing satisfactory results for fluences up to $2{\times}10^{16}\,n_{eq}\,cm^{-2}$. The use of "effective trap levels" instead of microscopically measured point and cluster defects is because cluster defects cannot be correctly modelled. The main challenge for the coming years is the parametrisation of cluster defects. One possible way to do this might be based on occupation-dependent ionisation energy. Another important limitation of the simulation tools is that for many materials (SiC or GaN for example) the physical models are not as accurate as for silicon or, in other cases, the numerical modelling tools do not exist (such as for Diamond). Future R&D will require the investigation of radiation hardness and the development of reliable TCAD models for such materials.

A well known limitation of TCAD tools is that they are very demanding on computing time and often do not easily allow integration with other tools in order to facilitate a Monte Carlo approach, an essential method in high-energy physics given the stochastic nature of particle interactions. Allpix^2 framework [Ch3-50] and Garfield [Ch3-51] were developed to combine TCAD-simulated electric fields with a Geant4 simulation of the particle interaction with matter and can be used to investigate the behaviour of silicon sensors or MAPS to compare the predicted performance with measurements recorded in a particle beam.

3.4 Observations

3.4.1 Testing infrastructures

Irradiation facilities
In the past years, HEP has manage to have access to irradiation facilities for neutrons, charged hadrons, and photons [Ch3-52]. This has been accomplished by a combination of national funding, CERN, and European funding. Notably, European programmes such as AIDA [Ch3-53] had a twofold beneficial fallout: (i) they provided funding and (ii) demonstrated to the managers of the various facilities the relevance of the HEP irradiation programme. Moving forward, it is very important to keep the level of funding and awareness high so that the needs of the future facilities will be met (see Chapter 10 and Chapter 11). One item is particularly important: how to test materials to the irradiation levels foreseen at FCC-hh.

- **Neutron irradiation:** Irradiation at reactors can achieve the required fluence ($1\times10^{17}\,\mathrm{n_{eq}\,cm^{-2}}$ to $5\times10^{17}\,\mathrm{n_{eq}\,cm^{-2}}$) in a reasonable time interval ($\mathcal{O}$(weeks)). The main issue is how to handle the irradiated material. Most sensors (and ASIC) carriers/cable/connectors will become activated. Remote handling might be required. Shipping of the material might become impossible;

- **Hadron irradiation:** Besides the problems connected with the activation of the irradiated material, hadron irradiation is much slower than neutron irradiation. Facilities able to irradiate at much higher rates are needed.

Test beam facilities
High-energy test beam facilities are critical infrastructures for R&D in detector technologies [Ch3-54]. Their relatively small number and high users' demand often make them the bottleneck for completing the many detector R&D programmes. A reduction in these facilities will pose a severe problem for the HEP detector R&D community. The delays in detector R&D for the HL-LHC introduced by the recent prolonged technical shutdown of the CERN accelerator complex and its associated test beam areas clearly illustrate how heavily the detector R&D community depends on these tests beam facilities. The maintenance and even increase of the test beam areas should be a priority for the laboratories hosting these infrastructures (again see Chapter 10 and recommendations in Chapter 11).

In addition to the beam facilities, current detector R&D programmes require additional ancillary instrumentation to achieve their characterisation goals. The beamlines need to have fine-pitch telescopes with fast read-out, precise time stamping of individual tracks, particle identification, magnetic fields, etc. In addition, and more importantly, dedicated user support in the operation of these auxiliary instruments is essential to optimise the use of the always scarce test beam time. Good models, illustrating the importance of such support, are the EUDET and AIDA beam telescopes that have been used very successfully in many detector R&D programmes. Maintenance and funding support of these auxiliary instruments should be implemented by the accelerator and detector R&D communities.

Finally, to facilitate more equitable user access to test-beam facilities, implementing transnational access programmes, such as those inherent in several EU-funded programmes, is highly desirable and should be promoted.

3.4.2 Industrialisation

Over the past years, several attempts to build a European (non-CMOS) large scale (order of several $100\,\mathrm{m}^2$) sensor production capability at microelectronics companies have failed. Several possible underlying reasons for these failures have been identified: (i) silicon sensors were considered a commodity bought from foundries without a sizeable monetary investment (of the order of 10 M€) to offset the R&D and production costs, (ii) the typical long R&D periods of the HEP experiments, and (iii) the uncertainty on the return of the initial investment (see Chapter 10). In the present scheme, R&D funding is provided via the experiments. There is no "oversight" body devoted to building the industrial capability of producing a large area of standard sensors in Europe. As an alternative R&D model, the magnets for LHC have been developed with solid financial investment from CERN. A similar investment in silicon sensors should focus on a partnership or collaboration with the foundries, including the post-processing companies, and the R&D efforts should be carried on jointly. The possibility of exploring this kind of approach would be highly beneficial in securing the survival of the manufacturing capabilities of standard silicon sensors.

The development of CMOS sensors (MAPS and passive) might provide an alternative solution for certain applications, for example in applications involving large areas of sensors. However, maintaining the production capability of standard sensors is fundamental to provide the required variety of detector design options and to offset the risk that the fast-evolving CMOS technology will not fully cover the needs of future experiments.

3.4.3 Related fields

The progress in solid state detectors and associated electronics in HEP feeds directly into many other fields, with a very fruitful interchange of technologies. One of the most valuable contributions is to the field of medical physics. Almost all countries have solid state R&D programmes dedicated to medical applications, where the technologies developed for HEP are transferred to the medical field. The importance of this transfer cannot be overstated, and it should be encouraged as an important aspect of what the particle physics community does for the wider community.

3.5 Recommendations

3.5.1 Detector R&D Themes

During the various ECFA Symposia (see Appendix C) and from the feedback through the National Contacts, four main areas of research were identified.

The further evolution of active monolithic sensors is considered key to achieving several of the goals at future facilities such as very small pixels, low material budget and large area. MAPSs are also in a position to benefit greatly from the further evolution of the main consumer electronics (DRDT 3.1).

The conditions at future facilities are making 4D-tracking a necessity, and not just a tool to enhance the physics reach. For this reason, it is deemed necessary to continue the research to identify the most appropriate sensors, with or without internal gain, monolithic or hybrid (DRDT 3.2).

The understanding of the silicon properties at fluences above $1\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ is a must for developing the sensors for experiments operating at or above that fluence level. This research will be driven by experimental data. The first need is to collect a large number of experimental measurements, and then it will be complemented by the development of corresponding TCAD models (DRDT 3.3).

In many experiments, the required accuracy in terms of space and time represents a true challenge for the electronics, as the space allowed for the circuitry is very limited, even using the most advanced nodes. It is a key need to build a demonstrator to show that 3D-vertical stacking is a possible option. In order for 3D-vertical stacking to happen, the development of suitable sensors is necessary (DRDT 3.4).

Figure 3.3 shows the development timeline for the different technologies in terms of years and facilities as presented in the ECFA Symposium of Task Force 3 (see Appendix C). The solid-state detector R&D programmes of the next 20-30 years, summarised in Figure 3.3, face the formidable challenge of providing the sensors needed to carry out the various physics programmes at the many forthcoming future facilities.

DRDT 3.1 - CMOS sensors.

- Develop MAPS sensors with very high spatial resolution and low mass;
- Design and produce MAPS sensors for high fluence environments;
- Develop MAPS with very large areas and reduced granularity for tracking and calorimetry applications;
- Develop CMOS passive designs for pixel and strip sensors, as a complement to present standard silicon sensors;
- Explore the use of state-of-the-art CMOS imaging sensors technology for tracking and vertex detectors.

DRDT 3.2 - Sensors for 4D-tracking.

- Understand the ultimate limit of precision timing in sensors with and without internal multiplication;
- Develop sensors with internal multiplication with 100% fill factors and pixel-like pitch;
- Investigate production of sensors with internal multiplication in a monolithic design;
- Increase radiation resistance, push the limit of 3D sensors and explore LGAD and MAPS capabilities;
- Investigate the use of BiCMOS MAPS, exploiting the properties of SiGe.

DRDT 3.3 - Sensors for extreme fluences.

- Measure the properties of silicon sensors in the fluence range $1\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ to $1\times10^{18}\,\mathrm{n_{eq}\,cm^{-2}}$. Map the limit of 3D sensors and evolve their design to cope with the highest possible fluences;
- Optimise the simulation models with the measurements at high fluence;
- Develop simulation models based on microscopically measured point and cluster defects (instead of a model based on "effective trap levels");
- Explore the use of WBG semiconductors as radiation detectors at high fluences;
- Develop innovative 2D-materials that can offer high radiation hardness and operate at room temperature.

DRDT 3.4 - A demonstrator of 3D-integration.

- Identify and produce silicon sensors designed to be used in multi-layer detectors;
- Develop flexible, cost effective and reliable chip-to-wafer and/or wafer-to-wafer bonding technologies;
- Build a multi-layer detector using vertically stacked layers of electronics interconnected by through-silicon vias;
- Include 3D-integration of a readout chip with a silicon photonics device.

"Technical" Start Date		< 2030			2030 -2035		2035 -2040	2040 - 2045		> 2045	
		ALICE LS3	Belle II CBM	NA62	LHCb, ATLAS, CMS (≳ LS4)[7)]	ALICE 3 - EIC	ILC	FCC-ee	CLIC	FCC-hh	Muon Collider
MAPS	technology node[1)]	65 nm - stitching	65 nm - stitching			28 nm		≲ 28 nm		≃ 10 nm	≲ 28 nm
	pitch	10 - 20 μm	10 - 20 μm			pitch ≲ 10 μm for σ_{hit} ≲ 3 μm in VD					
					Reduce z-granularity in TK - pad granularity in analog Cal.						
	wafer size[2)]	12"	12"			12"					
	rate[3)]		O(100) MHz/cm²						5 GHz/cm²	30 GHz/cm²	
	ultrafast timing[4)]				σ_t ≲ 100 ps					σ_t ≲ 20 ps	
	radiation tolerance				3 x 10^{15} neq/cm²					$10^{18(16)}$ neq/cm² VD/Cal.(Trk)	
Planar/3D/Passive CMOS	technology node[1)]				ASIC 28 nm	ASIC 28 nm		ASIC ≲ 28 nm		ASIC ≃ 10 nm	ASIC ≲ 28 nm
	pitch				≲ 25 μm in VD	≲ 10 μm for σ_{hit} ≲ 3 μm in VD					
					≲ 50 μm for σ_{hit} ≲ 10 μm in Trk						
	wafer size[2)]					12"					
	rate[3)]				6 GHz /cm²					30 GHz/cm²	
	ultrafast timing[4)]			σ_t ≃ 50 - 100 ps		σ_t ≲ 100 ps				σ_t ≲ 20 ps	
	radiation tolerance				6 x 10^{16} neq/cm²					$10^{18(16)}$ neq/cm² VD/Cal.(Trk)	
LGADs	technology node[1)]						ASIC 28 nm	ASIC ≲ 28 nm		ASIC ≃ 10 nm	
	pitch			≃ 300 μm (100% fill facor)	≲ 50 μm (100% fill facor)	same as for other technologies with ultimate pitch ≲ 10 μm for σ_{hit} ≲ 3 μm in VD					
	wafer size[2)]				> 3"	12"					
	rate[3)]				6 GHz /cm²					30 GHz/cm²	
	ultrafast timing[4)]				σ_t ≲ 30 ps	σ_t ≃ 20 ps (PID)	σ_t ≲ 20 ps VD/Trk/Cal.	σ_t ≲ 10 ps PID	σ_t ≲ 20 ps VD/Trk/Cal.	σ_t ≲ 20 ps VD/Trk/Cal.	
	radiation tolerance				≳ 5 x 10^{15} neq/cm²					$10^{18(16)}$ neq/cm² VD/Cal.(Trk)	
backend processing	sensor thickness[5)]	< 50 μm MAPS	< 50 μm MAPS		< 150 μm Plan/3D/Pas. < 50 μm LGADs	< 50 μm MAPS, Planar/3D/Passive CMOS, LGADs					
	3D integration[6)]										

Only the projects requiring a new feature first are retained in this table. Values are indicative of performance targets and of operating conditions relevant to R&D. The latter are reported for the regions most exposed to radiation. The colors indicate when key progress (red) would be needed for a given technology, or when they would be desirable (yellow). Green indicates requirements are being met. The different technologies are alternatives for the various detectors, final choices will depend on their ability to achieve different performance parameters together. Heterogenous layer designs can combine technologies to optimize the overall performance.

1) The evolution in technology node is progressive and indicative. It can depend on achievents in each node. It will also be driven by industrial standards.

2) The size of wafers achievable can depend on technology (industrial process, yield...) wiith a general trend of benefits from larger areas in all detectors. Either to bend sensors (depending on thickness and detector) or to house more than one sensor in a single substrate.

3) Reported rates are within bunch trains for ILC and CLIC.

4) The values reported are indicative of expected intrinsic performance, not excluding that it can be better with different achievements for sensors w/o amplification. Implementation of 4D-tracking at e-e colliders will depend on on ability to maintain low X/X0 for tracking precision.

5) Thin sensors is not a requirment for analog calorimetry energy resolution, while they could provide better timing precision.

6) 3D integration exist in commercial process (imagers) and could be beneficial in several perfomance aspects for future solid state devices. It may be needed to fulfill most stringent requirments and/or to enable desirable performance. Initial demonstrators could enter HL-LHC upgrades.

7) MAPS technology is only foreseen for use in the LHCb tracker. Planar/3D/passive CMOS are foreseen for the LHCb, ATLAS and CMS vertex detectors, rates and radiation tolerance are indicated for LHCb where values are the highest (conditions for ATLAS and CMS are already met).

Figure 3.3: Compilation of the technology R&D needs and timeline for future solid state detectors. The colour coding is linked not to the intensity of the required effort but indicates what key progress would be need for a technology to enter a project (red), when it would be desirable (yellow), or when it is being met (green).

3.5.2 "Blue-sky" Research

Developments on detector technologies typically span timescales of 20 or more years from the first idea to a functional detector. The solid-state detector R&D programmes of the coming years will have to provide innovative sensors to carry out the physics programmes at the forthcoming future facilities. In this respect, the goals are very well defined, and the research plans should focus on achieving them. However, it should be stressed that the actual engine for innovation resides mostly in "blue-sky" research, where groups can explore innovative avenues focusing on mid-term R&D plans (about five years), without a short-term goal. As a recent notable example, the 4D-tracking innovation, started as a "blue-sky" R&D programme, is now embraced by many detectors at future facilities. National programmes that foster "blue-sky" innovations should be strengthened, acting as incubators for new possibilities.

3.5.3 Further recommendations on industrialisation

Given the large demands of solid state sensors for future experiments, a major challenge relates to industrialisation where R&D funds are currently provided through experiments without concerted efforts devoted to building the industrial capability of producing the large areas of sensors in Europe. Although these are large orders by particle physics standards these are not by those of most semiconductor foundries. CERN should promote greater strategic coordination to achieve a stronger negotiating position with commercial partners and to provide them with relationships of greater continuity and depth.

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Chapter 4

Particle Identification and Photon Detectors

4.1 Introduction

Photon detectors are at the heart of most experiments in particle physics. Moreover, they are also finding application in scientific fields as distant as chemistry and biology and are ubiquitous in society in general. As we encounter new environments where we need to collect the light, we require both advances in existing technology and transformative, novel ideas to meet the demanding requirements. Advancement in photon detector technology is therefore essential to address all the science drivers of future high energy physics experiments.

Reliable particle identification (PID) methods have become an indispensable experimental tool, in particular for the physics of heavy flavours, in studies of heavy-ion collisions and in electron-hadron experiments. PID has significantly contributed to our present understanding of elementary particles and their interactions, and will continue to be an essential ingredient in several of the planned experiments. The continuous advances in the development of pixelated single photosensors and fast and low-noise read-out electronics have pushed PID detectors, in particular Ring Imaging Čerenkov (CHerenkov) (RICH) counters, to unprecedented levels of performance. This has allowed a very efficient identification of charged particles and an outstanding background rejection in a vast momentum range from a few 100 MeV/c up to several 100 GeV/c. However the ever-growing demands of the future physics programme, from underground facilities to high luminosity colliders, require mastering a novel generation of PID detectors with high separation power over four to five orders of magnitude in momentum.

In what follows, particle identification and photon detectors are discussed. For technical details on several of the concepts used as identification tools, such as drift and time-projection chambers and transition-radiation detectors, the reader is referred to Chapter 1.

4.2 Main drivers from the facilities

There is a wide range of primary drivers for particle identification detectors in future particle physics experiments. Flavour physics experiments such as LHCb, NA62 and Belle II, and into the far future FCC-ee, are wholly reliant on PID to fulfil their physics goals to study heavy-quark charm and beauty decays, often rare decays with high multiplicity where backgrounds can otherwise be overwhelming. The future evolution of new PID techniques is similarly important for hadronic and heavy ion experiments such as ALICE, EIC, and the FAIR experiments. Moreover, photon detectors will be an essential requirement of *all* future particle physics experiments, whether it be to instrument PID detectors, calorimeters, tracking, neutrino and dark-matter experiments; from ultra-high rates to extreme low-noise requirements, and for all particle astrophysics applications.

The development over time of the major TF4 technology drivers is illustrated in Figure 4.1. Development of RICH and DIRC (Detectors for Internally Reflected Čerenkov light) technology is essential for LHCb, Belle II and the EIC, where hadron identification is paramount. Time of flight (TOF) for PID is also important for many of the physics aims, usually providing low-momentum coverage complementary to RICH information. Picosecond timing is an important theme running throughout all future particle physics applications, including the LHC GPDs and FCC-hh, however particle identification applications of timing detectors for the latter experiments will only be useful up to the few (3-4) GeV/c level.

The vital importance of silicon photomultiplier (SiPM) technology across most aspects of future particle physics applications is striking, where radiation hardness, lower noise and faster timing are important drivers. These devices are also applicable for scintillating detectors operating with liquid noble gases, in particular, underground low-noise experiments, where radio-purity, vacuum ultraviolet (VUV) and cryogenic operation will be important. Vacuum photon detectors also have an essential future role, where timing, large-area operation, rate capabilities and lifetime must be further developed.

Given the requirements discussed above, four main lines of R&D will be have to be pursued:

DRDT 4.1 - Enhance timing resolution and spectral range of photon detectors.
This is needed for fast timing in Čerenkov and time of flight detectors, for operation with high particle fluxes and pile-up, and in extending the wavelength coverage of scintillation photons from noble gases and Čerenkov photons.

DRDT 4.2 - Develop photosensors for extreme environments.
This being essential for operation in the high-radiation environments at the HL-LHC, Belle II upgrade, EIC and FCC-hh; and similarly for cryogenic operation.

DRDT 4.3 - Develop RICH and imaging detectors with low mass and high resolution timing.
As required for particle identification at HL-LHC, Belle II upgrade, EIC, and FCC-ee.

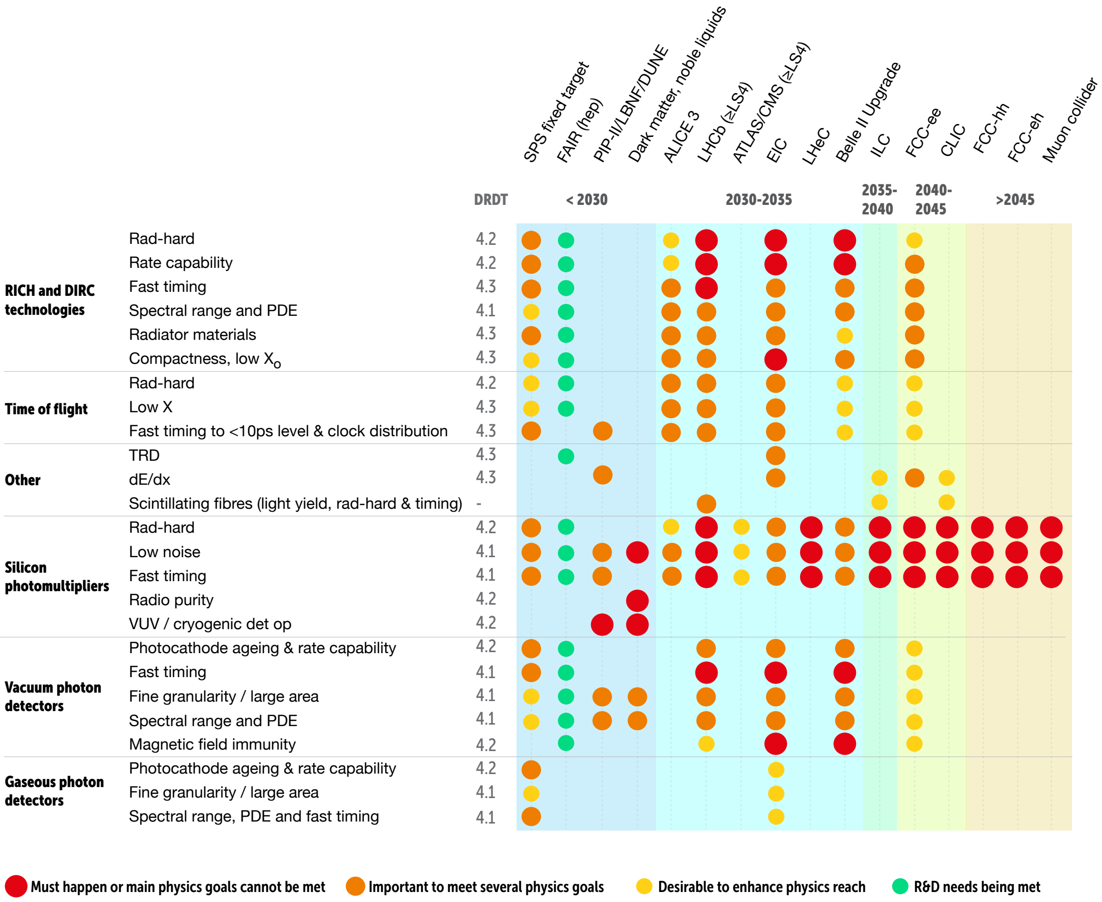

Figure 4.1: Schematic timeline of categories of experiments employing PID and photon detectors together with DRDTs and R&D tasks. The colour coding is linked not to the intensity of the required effort but to the potential impact on the physics programme of the experiment: Must happen or main physics goals cannot be met (red, largest dot); Important to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); No further R&D required or not applicable (blank). [PDE stands for photon detector efficiency].

DRDT 4.4 - Develop compact high performance time-of-flight detectors.
As a complementary approach for particle identification at HL-LHC, EIC and FCC-ee.

The R&D timelines for the above themes can be found at Figure 11.1 with attached explanation. R&D is needed for photon detectors in each of the half decade time blocks for facilities listed in Figure 3 and Figure 4 of the Introduction, all the way through to the FCC-hh/muon collider era (DRDT 4.1 and DRDT 4.2). For Particle Identification (DRDT 4.3 and DRDT 4.4), at the time of writing there were no definite plans for dedicated systems in experiments at the ILC, but several experiments requiring these techniques are expected in both the nearer term and looking forward to experiments during the FCC-ee/CLIC era. The future directions and advances of these key detector technologies and DRDTs are described below.

4.3 Key technologies: particle identification

Particle identification with a high separation power will continue playing an important role in future experiments. The growing demands of the physics programmes at forthcoming high luminosity facilities require a new generation of PID detectors, from RICH, DIRC and TOF detectors to gas-based dE/dx and transition radiation detectors, as discussed below.

4.3.1 RICH detectors

The particle separation power of a RICH detector (DRDT 4.3) relies on a combination of the single-photon angular resolution and the number of detected photoelectrons per track [Ch4-1]. The best performance is achieved by designing a device with the broadest possible detection bandwidth coupled to a radiator characterised by a low dispersion refractive index, in order to reduce the contribution of chromatic aberration to the angular resolution. Since the chromatic aberration of the radiating medium is usually the dominant contribution to the detector precision, the design of a RICH detector that operates in the visible region will improve the angular resolution. However, owing to the falling power law of the number of Čerenkov photons as a function of wavelength ($dN/d\lambda \propto \lambda^{-2}$), working at longer wavelengths requires photon detectors with a high photon detection efficiency to compensate the narrower detector bandwidth. The capacity to detect a large number of photoelectrons not only improves the particle separation power but also increases the pattern recognition capability in presence of complex multi-particle events.

RICH layout
The choice of the detector layout will have to adapt not only to the exacting physics goals but also, in the case of particle identification at high momenta, to the often-critical integration constraints. The limited space of the interaction region for hermetic-coverage collider experiments (mandatory at the EIC and FCC-ee) requires designing performant

RICH detectors with a total length shorter than a metre. This is a very challenging task given that a standard focusing RICH counter encompasses a gas vessel, mirrors and respective support structures, and often a second radiator must be added to cover a wider momentum range. Despite the compact radiator regions at the FCC-ee resulting in low photon yields from necessarily low-n radiators, the R&D challenge will be to use achromatic gases with fast, high quantum efficiency (QE), high-granularity photon detectors to push the RICH discrimination power above 100 GeV/c.

To overcome the above issues, two alternatives are under study for the EIC. The first is to mimic the refractive index of fluorocarbon gases, which will likely in the future become unavailable (see below), by pressurising noble gases to several bars [Ch4-2]. This requires innovative engineering solutions for minimising the material budget of gas vessels able to resist the required pressures. The second solution is to design a very compact RICH detector working in the VUV region where the large number of generated Čerenkov photons compensates the short radiator length. In order to maximise the number of photoelectrons, the windowless approach pioneered by PHENIX [Ch4-3] is envisaged, implying the use of gaseous photon detectors operated with the radiator gas itself. This latter requirement poses strong limits on the choice of the radiator gas, and the high chromaticity in the VUV region could jeopardise the overall performance of the RICH detector. Moreover, the design of mirrors with a high reflectance for VUV photons and the control of gas purity at a level of parts per billion (ppb) are quite challenging issues (see below).

For many future RICH layouts, the levels of radiation doses, especially from the high-luminosity hadron facilities, require the use of radiation-tolerant detector components throughout.

RICH detector timing

The capability to stand very high event rates in the harsh environmental conditions of future high-luminosity facilities requires the clean separation of signal from background hits. The spatial and temporal separation of events will be achieved by combining a precise Čerenkov angle measurement with accurate single photon timing (of order $< 50\,\text{ps}$) and a high rate capability. A time-stamp of the Čerenkov photon arrival coupled to short gate intervals around the relevant bunch-crossings will enhance the selection of true Čerenkov photons over spurious hits caused by electronic noise, dark counts and out-of-time events. Moreover, in HL-LHC conditions, associating the photon hits via timing will be essential in associating track PID hypotheses to the associated primary vertex. Therefore timing will be essential for RICH detectors at high-luminosity machines to actually operate.

Light collection systems

Usually a gas radiator is associated with a large gas-tight vessel of $\mathcal{O}$(1-20 m), application dependent, to obtain the necessary light yield, and this necessitates an optical mirror system. The mirrors can often be in the detector acceptance (e.g. at LHCb), hence the development of spherical, parabolic and flat lightweight mirrors is essential. Lower-cost carbon-fibre technology is key to this. Moreover, the design of mirrors with a high reflectance for VUV operation is a necessary development. The mirror alignment is also essential to achieve optimal performance.

With the aim to improve signal-to-noise ratios, further developments should be pursued in designing dedicated light collectors (concentrators), either as quartz Winston cone-like arrays, or dichroic reflectors. In this way, photons would propagate from a larger entry window to a considerably smaller sensor, resulting in an improved signal photon to dark count ratio. Methods have to be found to minimise the complication of design of large RICH photon-detection planes.

Photon detectors

The development of large area single photon detectors capable of sustaining high counting rates, and a total ionising dose up to a few Mrad and beyond $1\times10^{12}\,\mathrm{n_{eq}\,cm^{-2}}$ for single photons (DRDT 4.2), is of paramount relevance for the next generation of RICH counters at the high luminosity expected at HL-LHC (up to $1.5 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ in the LHCb interaction region). Moreover, the use of photon detectors featuring a high granularity (1 mm pixel size) and timing resolution of the order of a few tens of picoseconds (DRDT 4.1) is mandatory to improve the background rejection capability, maintain a manageable detector occupancy, and to allow a robust pattern recognition in view of the anticipated high photon and charged particle fluxes exceeding several $\mathrm{MHz/cm^2}$. In addition, a good tolerance to magnetic fields is required in most applications in particle physics.

SiPMs and micro-channel plates photomultiplier tubes (MCP-PMTs) seem the most promising photon detector technologies that could suit the above features. The main challenge for using SiPMs in a RICH detector is their high dark count rate with a pulse height spectrum identical to that from individual Čerenkov photons; these rates can be as high as tens of $\mathrm{MHz/cm^2}$ at room temperature and increase with irradiation. Commercial MCP-PMTs are presently limited in size and lifetime at high rates; their high cost is a further major issue, as the total area to be instrumented will likely be in the region of several square metres in any detector design.

In compact RICH counters for identification of high momentum particles at the EIC, the implementation of solid photocathodes in micro-pattern gaseous detectors (MPGDs) will continue playing a relevant role. These provide an affordable and low material-budget approach to large surfaces in the presence of magnetic fields, in particular if R&D efforts result in novel photo-sensitive materials that are more radiation-hard and chemically more inert than CsI. These photocathodes should preferably be sensitive to visual light, and where the positive-ion backflow and photon feedback that limit the photocathode lifetime and operating speed are reduced. In the long term, an attractive choice for RICH photon detectors may also be superconducting sensors, but the integration of these devices into accelerator-based experiments will be challenging.

Radiator materials

For the momentum region higher than $10\,\mathrm{GeV}/c$, gas radiators are almost unique candidates, and many RICH devices employ fluorocarbon gases like C_4F_{10} or CF_4 because of their optical quality. Gas purification systems are indispensable to maintain high transparency, and typically impurity quantities of H_2O and O_2 can be suppressed by a level of several ppm. In the coming years, new developments, working with industry, may reinforce gas purity performance to a level of ppb for VUV operation.

A further issue is the high greenhouse-gas Global Warming Potential (GWP) of fluorocarbons, for instance C_4F_{10} where the GWP is 4800. C_4F_{10} represents a prime choice for RICH radiators because of its good optical transparency and relatively low chromaticity. Such fluids will experience increasing use restrictions and future shortage of supply and, if used, leak-less systems will be imperative. New alternative gases to replace fluorocarbons must be investigated and, whilst there are candidates, they are flammable [Ch4-4]. New gas mixtures may be the way forward, e.g. by adding a large quantity of stable gas such as neon to satisfy the non-flammable conditions, implemented in association with photocathode development to longer wavelengths.

Regarding liquid radiators, and referring to Chapter 1. the biggest challenge is the water Čerenkov detector of Hyper-Kamiokande [Ch4-5] which stores a 280 kton volume, corresponding to a factor 10 larger fiducial mass than Super-Kamiokande. The most critical issue is the optical transparency of the water which must be retained with the larger volume, and this brings a major challenge for the re-circulation purification system.

Silica aerogel has been used successfully for many years in RICH detectors for PID below around 10 GeV/c, with the advantage that the refractive index can be adjusted by changing parameters in the synthesis process. The disadvantage is that the photon yield is low, which makes operation in a high occupancy environment problematic. Up to now, the refractive index of aerogel covers a wide range of 1.01 to 1.2 although tile dimensions may be limited, in particular, for higher refractive index [Ch4-6]. There is therefore scope for improvement of the process by producing larger aerogel tiles of high transparency, lower scattering, higher photon yield, and customised refractive index. Special skills to develop silica aerogels are available in only two production facilities in the world which could be a potential worry in the long term.

A long-term breakthrough in radiator materials could be the development of photonic crystals [Ch4-7] and meta-materials [Ch4-8] which match the refractive indices needed to identify particles at low and high momentum. The photonic crystal is a potential example of a material with a "tune-able" refractive index, consisting of two different materials with the thickness of sequential layers controlled to be the order of the photon wavelength. These technologies are still at a primitive stage, and there is vast scope for further study. Close cooperation with other disciplines and industry will be crucial to search for appropriate material characteristics, radiation hardness etc.

4.3.2 Detectors for Internally Reflected Čerenkov light

DIRCs were first pioneered by the BABAR collaboration [Ch4-9] and more recently by Belle II, extending the DIRC principle to measure Time of Propagation [Ch4-10]. These applications were for flavour physics experiments, where PID is essential. The DIRC techniques have now been further developed by, for example, PANDA [Ch4-11] and GlueX [Ch4-12].

The advantage of a DIRC detector is that it provides an extremely compact PID device in the barrel and endcap regions of an experiment, facilitating space for calorimeters and tracking detectors. DIRCs cover the low momentum region; current detectors provide π/K separation up to around 4 GeV/c, hence are much more suited to lower energy machines. An advantage is they cover the relatively inaccessible region for dE/dx from 1-2 GeV, which suffers from crossing $\pi/K/p$ bands. The main disadvantage is that the momentum range is not so suitable for high energy machines. Also multiple Coulomb scattering can be problematic.

Regarding future challenges (DRDT 4.3), R&D is required to make DIRC readout even more compact, to expand the momentum reach, and to facilitate more extensive use in the endcap region. It is also necessary to explore mitigation of RICH resolution terms, i.e. the chromatic dispersion and multiple scattering. Improved focusing design of the Čerenkov light is required, emphasising improved spatial resolution. Major advances, for example for the EIC, are necessary for a high performance DIRC [Ch4-13], with momentum reach up to about 7-8 GeV/c and above. A general requirement is to improve quartz technology, traditionally used as the DIRC radiator. Surface quality (sub $\sim$ nm surface roughness) is the current cost driver, plus uniform material quality; working with industry to drive down prices will be mandatory. State of the art timing will also be important ($\mathcal{O}$(10 ps) binning) to reduce backgrounds, for example, facilitated by the recent picoTDC development [Ch4-14]. To this end, photon detection with fast (few tens of ps) timing performance will be essential; MCP-PMTs are currently the detectors of choice, but SiPM readout needs to be developed. Fine-pitched photon detector granularity, radiation tolerance, low noise and photon sensitivity are important. There is recent common synergy with TOF applications, which can extend the PID performance to higher momenta (see below).

4.3.3 Time of flight detectors

TOF is a simple concept in principle and, like the DIRC technique, provides good PID separation in the low-momentum region. Here the RICH technique would have to rely on solid radiators where the use of aerogel, located in the acceptance region, has been problematic for high occupancy applications. Naturally for TOF, highly precise timing of order 10 ps is mandatory (DRDT 4.4).

The disadvantage of TOF is that the technique does not readily cover π/K discrimination above 10 GeV/c for flight paths $\lesssim$10 m, and the separation power falls rapidly with momentum [Ch4-15]. Also the TOF technique provides only complimentary low-momentum PID coverage at high energy machines. The technique requires a large TOF distance, so multiple Coulomb scattering can become problematic. Since the detector area is often proportional to distance squared (d^2), there is also a trade-off between instrumenting a large area with the associated cost. In addition, a suitably accurate start time needs to be available. Despite these challenges, the scope for R&D in this area is very encouraging.

TOF is a very promising PID technique for flavour physics and hadronic physics experiments; examples are Panda/CBM, NA62/TauLV, ALICE, LHCb and FCC-ee etc. Timing is now compulsory for many future applications (for example, pile-up suppression for ATLAS/CMS and the FCC-hh). Hence there are several synergies with timing layers also providing PID using TOF, for example the addition of timing layers for calorimetry and 4D-tracking silicon detectors.

There are several TOF techniques, all of which have their own specific R&D challenges, with the dream of pushing below the 10 ps level:

Scintillators
Scintillator arrays have been developed for timing layers with fast photomultiplier readout, and the current state of the art is around ~ 100 ps [Ch4-16], combining readout from both scintillator ends. Similar performance can also be obtained with SiPMs [Ch4-17]. The CMS scintillator timing layers will bring a significant improvement using L(Y)SO:Ce crystals and SiPMs, where 35-60 ps is expected [Ch4-18]. An added benefit will be modest π/K separation, however only up to $\sim 3\,\mathrm{GeV}/c$. Another technique with an area for development is in colloidal quantum dots for Dark Matter detectors (see Chapter 5). Scintillator TOF performance needs to be pushed with further R&D.

Gaseous detectors
Referring to Chapter 1, multigap RPCs are a well established technique, with ALICE providing the state of the art resolution at 56 ps [Ch4-19]. Future R&D needs to improve performance by increasing the number of gaps and providing a higher rate capability. There should be a push to improve timing resolution and high flux performance further with micro pattern gas detectors (MPGDs). The RD51 Picosecond project [Ch4-20] detecting Čerenkov light with a CsI photocathode and Micromegas detector is an exciting development highly applicable for future applications.

Silicon detectors
Silicon sensors are covered in detail in Chapter 3. Low-gain avalanche diodes (LGADs) have huge potential for TOF detectors and have common use for timing layers (e.g. ATLAS/CMS). The aim is to achieve a timing performance below the 10 ps level for the FCC-ee and FCC-hh. Further development of AC-, DJ-, TI-, iL-LGAD sensors should move forward, where 20 ps can be achieved [Ch4-21]. The radiation tolerance of LGAD technology also needs improvement (see Chapter 3).

Large area MCP arrays
The principle is to tile large areas with MCP-PMTs, in which Čerenkov light can be detected from a charged particle passing through the PMT entrance window. At least a $\mathcal{O}(15\,\mathrm{ps})$ resolution per MIP needs to be achieved for useful TOF (DRDT 4.1). An example of an MCP-PMT with a large area coverage is the LAPPD [Ch4-22] (see Section 4.4.1). Challenges to overcome are the rate tolerance, radiation hardness and granularity, and operation is a high luminosity environment will require pixelated readout rather than strip. To make the technique feasible will also require an affordable cost per square metre.

Čerenkov (DIRC)-based detectors
An operating example is the ATLAS Forward Proton TOF detector [Ch4-23], located 210 m from the interaction point, and utilising quartz fingers read out by commercial MCP-PMTs. A resolution of about 20 ps has been achieved. A more challenging project is the TORCH TOF detector [Ch4-24] based on the DIRC technology, developed for the LHCb Upgrade II, and which utilises large 10 mm thick quartz plates as Čerenkov

radiators. The quartz allows a large active area (30 m^2) and is read out with customised MCP-PMTs. A 10–15 ps per-track resolution is achievable in providing π/K separation up to 10–12 GeV/c for a 10 m flight path. The technique requires 1 mrad precision for the detected photons, which dictates a detector measurement resolution down to the 100 μm level. The technology is also applicable to TauFV and FCC-ee. As for the DIRC technology, polished quartz surface quality (sub $\sim$nm surface roughness) needs to be achieved at lower price.

In summary, there are several future R&D challenges common to all these technologies: a state of the art timing ASIC is compulsory ($\mathcal{O}$(10 ps) binning), detectors with fast timing to the 10–20 ps level (e.g. MCP-PMTs, SiPMs, LGADs), radiation tolerance, low noise, and good photon sensitivity. Finally timing (clock) distribution R&D is essential, with very precise calibrations necessary.

TOF is also interesting in searches for long-lived Beyond-the-Standard Model particles where the signals would be delayed with respect to low-mass Standard Model hadrons. This places different requirements on the readout electronics which would need to provide timing resolution of $\mathcal{O}$(1 ns) within a significantly larger time window.

4.3.4 Particle identification through dE/dx and TRD

The resolution of a dE/dx measurement can be parametrised as $\sigma(dE/dx) = 5.4\% \cdot (LP)^{-0.37}$, with length L in m and pressure P in bar [Ch4-25]. The P term is of interest when excellent PID is needed together with a large mass of the chamber gas (TPC, time-projection chamber, as a target). In this case, R&D topics include the search for suitable gas mixtures for high-pressure operation (as discussed in Chapter 1).

A sizeable improvement by a factor of about two in the dE/dx resolution could come from the determination of the energy loss via cluster counting rather than by measuring the charge [Ch4-26], [Ch4-27], [Ch4-28], [Ch4-29]. The two cluster counting methods are counting in time and counting in space. Cluster counting therefore requires fast electronics and sophisticated counting algorithms, or alternative readout methods. The main R&D topics are the development of readout electronics (e.g. wave-form sampling front-end electronics with FPGA processing) for the cluster counting in time, and a development of 2D-micropattern readout and cluster identification algorithms for cluster counting in space. In the latter case, studies are also needed to understand possible systematic uncertainties in cluster counting due to diffusion, and to optimise the gas composition. More details on gas chambers with dE/dx and cluster counting functionality are discussed in Chapter 1.

Transition radiation detectors (TRDs) work on the principle that transition-radiation X-rays are emitted when a highly relativistic charged particle with a Lorentz factor γ exceeding 10^3 crosses a boundary of two media with different refractive indices. TRDs with gas-based X-ray detectors are a mature instrument for identification at high energies. Due to the overlapping of the transition radiation signal with ionisation, a precise knowledge (and simulation) of the ionisation contribution is required. Another novel feature in TRDs is a GEM-based read-out of the chamber.

An attempt has been made in TRDs to improve cluster counting by means of a

GridPix readout. Some improvement was observed, although not sizeable with such a device [Ch4-30]. Another potential improvement may be reached by differentiating the response to X-ray photons and to particle ionisation; here extensive R&D is required. A completely new avenue could involve imaging the transition radiation X-rays with a high granularity 2D-detector like Timepix3 [Ch4-31], of potential relevance for hadron identification into the TeV range.

4.4 Key technologies: photon detection

For most of the last century, the photomultiplier tube has been the most important sensor for low light levels due to its excellent noise characteristics and scalability. Photon detection is crucial for a wide range of applications from high luminosity facilities to the ultra low-noise requirements of underground detectors. This requires an evolution of existing photon detectors, from traditional vacuum-based devices, silicon-based technologies and gas detectors, to novel superconducting devices (DRDTs 4.1 and DRDT 4.2). Detection of photons is a vital component also in neighbouring fields, e.g. in astroparticle physics, for neutrino observatories, or in applications such as medical imaging. For some technologies such as semiconductor photon detectors, a strong driver for R&D will be industrial applications, for example the automotive industry. For others, in particular in the detection of single photons, the R&D will remain in particle physics where advances in existing technologies are needed together with transformative, novel ideas. Photon detector technologies are discussed below.

4.4.1 Vacuum-based photon detectors

A number of photon detectors have evolved from the classic photomultiplier concept (PMT), based on the photoemission from a photocathode in vacuum and the subsequent electron multiplication by secondary emission. More recent developments focus on detectors which allow for high segmented anodes down to the millimetre scale [Ch4-32]. In vacuum detectors such as Hybrid Photon Detectors (HPDs) and Hybrid Avalanche Photo Detectors (HAPDs), the anode consists of a (segmented) silicon sensor leading to a single-step gain mechanism.

Micro-channel plate detectors (MCP-PMTs)
An MCP consists of a compact and close-packed set of miniature channel electron multipliers each acting as a continuous dynode. The geometry of the MCP and its surface have crucial impact on the detector performance. The geometry is characterised by the pore diameter (6-25 μm), the channel length (400–1000 μm), the length-to-diameter ratio (40-100) and the open-area ratio OAR (55-65%). For integration in an MCP-PMT, two MCPs are stacked in a “chevron” configuration that alternates their bias angle. This reduces ion and photon feed-back effects and optimises the overall amplification gain that reaches $10^6 - 10^7$. Segmentation of the readout anode allows to adapt the readout geometry to the application. Due to their compact size, MCP-PMTs are essentially immune to high magnetic fields (up to 1-2 T) as long as E and B fields are aligned, and also intrinsically feature high spatial and time resolutions (100 μm and 30 ps, respectively).

The technology has evolved significantly over the past ten years [Ch4-33]. A main breakthrough to increase lifetime ($>20\,\mathrm{C/cm^2}$) has been the introduction of atomic-layer deposition (ALD) coatings on the MCP to mitigate QE degradation from ion feedback. Modern tubes in flat-panel geometry show high area coverage ($>80\%$) and satisfactory QE although there is still a deficit of 10-15% absolute compared to high performance PMTs. Further developments are essential in the future in terms of QE, collection efficiency, lifetime (up to $>50\,\mathrm{C/cm^2}$) and rate limitation caused by saturation of the MCP (currently $10^5\,\mathrm{cm^2}$ which needs an improvement of at least a factor of 10). Operation at significantly lower gain $\sim 10^5$ will relax the lifetime and rate issues, and this will require customised electronics development. An alternative to facilitate running at lower gain is the future development of hybrid MCP-HPD devices [Ch4-34], which would need to preserve the few 10's of picosecond timing capabilities. At present the suppliers of MCP-PMTs do not produce devices with massive parallelisation, which could bring down the current high cost of MCP-PMTs.

The Large Area Picosecond Photo-Detector (LAPPD) [Ch4-22] is produced on a pilot plant and commercialised by INCOM Inc. Close to ten years of development has led to an impressive MCP-PMT detector which combines flat 20 by $20\,\mathrm{cm^2}$ tile geometry with MCP-typical timing performance (a transit time spread of 50-70 ps). The great advantage of the LAPPD development is the large area, which is well suited for a variety of applications, from RICH, TOF and dark matter detectors. The MCPs are ALD processed and deliver a gain of up to 10^7. In the future, the QE (currently 25% at 365 nm) and other performance parameters will need to improve in routine production. The current GEN-I tubes are read out by strip line anodes (resolution 2.4 mm along and 0.76 mm across strips); further generation tubes will have capacitively coupled pad read-out, essential for high-rate high-granular applications, for example at the HL-LHC. For tiling large areas, the price per square metre will ultimately need to be more competitive.

Photo-multipliers (including large areas)

Whilst the use of classic PMTs in accelerator-based HEP detectors is dropping, large-size PMTs are still the first choice in numerous applications such as water Čerenkov and liquid (noble and organic) scintillation detectors. In these experiments typically very large surfaces have to be covered (see Chapter 2). In recent years, new suppliers have adapted known concepts to large area phototubes with impressive performance [Ch4-35]. Parameters such as light collection efficiency, sensitivity (in the VUV) and operation at cryogenic temperatures have to be further optimised.

The radio-purity (radioactivity) of PMTs has improved by over a factor 100 in the last decade and is already adequate for existing dark matter experiments. However a further $\sim$5-10 fold reduction, down to $\sim 10^{-3}\gamma\,\mathrm{s^{-1}}$ for a standard 3-inch PMT, is required for the new generation of $0\nu\beta\beta$ decay search experiments. A commensurate decrease in radioactivity from PMT bases is also required.

Multianode PMTs (MaPMTs)

MaPMTs are based on the parallel (side-by-side) arrangement of several dynode channels and anodes in the same tube, requiring advanced micro-machining and processing techniques. Two decades of continuous evolution has led to a family of devices of up to $5 \cdot 5\,\text{cm}^2$ in size, with high QE ($\geq$30%) and active area coverage, and mm-segmentation. MaPMTs are being deployed as photosensors in the current LHCb RICH upgrade [Ch4-36]. Further major improvements (QE, gain uniformity, timing) and significant cost reduction would be much welcomed, but not readily foreseeable.

Hybrid photon detectors (HPDs)
Hybrid photon detector tubes combine vacuum photo-cathode technology with solid-state technology. In a "classic" HPD, the photoelectrons are accelerated to multi-keV energies (6-20 keV) and bombarded onto the backside of a standard silicon p-in-n sensor. In an HAPD, the Si sensor consists of an avalanche photodiode (APD) leading to an extra gain factor. The attractive features of H(A)PDs such as gain uniformity, low gain fluctuations, linearity, low noise, high speed and high-resolution photon counting capabilities have led to applications in high-energy physics for calorimetry and RICH detectors [Ch4-37], [Ch4-38]. Conversely, HPDs are in general highly sensitive to magnetic fields; an exception are proximity-focused H(A)PDs that can be operated in a B-field direction which is aligned with the sensor's E-field. With the exception of the MCP-HPD hybrid, the need to encapsulate the readout electronics inside the vacuum envelope (in highly segmented devices) and their elevated cost mean H(A)PDs devices are less considered for future particle physics facilities.

Other developments
There are relatively few groups developing novel types of vacuum photon detectors. Some groups work on the replacement of the glass MCP by amorphous silicon [Ch4-39], where the dynode channels are produced by dry ion etching techniques, or propose specially shaped and coated input geometries of the MCP in order to increase collection efficiencies and reduce late pulses.

The Vacuum Silicon PhotoMultiplier Tube (VSiPMT) concept [Ch4-40] integrates a SiPM as anode in the glass envelope of a PMT. Successful prototypes up to two-inch diameter have been built and tested. They work with a reasonably low HV (e.g. 2 kV) and achieve the expected high gain of the SiPM (10^6). However they also feature the typical dark count rate of the SiPM of $\mathcal{O}(100\,\text{kHz/mm}^2)$ at the single photon level. The VSiPMT can also be considered as a low-radioactive sensor; SiPM materials are intrinsically radio-clean, comparable to or better than PMT devices. However, this does not include interconnects or cold electronics which become the critical components, and for which R&D will be required.

The tynode concept [Ch4-41] places, in vacuum, a stack of transmission dynodes (tynodes) on top of a CMOS pixel chip, resulting in a single free electron detector. The assembly relies on Micro Electro Mechanical Systems (MEMS) fabrication techniques which could also serve for adding a photocathode and produce a very fast high-resolution photodetector.

4.4.2 Gas-based photon detectors

Gaseous Photon Detectors (GPDs) still represent the most effective solution for instrumenting large imaging surfaces (up to several square metres) which are embedded in high magnetic fields, especially when low material budget and affordable costs are required, as discussed in Chapter 1. A further advantage offered by GPDs is the possibility to define a flat geometry for optimising detector acceptance and limiting dead regions. They also have sensitivity to single photoelectrons and the capability to perform photon counting due to the high gains achievable (up to 10^6) via a virtually noise-free amplification mechanism [Ch4-42].

Over the last two decades, the revolutionary technology on which are based Micro-Pattern Gaseous Detectors (MPGDs) [Ch4-43], has allowed GPDs to achieve the localisation of photon conversion points to an accuracy of a few-tens of μm, good time resolutions (~ 1 ns) and a rate capability exceeding 1 MHz/mm^2. Furthermore, the implementation of elaborate combinations of GEMs [Ch4-44] and Micromegas [Ch4-45], the two basic MPGD architectures, had the great advantage of reducing the positive-ion backflow. Amongst the various phenomena leading to GPD performance degradation, this is the dominant mechanism for photocathode ageing. Such improvements have enabled GPDs to find wide applications in calorimetry, Čerenkov detectors, readout of scintillating fibre trackers and detection of electroluminescence photons. Future challenging applications require higher single photon detection efficiency, radiation hardness and improved time resolution. As an example, MPGD-based photon detectors are an option for equipping the windowless RICH detectors for the identification of particles at high momenta, under design at EIC [Ch4-2]. The devices envisaged must operate at a GHz or greater collision rate, with minimal material budget, and must be compact to fit within space requirements. The ongoing developments at the EIC, if successful, will pave the way for a wide use of GPDs in RICH detectors operated at upcoming fixed-target and collider experiments. Further applications are foreseen for the imaging of rare processes with large volume cryogenic detectors [Ch4-46].

Amongst the existing solid photocathodes for GPDs, CsI has been widely used for its easy implementation and storage in almost any moisture-free gas. However, high-rate applications of CsI photocathodes are limited by charging-up effects causing a severe decrease of the quantum efficiency after a collected charge of the order of around 1 mC/cm^2. In the quest for alternative photosensitive materials that are more radiation-hard and chemically inert than CsI, the ongoing investigation on the photo-emissive properties of layers of hydrogenated nano-diamond powders has provided promising results for applications in the VUV domain. However, further studies are required together with the exploration of novel materials.

4.4.3 Semiconductor photon detectors

Silicon Photomultipliers (SiPMs; also G-APD, SSPM, MPPC) are modern, nowadays well established, photon detection devices with a large number of applications in particle physics experiments and beyond [Ch4-47], [Ch4-48]. SiPMs consist of an array of typically 1000 single-photon avalanche diodes (SPADs, or pixels) per 1 mm^2, which in analogue devices are all connected in parallel. Each pixel is formed by a photodiode and a quenching element connected in series. The photodiode is operated at a few volts above the breakdown voltage such that an avalanche breakdown occurs if a photoelectron is generated in the active volume; the avalanche multiplication is interrupted through the quenching circuit which can be either passive (analogue SiPMs) or active (digital SiPMs).

Important features of SiPMs are their compactness, a low operation voltage, insensitivity to magnetic fields and the low price-tag; these properties distinguish them, in particular, from PMTs. Today SiPM photon detection efficiencies (PDEs) commonly reach values of up to 60% in the visible range (350–600 nm). Disadvantages are their relatively high noise levels, with dark count rates (DCRs) at the present time typically 10 to 100 kHz/mm^2 at room temperature, and a somewhat limited dynamic range, depending on the pixel and SiPM array sizes used. Another disadvantage is only a moderate tolerance to radiation fields, particularly if detection of single photons is required. At fluences of a few times $1\times10^{11}\,\mathrm{n_{eq}\,cm^{-2}}$, SiPMs have no single photon sensitivity at room temperature.

Many novel detector concepts consider SiPMs for use in future particle physics experiments, however with the expectation of further-developed performance parameters. Required improvements include the following: reduced dark count rates well below 1 Hz/mm^2 especially for low rate, low light-level experiments in cryogenic conditions (e.g. DARWIN [Ch4-49], nEXO [Ch4-50] etc.); increased radiation tolerance for radiation levels of $\mathcal{O}(1\times10^{14}\,\mathrm{n_{eq}\,cm^{-2}})$ and above; reduced temperature parameter dependence; fast timing response at the 10 ps-level; highly efficient VUV and IR light detection; small cell sizes for larger dynamic range; large area coverage as well as low-noise; low-power dedicated multi-channel readout electronics. For ultra-cold applications, the cryogenic SiPM performance also needs to be better understood.

Basic SiPM Technologies

Most SiPM devices presently make use of the analogue approach with a passive quenching circuit and all SPADs within the SiPM array connected in parallel. Advantages are a high yield and low-cost production process, the accomplishment of rather large PDE values and a comparably good control of DCR, cross talk and after-pulsing (the latter heavily rests on the customised SPAD production process). However, digital devices are a very viable alternative as they ultimately promise improved performance. Digital SiPMs (d-SiPM) utilize an active quenching circuit with a fast response time integrated for each SPAD; in the fully digital form each SPAD is in addition connected to its own readout circuit which discriminates and registers the SPAD signal [Ch4-51]. The production of d-SiPMs is still presently constrained to certain CMOS processes which are also used by industry for integrated circuit fabrication, with only minor modifications. This generally results in d-SiPMs being more noisy than their analogue counterparts, though recent developments seem promising. The individual SPAD readout of d-SiPMs offers several particular advantages, for example high single-photon time resolution and DCR control by disabling individual pixels. In addition, the use of industrial CMOS processes promises a high degree of scalability. However, the additional heating from the digital circuitry has to be dealt with.

More recent research activities attempt to combine the best of both worlds by 3D-integration or hybrid technologies with custom production of the SPADs connected to

CMOS-based readout electronics using, for example, through-silicon vias (TSVs) or other interconnection methods. Whether such complex approaches lead to viable and affordable solutions for future particle physics experiments will need to be demonstrated. Presently 3D-integration for single photon detection is driven by consumer electronics and industry, with emphasis on infrared sensitivity.

Recent Developments and Future Challenges
Future SiPM applications in particle physics (and other research fields) require further developments and improvements, in particular, concerning PDEs in the infrared and deep UV, radiation hardness, fast timing, noise, cross talk and after pulsing, cell sizes and dynamic range, reduced cryogenic operation, improved temperature dependence, as well as dedicated fast, low-power readout electronics. There are many ongoing R&D activities, either generic, or in the context of a particular experiment. Several of the challenges and recent developments relevant for future particle physics applications are summarised below.

Photon Detection Efficiency: Modern SiPM devices reach PDEs as high as 50 to 60% depending on the wavelength and bias voltage; for blue and near-UV sensitivity n-on-p structures are used, whilst p-on-n SPADs are better for detecting green/red light. The main reasons for the increased PDE performance over the last decade are higher geometric fill factors and reduced noise levels, allowing SiPM operation at higher bias voltages. Present PDE research focuses mainly on improved efficiencies in the VUV and IR range. In particular, high VUV sensitivity is required for SiPM applications in dark-matter experiments and searches for $0\nu\beta\beta$ decays using large-scale liquid noble gas detectors. In addition, fast timing applications using Čerenkov radiation could profit from improved SiPM sensitivity in the UV range. A particular issue for extending SiPM PDEs into the deep UV is the fabrication of very thin, UV-transparent entrance windows. This requires a good understanding of the VUV optical properties of silicon. Alternative readout techniques for two-phase argon detectors have been proposed [Ch4-52], based on non-standard electroluminescence in the visible and near infrared (NIR). An increase of SiPM sensitivities in the red and IR range is also required outside HEP, for example for laser imaging, detection, and ranging (LiDAR) applications. This necessitates thicker depletion regions with possible limitations on breakdown uniformity and temperature stability.

Timing: SiPMs intrinsically provide very fast response, with single-photon time resolutions (SPTRs) reaching values of well below 100 ps. For a single SPAD, the timing spread is below 20 ps. SPTR limitations for multi-cell SiPMs include pixel non-uniformities (i.e. the timing spread between micro-cells), the overall SiPM capacitance, and wavelength-dependent tails. However, the main factor is the parasitic capacitance yielding a reduced signal slope and a degradation of the signal-to-noise ratio, particularly for large devices. The timing jitter due to the influence of electronic noise is the dominant factor degrading the SPTR for large area sensors [Ch4-53]. Possible ways to improve the SPTR degradation due to electronic noise are optimisations of the front-end electronics with respect to bandwidth, power and signal fluctuations, or improving the photon response at the device level. Operation at higher over-voltages can also yield a better timing performance due to an increased signal slope. Hence, also lowering the DCR is a path to faster devices. Particularly good SPTR is promised by digital SiPMs with a single pixel readout and active quenching elements, as these offer high uniformity and a much-reduced capacitance. In general, the ability of digital SiPMs to record and digitise the individual time stamps of all incoming photons, giving the full time information of a detected light pulse, might eventually lead to an ultimate timing performance of $\mathcal{O}(10\,\mathrm{ps})$ and below.

For the overall timing performance of a detector system with SiPM readout of light, the SPTR is only one performance parameter. Depending on the particular application, equally or even more important is the size and shape of the incoming light pulse, the optical coupling of the SiPM to the photon source (e.g. scintillator) or the SiPM PDE, which all have to be considered for an optimal timing response.

Dark-count rate, cross talk and after-pulsing: DCR, cross talk and after-pulsing are very important performance parameters of SiPMs. Dark counts are generated thermally at room temperature. Improved process engineering has led to a substantial reduction of the DCR component, at present yielding DCR values that can be as low as $10\,\mathrm{kHz/mm^2}$. Operation at lower temperatures further reduces this value by about a factor of two every 10°C. However, at cryogenic temperatures ($\mathrm{T} < 200\,\mathrm{K}$), the DCR is dominated by trap-assisted and band-to-band tunneling which primarily depends on the internal electric field strength. Very low noise applications at cryogenic temperatures thus require a very careful engineering of the high-field region within the SiPM SPADs. It has been observed that only a small number of SPADs are responsible for the majority of dark counts in a single SiPM array. Thus, SiPMs with single pixel readout provide the option to individually turn off single "screamer" SPADs for a substantial overall DCR reduction [Ch4-54]. However, whether this approach also helps to reduce the noise level for highly irradiated devices requires further research. One way to further improve the signal-to-noise ratio in SiPMs is to employ dedicated light collectors, either as Winston-cone-like arrays, or suitably designed meta-materials as discussed in Section 4.4.5.

After-pulsing occurs if charge carriers of the primary event are trapped during the avalanche process and released with a time delay, triggering a second discharge. As the trapping probability depends on the number of defects inside the silicon, after-pulsing can be reduced by careful process engineering. Optical cross talk comprises an additional SiPM noise component. This arises if photons generated within the signal avalanche induce a secondary event in a neighbouring pixel. The reduction of this cross talk is achieved by introducing trenches between pixels, with the challenge to retain high fill-factors for large PDEs.

Radiation hardness: For future applications in experiments with high radiation levels, radiation hardness of SiPMs is a key requirement. Many groups have studied the impact of radiation damage on the SiPM performance, the most evident being a substantial increase in DCR and a reduction of signal amplitudes. For multi-photon detection, available SiPM devices have been shown to work up to fluences of $1\times10^{14}\,\mathrm{n_{eq}\,cm^{-2}}$, although requiring operation at lower temperature and optimised bias voltage to maintain acceptable signal-to-noise ratios or timing performance. Conversely, single photon sensitivity is already lost at fluences of a few times $1\times10^{11}\,\mathrm{n_{eq}\,cm^{-2}}$. The increase of

SiPM radiation hardness is the first and foremost mechanism to reduce the DCR. This can be achieved for example by lowering the maximum electric field value (as above) or by reducing the active volume of the SPAD cells, which can be realised by thinning the depletion layer at the expense of increased tunnelling noise. To avoid a drop of the PDE caused by damage and charge trapping in the non-depleted SiPM entrance layer, optimisation of the dielectric-silicon $SiO_2/S_3N_4/Si$ interface needs to be investigated. Moreover, the requirement of operating irradiated SiPMs at low temperatures necessitates easy integration of cooling infrastructure, heat removal and temperature sensors. In addition, the possibility to heat for accelerated annealing also needs to be considered.

Radiation hardness of solid-state photo-multipliers could also be improved by exploring other semiconducting materials with wider band gaps and different material properties, like gallium indium phosphite (GaInP), gallium arsenid (GaAs), galium nitrate (GaN), or silicon carbide (SiC).

Cryogenic application: Application of SiPMs in large-scale cryogenic detectors such as nEXO, Darkside-20k, DARWIN or the DUNE Liquid Argon TPCs requires experiment-dependent very small DCR of less than $0.1\,\mathrm{Hz/mm^2}$, reduced after-pulsing, NUV- and VUV-sensitivity, large area coverage with a high fill factor, good timing resolution and ultra-low intrinsic radioactivity. In addition, readout schemes suitable for large-scale, low temperature operation need to be developed. The first VUV-sensitive devices have been developed, e.g. for use by the MEG-II experiment [Ch4-55] or the nEXO experiment [Ch4-56] with PDEs in the 20% range. Particular challenges are the provision of UV-transparent entrance windows and a thin contact layer to accommodate the low penetration depth of VUV photons.

Optimisation and integration

The performance of light detection with SiPMs must be seen in the context of a particular experiment, as the optimal performance parameters depend on the specific application. Hence many different aspects need to be considered when optimising SiPM parameters. Fast timing also requires fast input, hence depends on the radiator/scintillator used, its light yield and the spectral and temporal shape of the generated photons. Issues of potential wavelength-shifting, light collection efficiency or optical coupling including micro-lenses are also important. Readout electronics for fast timing must fulfil requirements of low power and low noise, and the need for cooling infrastructure and integration must be considered in both cryogenic and large-scale applications.

Finally, SiPMs are increasingly used in industry applications, also with very special performance requirements. Future particle physics experiments will benefit from the trends and possible performance development in this area, which requires a close exchange between industry and science.

4.4.4 Superconducting photon detectors

In this rapidly developing technology field, the three most established technologies are the superconducting nano-wire single photon detector (SNSPD), the transition edge sensor (TES), and the microwave kinetic inductance detector (MKID). The integration of these cryogenic sensors into accelerator-based experiments would be challenging, but the sensor performance is impressive.

An SNSPD consists of a thin (4 nm) and narrow (100-250 nm) superconducting nanostrip that is current-biased just below its critical current. Absorption of a photon generates a resistive domain in the superconducting nanostrip, which leads to a transient voltage signal that can be detected. SNSPDs offer a unique combination of speed, both in terms of count rate ($\sim$ GHz) and low timing jitter (< 3 ps [Ch4-57]), a large range of wavelength sensitivity from VUV (120 nm) to mid-IR (10 μm), high detection efficiencies (approaching 100% for UV to near-IR), and low dark count rates ($\sim$ 5-10 Hz), making them appealing for a wide variety of demanding applications. These devices have been an enabling technology for quantum information science (QIS) applications. Outside of QIS, SNSPDs have been used for time-correlated single-photon counting (TCSPC), characterisation of single-photon emitters, molecular spectroscopy, space-to-ground communications, integrated circuit testing, fibre temperature sensing, and LiDAR systems.

Examples of SNSPDs in present use in particle physics are nanowire detectors for dark matter and dark photons. Work is in progress that could make these sensors relevant to HEP applications by lowering the energy threshold, increasing the area (using 300 mm wafers and larger) and pixel size, coupling via windows to cryogenic stages, and readout of arrays (superconducting electronics for data processing). Any application of these sensors with severe cryogenic requirements in large accelerator-based detectors would require an extensive R&D program.

4.4.5 Novel optical materials for fibre trackers and light collection

Scintillating fibres

Scintillating fibres offer a cost-effective way of instrumenting large areas for charged particle tracking at relatively low material budget. With the availability of small-pitch SiPM arrays, high resolutions are possible, as shown with the LHCb SciFi tracker upgrade [Ch4-58] presently being completed. To further advance the technology, e.g. for a second upgrade of the tracker envisaged for the HL-LHC, both the photosensor and the optical fibres need to be re-optimised to obtain higher light yield, allowing for smaller diameters, and thus higher precision and improved radiation tolerance.

Innovative materials such as Nanostructured-Organo-silicon-Luminophores (NOL) scintillators, exhibit stronger and faster light output than presently achieved; here the energy transfer from the primary excitation to the wavelength shifter is enhanced by silicon links, with respect to the radiative processes in standard materials [Ch4-59]. NOL fibres are almost a factor two (six) faster than the best blue (green) standard fibres, which makes them very interesting for timing-critical applications. Radiation-hardness tests by X-rays to a dose of 1 kGy have shown that the damage is at a level comparable to reference fibres [Ch4-60]. These are promising results but clearly more R&D is required.

Light collection methods

One way to improve the signal-to-noise ratio in photon detectors (of particular importance in SiPMs with high dark count rates) is to further develop dedicated light collectors, either as quartz Winston-cone-like arrays [Ch4-61], [Ch4-62] or suitably designed metamaterials [Ch4-63]. In this way, photons would propagate from a larger entry window to a considerably smaller sensor, resulting in an improved signal-photon to dark-count ratio. Another interesting idea uses light concentrators constructed from di-chroic reflectors. These sort photons by wavelength to aid Čerenkov-scintillation separation and ultimately direction reconstruction in kiloton-scale neutrino detectors [Ch4-64].

Scintillation light emitted by LAr and LXe (128 nm and 178 nm, respectively) requires the use of wavelength shifting materials and di-chroic filters to bring the wavelength into the sensitive range of the photon detector (see Chapter 2).

4.5 Observations

The necessary development of PID and photon detectors for such a wide range of applications at future facilities presents a major challenge. "Blue-sky" R&D will be necessary, and on the timescale of 20-30 years, totally new ideas and developments will surely evolve, and even replace several of today's preferred technologies, described above.

The development of innovative photon sensors requires cutting-edge technologies available only in very specialised industrial companies. Close collaboration with these industries will be essential. Industry is often driven by mass production outlets, and photon detector evolution should try to align itself to these drivers in order to ensure supply and lower cost. An example for SiPMs could be the automotive industry. A close synergy should also be developed with other research areas.

It is important to stress that the HEP community has very demanding requirements (speed, radiation tolerance, cost) which drive the R&D and ultimately benefit other communities and society in general. Teams with in-depth experience in HEP instrumentation are highly qualified for specifying, testing and characterising new devices and for suggesting technical improvements which feed through into other fields.

There will be benefit to establish a series of interdisciplinary workshops between experts of different research fields and representatives of the major companies developing innovative photon sensors. The goal would be to organise rather small workshops for experts meant to convey the needs of our community to industry, discuss technical challenges and trigger the interest of industry on novel ideas. There may be a benefit of R&D collaborations, e.g. on SiPMs, where issues of standardisation across research areas can be established. Device testing is an example.

The design and construction of PID detectors is in general a specialised area within particle physics, although with clear synergies with other fields (e.g. in PET scanning etc). Whilst participation of industry will be important, the detectors are driven by physicists to fulfil the specific physics requirements of the experiments. The development of PID devices requires highly skilled personnel, both physicists and engineers, and the availability of specialised technical workshops in the institutes. It is important to define a sustainable plan to recruit and train future HEP instrumentation experts for avoiding generational gaps and maintaining dedicated technical facilities and infrastructures in our European laboratories.

4.6 Recommendations

There are important recommendations to enable the implementation of the research directions discussed above.

DRDT 4.1 - Enhance the timing resolution and spectral range of photon detectors.
Sensors are required for fast timing in Čerenkov and time-of-flight detectors, and in extending the wavelength coverage of scintillation photons from noble gases and Čerenkov photons. In the shorter term (the next five years), advances in SiPMs for faster timing and UV sensitivity need to be made. In addition, light collection systems for SiPM arrays (quartz based, micro-lenses, meta-materials) must be developed. For MCP-PMTs, improvements of quantum and collection efficiencies and granularity are required, and extending to large area. Incremental improvements extending over the next 10 years need to be made in large-area gaseous photon detectors, in particular fine granularity, and incorporating fast timing.

DRDT 4.2 - Develop photosensors for extreme environments.
This is necessary for operation in the high particle fluxes and pile-up conditions of the HL-LHC, Belle II upgrade, EIC, and FCC-hh, and for experiments at fixed target facilities. In the shorter term (the next five years), improvement in the radiation hardness of SiPM technology is required. Also, for high-sensitivity experiments, radio-pure SiPM technology and operation in cryogenic systems must be realised. For MCP-PMTs, significant progress in detector ageing and high-rate performance needs to be made. Advances in gaseous photon detectors regarding photocathode ageing and rate capability are required, with evolving improvements over the next 10 years. NOL-based scintillation-fibre materials with higher light yield and shorter decay time must also be developed. Finally, on the timescale of 20 years, further advances in radiation hardness of SiPMs or other solid state sensors at and beyond $\mathcal{O}(1{\times}10^{14}\,\mathrm{n_{eq}\,cm^{-2}})$ will be essential.

DRDT 4.3 - Develop RICH and imaging detectors with low mass and high resolution timing.
This will be needed for particle identification at the HL-LHC, Belle II upgrade, EIC, and FCC-ee. In the shorter term (the next five years), picosecond timing for RICH systems must be developed. Greenhouse-friendly radiator gases (including pressurised systems) will be necessary, together with highly-polished quartz and transparent aerogels. In the longer term (the next ten years), compact RICH systems with low X_0 will be required.

DRDT 4.4 - Develop compact high performance time-of-flight detectors.
This development is required for particle identification at the HL-LHC, EIC and FCC-ee. In the the next 5-10 years, picosecond timing for TOF systems must be developed, together with high-granularity photosensors having long lifetime and high-rate capabilities.

Further recommendations
It is recommended that several "blue-sky" R&D activities be pursued. The development of solid state photon detectors from novel materials is an important future line of re-

search, as is the development of cryogenic superconducting photosensors for accelerator-based experiments. Regarding advances in PID techniques, gaseous photon detectors for visible light should be advanced. Meta-materials such as photonic crystals should be developed, giving tune-able refractive indices for PID at high momentum. Finally, for TRD imaging detectors, the detection of transition radiation with silicon sensors is an important line of future research.

References Chapter 4

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Chapter 5

Quantum and Emerging Technologies Detectors

5.1 Introduction

Devices exploiting the extreme sensitivity of quantum systems hold the promise to address, in a completely novel manner, the fundamental properties of space and time, and of particles and their interactions. The rapid progress being made in their development opens up new realms of exploration, complementary to traditional high energy physics approaches, with the prospect of significant advances on the time scale of a decade or less. A wide range of quantum technologies and methodologies is currently being actively explored, which have the potential that dedicated R&D in these areas could have profound impact in answering some of the most puzzling questions in fundamental physics. Several specific observations matched to specific time horizons can be articulated:

- With the current rapid growth of quantum technologies that may be relevant for particle physics, wide exploration of their potential and consolidation of promising approaches can open up the rapid exploration of new regions of parameter space, thus providing valuable and complementary windows on fundamental physics;

- On a time scale of ten years, the use of networks of quantum sensors holds the promise for significant further advances for fundamental physics beyond the reach of individual sensor systems;

- Similarly, the need to avoid environmental disturbances as well as rapidly falling costs encourages the development of devices that are suitable for operation on space-based science platforms, with impacts on the needs for e.g. miniaturisation, standardisation, cost reduction and scalability;

- On a longer time scale, major advances and improvements in quantum technologies will be required to address a breadth of physics topics of fundamental importance ranging from exploration of the dark universe to detection of relic neutrinos to probing the foundations of our understanding of the fabric of the universe;

- Next steps in developing and exploiting the wide range of quantum sensor technologies involve both exploration of emerging, or completely novel, technologies, as well as scaling up existing successful technologies. With its decades-long experience of large high energy physics collaborations and concomitant quasi-industrial detector fabrication, integration, characterisation and operation as well as project management, the HEP community has an important role to play in facilitating this via several routes: (a) developing effective distributed experimental collaborations; (b) where relevant, the provision via national/international laboratories of (i) ultra-low temperature test stands and other test facilities (ii) mechanical, cryogenic, vacuum, magnet or electronic engineering to design prototypes and build, test and commission at large scales and (iii) where relevant the provision of civil infrastructure such as accelerator tunnels and access shafts.

To reach such ambitious (but achievable) goals, support for both a dedicated expert workforce and for exploratory devices will be required. In particular, interdisciplinary training for both early-stage and experienced researchers will ensure the widest possible uptake of these rapidly growing technologies, while allowing developments to benefit from existing local, national and supranational research infrastructures and test facilities, for which it is thus equally important to sustain and provide stable support.

Major R&D themes for quantum sensing and other emerging technologies that have been identified in the framework of this Task Force (common to the different detector areas presented in Figure 5.1) include:

DRDT 5.1 - Promote the development of advanced quantum sensing technologies.
Given the demonstrated and potential further substantial impact of advanced quantum sensing technologies on particle physics as well as in fundamental physics, their development across the full range should be promoted.

DRDT 5.2 - Investigate and adapt state-of-the-art developments in quantum technologies to particle physics.
Developing new probes for the investigation of matter and fields will greatly benefit from exploring and adapting methodologies and technologies from quantum sensing, quantum materials, quantum computing and quantum communication. Investigation of their potential benefits to accelerator-based physics should be encouraged.

DRDT 5.3 - Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies.
Funding opportunities need to be put in place for rapid exploration of the potential of fundamentally new approaches as well as for consolidating longer term experimental efforts that build on and expand the initial proof-of-principle investigations; close ties to research in neighbouring fields and to industrial efforts, resulting in mutually beneficial cross-pollination, need to be established.

DRDT 5.4 - Develop and provide advanced enabling capabilities and infrastructure.
Key advanced enabling capabilities such as cryogenic electronics, tailored coatings or dedicated developments in material science for quantum sensing devices need to be put in place; access to common infrastructures at the national and supranational levels for testing and evaluating the suitability of specific quantum technologies for their use in probing fundamental physics needs to be provided.

Many ambitious physics targets have been identified that could benefit from quantum sensing and other emerging technologies. In the following sections the physics motivations and quantum methodologies will be described in greater detail. To attempt to represent the rapidly evolving technological base, specific families of detector technologies have been identified that address various categories of physics targets. Figure 5.1 shows a range of technology areas and physics targets for various time frames and indicates the urgency of investment to enable these programmes. The colour coding for the detector R&D readiness is similar to that of the other Task Forces, with some slight adaptations as is described in the caption. Given the shifting landscape over time, specific physics targets are sometimes regrouped or merged under larger umbrellas (indicated by the same hues of grey), or new targets have been introduced.

Figure 5.1 covers the very wide range of physics targets and technologies discussed in Section 5.3, starting from current state-of-the-art small-sized, local setups to networked ensembles to space-based detector systems to address the rapidly expanding explorable parameter space in dark matter (DM) searches, in searches for new interactions or in probing fundamental symmetries or even foundational aspects of Quantum Mechanics (QM); longer term prospects (but still within the 2-decade framework) include transforming conceptual ideas for HEP detectors based on quantum sensing ideas into prototype or even functional HEP detectors, or even addressing completely new fields, such as searches for relic neutrinos. In Section 5.2 the physics targets that these approaches are particularly well suited to explore will be described. A representative summary of the expected impact on these physics targets of R&D in selected areas of quantum technologies is discussed in Section 5.4 and presented in Figure 5.3.

5.2 Theory Motivation

The unprecedented sensitivity and precision of quantum systems enables the investigation of questions of fundamental concern to particle physics. These include the nature of dark matter (DM), the existence of new forces, the earliest epochs of the universe at temperatures $T \gg 1\,\text{TeV}$ and the possible dynamics of dark energy (DE), the possible existence of dark radiation (DR) and the cosmic neutrino background, the violation of fundamental symmetries, and even the nature of interactions and space-time at scales as high as $M_{\text{planck}} \sim 10^{19}\,\text{GeV}$.

The pseudo-scalar QCD axion is motivated as a leading solution to the strong CP problem [Ch5-1], [Ch5-2], [Ch5-3]. For the QCD axion there is a precise relation be-

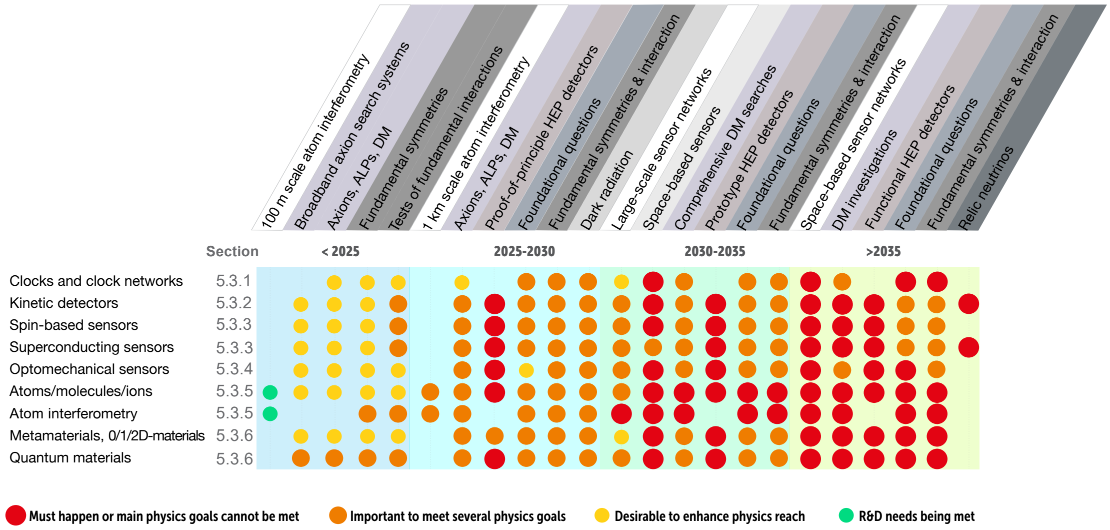

Figure 5.1: Schematic timeline of categories of experiments employing detectors from the quantum sensing and emerging technology areas discussed in Section 5.3. A wide range of related topics are grouped under a common heading (e.g. tests of fundamental interactions also includes measurement of neutrino properties). The colour coding is linked not to the intensity of the required effort but to the potential impact on the intended physics programme and experiments. Must happen or main physics goals cannot be met (red, largest dot); Important or required to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); Not applicable or fundamentally new approaches needed (blank).

tween the large energy scale, f, whose inverse sets the overall size of the feeble couplings of the axion to the Standard Model (SM) and the particle mass $m_a \simeq 6\,\text{meV}$ ($10^9\,\text{GeV/f} \simeq 1.5\,\text{THz}$) [Ch5-4]. Axion-like-particles (ALPs), a generalisation of the QCD axion, have interactions again parametrically set by $1/f$, but now the ALP mass is a free parameter. The theoretical attractiveness of the QCD axion and ALPs is enhanced both by their natural, symmetry-protected light mass, and their ubiquitous presence in realistic completions of the SM and gravity, especially string theory [Ch5-5], [Ch5-6]. The details of their couplings and the relation between $1/f$ and their mass provides information on extremely high energy scales, potentially including Planck-scale physics. Importantly, both provide attractive DM candidates with natural early-universe production mechanisms [Ch5-7], [Ch5-8], [Ch5-9], [Ch5-10].

Massive spin-1 "dark photons" (ultra-light dark Z'), A'^{μ}, are another attractive DM candidate with motivated production mechanisms [Ch5-11], [Ch5-12], [Ch5-13], as well as couplings to the SM, particularly kinetic mixing $\epsilon F_{\mu\nu} F'^{\mu\nu}$ with the photon [Ch5-14], [Ch5-15], [Ch5-16], [Ch5-17]. Here $\epsilon \ll 1$ is sensitive to physics even at the highest energy scales. Similarly to axions, vector bosons, either broken (massive) or massless (so they could be dark radiation - see below), are ubiquitous in string theory and their light masses are symmetry-protected; such fields are again well-motivated by UV considerations. Another important target are ultra-light spin-0 CP-even particles such as dilatons or string moduli, which parameterise the size and shape of extra space dimensions which may exist, and whose variation generically leads to time- and space-varying SM couplings and masses. If light, they must be feebly-coupled to the SM to survive fifth-force and astrophysical constraints.

If such bosonic states comprise a substantial fraction of the DM density and their mass satisfies $m \lesssim 1\,\mathrm{eV}$, then they are well-described as a classical field oscillating at the Compton frequency $\nu_0 = 2.4 \times 10^{11}\,\mathrm{m/meV\,Hz}$ with a $\mathcal{O}(10^{-6})$ fractional line-width due to the virilised motion of DM in our galaxy [Ch5-18]. Thus, resonant detection of light QCD axion, ALP, dark photon and scalar moduli DM is possible via the limited number of leading couplings of the relevant classical field to the SM. As such, the QCD axion, ALPs, and the dark photons provide windows to *both* the earliest moments of the Big Bang via their production mechanisms and also the very highest energy scales (equivalently smallest lengths) via their feeble couplings and tiny masses.

Irrespective of whether such bosonic states comprise a component of the DM, they give rise to new "fifth" forces with a wide variety of possible types of couplings to the SM. At long-range compared to their Compton wavelength, λ, these new forces will be Yukawa-suppressed $\sim \exp(-\mathrm{r}/\lambda)$, but at distances $r \lesssim \lambda$ the suppression is only power-law in r, the precise form depending on the spin and interactions of the exchanged particle [Ch5-19], [Ch5-20].

For almost all light ($m \lesssim 1\,\mathrm{MeV}$) feebly-interacting particles, whether constituting a component of the DM or not, astro-physical constraints are significant and must be taken into account when assessing the reach of proposed quantum-enhanced detection experiments. Although in principle these constraints can be avoided by more complicated constructions, these same complications can often invalidate the analysis or assumptions underlying the experimental search.

DM with $\mathrm{m} \gtrsim 10\,\mathrm{eV}$ is better described as individual particles scattering off a detector. Both light ($\mathrm{m} < 1\,\mathrm{GeV}$) WIMP DM and feebly-interacting massive particle (FIMP) DM candidates with sub-weak-interaction strength populate this low-mass particle-like regime below 1 GeV [Ch5-21], [Ch5-22], [Ch5-23], [Ch5-24]. Non-WIMP heavy ($\mathrm{m} \geq 100\,\mathrm{TeV}$) DM is also a possibility, whether particle, soliton, or a composite state of asymmetric DM. Searches for DM with $\mathrm{m} \gtrsim 10\,\mathrm{eV}$, involve ultra-sensitive quantum-enhanced detectors for photons, phonons, magnons, and sometimes exotic collective excitations of quantum materials or substances (see Chapter 2). Figure 5.2 highlights the potential mass ranges that quantum sensing approaches open up.

New CP-violating physics at high energy is motivated by the required generation of the observed matter-antimatter asymmetry (leptogenesis and/or baryogenesis). Searches for e^- and nucleon Electric Dipole Moments (EDMs) using high precision atom and molecular experiments can explore new CP-violating physics at $\sim 100\,\mathrm{TeV}$ scales, with a reach that will only improve as the precision of these experiments improves with new quantum techniques.

Another well-motivated possibility is dark radiation (DR), a relativistic population,

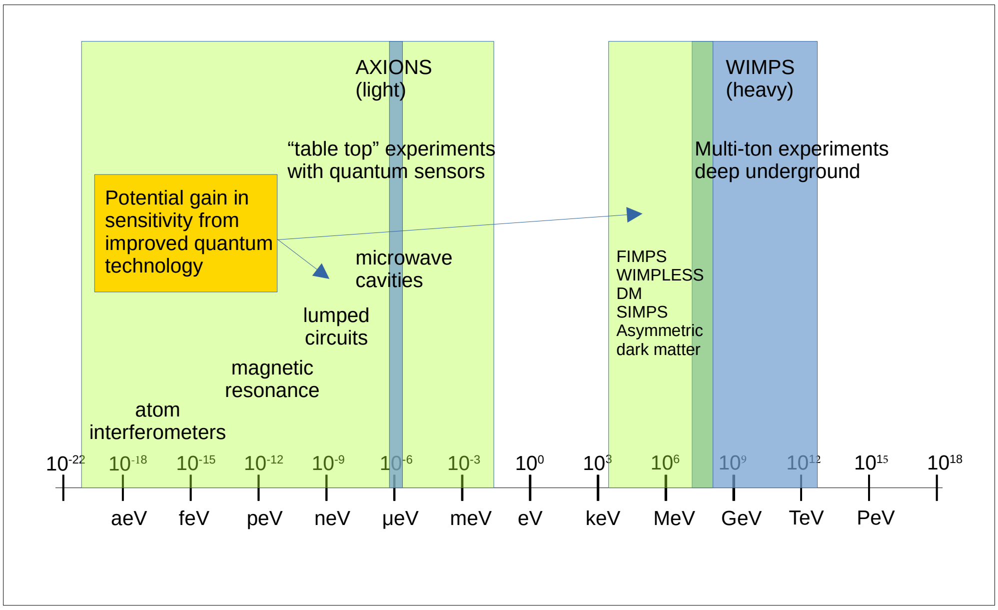

Figure 5.2: Axion mass range accessible via novel advanced quantum sensing techniques compared to current experiments.

not necessarily thermal, of new ultra-light or massless particles in the universe. While DM is known to exist, it is not known if there is DR. However DR arises frequently, especially in theories with new light particles, and it often arises in theories of DM. For example for any of the light DM candidates, e.g. axions, dark photons, etc., an abundance of relativistic particles, thus DR, would necessarily be produced alongside the DM. They could also be produced as a component of the dark energy (DE) density if the DE is dynamical [Ch5-25]. Such "DE radiation" can have significantly higher energy densities than other forms of DR, well above the usual Cosmic Microwave Background Radiation (CMBR) and Big Bang Nucleosynthesis (BBN) bounds on relativistic species, because they are produced at late times. DR of particles such as axions or dark photons would be an exciting signal to look for, quite distinct from cold DM. The cosmic neutrino background (CNB) is DR that is believed to exist. While challenging [Ch5-26], observation of this CNB would provide one of the only ways to probe the early pre-CMBR-formation universe. Further, a higher temperature population of cosmic neutrinos can also be produced by dynamical DE which would be significantly easier for experiments to detect [Ch5-25] and would shed light on the nature of DE.

The success of LIGO and VIRGO in detecting gravitational waves (GWs) in the $10\,\text{Hz} \lesssim \nu \lesssim 10\,\text{kHz}$ band has vividly demonstrated the power of quantum detectors to advance fundamental physics [Ch5-27]. GWs enable investigations of general relativity, black holes and neutron stars, tests of a variety of Beyond-the-Standard Model (BSM) theories, and give a direct window on the earliest epochs of the Universe via primordial stochastic GWs. Near-future instruments will cover the 0.1-30 mHz (LISA) and 0.1 μHz

Pulsar Timing Array bands, while the Einstein Telescope (ET), a newly accepted European Large-Scale Next Generation Facility ESFRI[1] project, will cover the frequency range from a few Hz to a few kHz. It is vital to extend this coverage to as wide a frequency range as possible. The $\sim$0.03-3 Hz "mid-band" is a prime target for detectors based on atom interferometry, with MAGIS-100 [Ch5-28], AION [Ch5-29], MIGA [Ch5-30], already in early stages of construction. Future km-scale (such as ET) and satellite-based observatories (such as LISA) will have the capability to detect known astrophysical sources, as well as primordial GWs generated by physics at 1-100 TeV scales and above. Above VIRGO and LIGO, the band $\nu \gtrsim 30$ kHz is free of conventional astrophysical sources, and thus is a prime region to explore new physics [Ch5-31], e.g. via levitated sensors with sensitivity in this frequency range. Potential novel sources in all these bands include GWs from quantum super-radiance produced particle clouds around black holes, from axion inflation and oscillons, cosmic strings, and 1st-order phase transitions. Even smaller scale atom interferometers possess good reach for ultra-light "fuzzy" DM, some fifth force candidates, and equivalence principle and other tests of gravity.

Finally, improved macroscopic tests of QM, or of explicit violations of fundamental symmetries, such as CPT or high-energy Lorentz-invariance (low energy spontaneous breaking of either are better described as due to the presence of background "dark fields" such as DM, DR, or DE), are also a fascinating prospect. Modifications of QM are, of course, much less grounded in a reliable theoretical structure, so one must be careful in assessing the limits from any particular experiment, and also what limits may exist from other ultra-precise tests, such as those of CPT- or Lorentz-invariance.

5.3 Quantum Methodologies and Techniques

A wide range of technologies under development and being applied to ongoing or planned low-energy particle physics experiments build on advances in the fields of superconducting devices, atomic and molecular optics or in quantum technology-based materials science that have taken place in the past decades. A discussion of the domains of applicability of the individual technology families, together with an expectation for their further progress allows extrapolating which central questions of particle physics can reasonably be addressed in the coming two decades, and where targeted R&D would hold most promise. Several of these technologies appeared only very recently; flexibility in defining goals and means is thus central to unlocking the potential of quantum technologies.

5.3.1 Clocks

Optical atomic clocks now support frequency ratio measurements with fractional uncertainty below the level of $1 \cdot 10^{-17}$. Since atomic clock frequencies are defined by the laws of nature and the fundamental constants, these measurements are exceptional probes of fundamental physics. They test the symmetries of nature, such as Lorentz-invariance, and provide probes for BSM physics, such as the nature of dark matter.

[1] The European Strategy Forum on Research Infrastructures

In contrast to the situation with microwave atomic clocks, this level of clock performance is accessible in a large array of optical clock species. Eight optical transitions are currently listed as secondary representations of the second and dozens more have been proposed as excellent clock candidates. Included in this list are atomic and molecular species that exhibit high sensitivity to BSM effects and variations of fundamental constants. The breadth of atomic systems amenable to high precision measurement thus gives rise to numerous opportunities for fundamental physics. There also exists one low-energy nuclear transition (^{229}Th) that is amenable to laser spectroscopy and could give extremely high sensitivity to variations in fundamental constants.

Extending the reach of optical clock measurements to new species requires the development of new protocols for laser cooling, trapping and state detection. One example is the technique of quantum logic spectroscopy, which has enabled the highest accuracy optical clocks to date, based on the $^1S_0$ – $^3P_0$ transition in $^{27}Al^+$. Adaptation of this technique has now allowed for precision spectroscopy on molecular and highly-charged ions. Further developments are aimed at applying this technique to new systems and scaling it to larger numbers of ions for improved measurement stability.

Quantum enhanced metrology also promises to improve measurement stability using spin-squeezed states of atoms or even maximally-entangled GHZ states. These techniques allow for frequency measurements beyond the standard quantum limit approaching the Heisenberg limit of measurement uncertainty. They have been demonstrated both for trapped ion systems and for atoms trapped in optical lattices. Future research will focus on improving this quantum advantage further and applying it to the stringent requirements of optical clock measurements.

Several grand challenges are evident in the field of frequency metrology. Building a global network of high-stability and high-accuracy clocks is essential for advancing international time and frequency standards and would allow applications such as relativistic geodesy and unprecedented sensitivity in the search for new physics such as ultralight dark matter. Secondly, sending optical clocks to space would allow more stringent tests of relativity and could enable the detection of low frequency gravitational waves. Lastly, optical clocks based on entangled states of atoms would lead to measurements with even higher stability, ultimately approaching the Heisenberg limit.

5.3.2 Spin-based sensors for axions and axion-like-particles

Spin-based sensors operating on the principles of Nuclear Magnetic Resonance (NMR) are a promising avenue for searching for the QCD axion in the mass ranges of 1 peV-10 neV with haloscopes, such as the CASPER experiment [Ch5-32], and 10 μeV-10 meV with fifth-force searches, such as ARIADNE [Ch5-20]. Ultimately limited by spin-projection noise, a figure of merit in these experiments is $p\sqrt{N\tau}$, so efforts to increase the relevant spin coherence time τ, the number of interacting spins N, and the polarisation fraction p are common to these approaches. Additional considerations regarding choice of material for the NMR medium may provide further enhancements in sensitivity. In addition, new quantum protocols may enable experiments to beat quantum projection noise with spin squeezing in nuclear magnetic resonance based detectors for QCD axion coupling to the strong force below $\sim 1\,\mu$eV, and for the detection of short-range spin-dependent interactions above $\sim 1\,\mu$eV up to 10 meV.

Spin-based sensors are also able to perform sensitive searches for fifth-force axion-induced couplings to electron spins, for example in the QUAX-gpgs experiment [Ch5-33], or for the gradient of the cosmic axion field coupling to electrons as in the QUAX-*ae* experiment [Ch5-34]. In the latter case, magnons, quanta of collective spin wave excitations that arise in condensed matter systems, are coupled to photons of a microwave cavity mode to realise a variant of the cavity haloscope. This scheme, that has excellent prospects for model discrimination in the event of discovery, has been used for a preliminary axion DM search based on a photon-magnon hybrid system consisting of ten small spheres of yttrium iron garnet (YIG) coupled to a cylindrical cavity mode [Ch5-35]. To improve on the reported limit of the axion-electron coupling constant[2], significant R&D activity is required on magnetic materials and hybrid systems. Capability of single magnon readout based on superconducting transmon qubits is also necessary.

Magnons are also promising channels for detection of DM with spin-dependent interactions in the 10 keV to 10 MeV range. Their discovery potential has recently been demonstrated for a YIG target with kilogram·year exposure [Ch5-36]. In this case the DM scattering creates magnon excitations, to be detected with with novel SC detectors with less than 40 meV thresholds or single microwave photon counters.

An exciting possibility which combines quantum and traditional accelerator based technologies is the use of storage rings as spin detectors. For example, using the frozen spin method, storage rings could be used to search for a proton EDM (see e.g. [Ch5-37], [Ch5-38]). The same technology would also allow one of the most sensitive searches for axion (and other ultralight) dark matter in the lowest mass range, by searching for the spin precession caused by the dark matter field [Ch5-39]. These applications require the use of both particles accelerated to relativistic speeds and held for long periods, as well as high precision quantum sensors for measuring the spin precession rate (and potentially also as beam position monitors).

5.3.3 Superconducting approaches

Over the last 30 years, the development and technological refinement of a broad class of superconducting detectors has revolutionised major areas of experimental astrophysics. The study of the large scale structure of the Universe through observations of the CMB, the study of galaxy formation and evolution at high redshifts, the study of the chemistry and dynamics of star formation in the local Universe, and the observation of black holes and other highly energetic events have all benefited substantially from the development of this technology.

The closely linked enabling technology of complex superconducting electronics has been deployed in many ground-based, aircraft-based, high-altitude-balloon and space-based observatories, indicating the degree to which this technology has been understood and refined. Superconducting electronics is now playing a major role in quantum com-

[2]The obtained limit on axion-electron coupling constant $g_{aee} \sim 2 \cdot 10^{-11}$ at $43\,\mu$eV is four orders of magnitude above the QCD axion line.

puting and communications, in the form of qubits, quantum state memory, and quantum noise limited detectors and amplifiers. The unique characteristics of these devices means that they will also play a pivotal role in a new generation of national and international particle and fundamental physics experiments, and any roadmap aimed at exploring the fundamental nature of space-time and low-energy excitations of quantum fields, must have the further development of superconducting electronics as one of its core priorities.

Crucially, over the past 30 years the vast majority of the development work has taken place in university and government laboratories, which brings into play the question of how best to ensure long-term continuity of supply and the guarantee of decades-long provision and support, and how best to provide science grade devices, and subsystems, which are compliant with high standards of reproducibility, durability and traceability.

A superconducting roadmap must simultaneously address four areas: (i) the innovation and exploration of new device physics; (ii) the processing of science-grade devices in a production environment; (iii) packaging, EMI and stray light mitigation, and general environmental control; (iv) readout and subsystem control electronics. These themes are closely related, and are all needed in order to realise operational experiments. Ultimately, the experimenter is not interested in what is in the box, but requires reliable performance, ease of operation, and above all artefact-free behaviour. The creation of robust, reliable, reproducible behaviour should be an intrinsic part of any development programme.

Fundamentally, superconducting devices work on the basis of either breaking Cooper pairs, or on exploiting the long-range order of the coherent superconducting state, and therefore not breaking pairs, and this determines the limits of applicability in each case. All, however, are capable of exceeding the operational performance of "classical" devices by orders of magnitude, and it is usually second-order effects, such as two-level-systems in deposited and surface oxides, impurity and defect scattering, magnetic flux trapping, proximity effects between dissimilar films, and quasiparticle heating that limit behaviour. Nevertheless a large repertoire of materials and processing techniques exist, which can be used to isolate and enhance the mechanisms of interest. All high-performance devices are based on either elemental materials, such as Nb, Al, Mo, Ti, Hf, Ir, Ta, or, in cases where short quasiparticle lifetimes are needed, the nitrides NbN, TiN, NbTiN; the silicides are also of interest, but have not been exploited much to date. These materials are combined with normal metals, and patterned dielectrics such as Si, SiO, SiO_2, and SiN, to create large-scale integrated electronics, often incorporating hundreds of devices on a single wafer. Because most devices are tens of microns in size, large-scale integration is straightforward where needed.

The devices of central importance are: (i) Superconductor Insulator Superconductor (SIS) mixers, which are based on the photon assisted tunneling of quasiparticles across a dielectric barrier to achieve frequency conversion. They allow conversion gain, which is a non-classical process, and quantum-noise limited sensitivity. (ii) Hot Electron Bolometer (HEB) mixers that operate at frequencies above the superconducting energy gap, and achieve frequency conversion through a power mediated non-linearity. (iii) Cold Electron Bolometers (CEB) achieve detection through a pair breaking process, but prevent the build up of a hot population of quasiparticles, which would otherwise generate noise. They are extremely sensitive detectors, which have not yet been fully exploited. (iv) Transition Edge Sensors (TES) use the sharp normal-metal to superconducting transition in a thin film to detect radiation. Several modes of operation are possible. They can work from microwave to x-ray wavelengths, including gamma-ray spectroscopy, and are exceedingly popular in the most demanding astronomy applications. They are also being developed for massive particle detection, such as low-energy electron spectroscopy. (v) Kinetic Inductance Detectors (KID) are based on microwave thin-film distributed- or lumped-element resonators. When a photon is absorbed, quasiparticles are created, the inductance changes, and the resonant frequency shifts. A large array of KIDs can be fabricated, all connected to a single microwave readout line, and read out using digital electronics — essentially software-defined radio techniques. KIDs are also exceedingly well suited to a wide range of applications across the whole of the electromagnetic spectrum. (vi) In Superconducting Nanowire Single Photon Detectors (SNSPD) a long, very narrow ($\sim 100\,\text{nm}$) meandering superconducting wire forms a pixel. When a single optical or infrared photon is absorbed, it forms a "hot spot" where the line reverts to its normal state, and this is detected by a readout current. SNSPDs are exceedingly fast, and can be used for low-dark-count optical photon counting statistics. (vii) The Superconducting Quantum Interference Device (SQUID) is an ultra-low noise magnetic flux, or electrical current to voltage converter. A superconducting tunnel junction forms part of a small superconducting ring. The magnetic flux passing through the ring can only be changed in discrete quanta, and then the superconducting wave-function around the loop requires the voltage across the tunnel junction to change, which can be measured. SQUIDs are used for sensitive magnetic field measurement, and as ultra-low-noise current-to-voltage converters for reading out TESs. They are now also being used to realise quantum noise limited microwave parametric amplifiers. (viii) Josephson Junction Parametric Amplifiers (JJPA) are used routinely to achieve quantum noise limited microwave amplification. When the current through a superconducting tunnel junction changes, its inductance changes in a nonlinear way, and this can be used to achieve parametric amplification. (ix) Travelling Wave Parametric Amplifiers (TWPA) modulate the kinetic inductance of a long superconducting transmission line by applying a high-power $\sim 0\,\text{dBm}$ RF current. They have been developed to allow quantum noise limited amplification across wide instantaneous bandwidths and at millimetre wavelengths. They can also be used to generate a squeezed vacuum state, and so have numerous potential applications. Quantum noise limited amplification from $\sim 1\,\text{GHz}$ to $1\,\text{THz}$ is entirely feasible. (x) Although the above list concentrates on the devices themselves, SQUID-based superconducting electronics has been developed to a high degree of sophistication to achieve Frequency Domain Multiplexing (FDM) and Time Domain Multiplexing (TDM), which is essential when reading out very large imaging arrays.

It should be appreciated that superconducting electronics is a complete technology, not merely a collection of individual device types. All of the above devices use the same thin-film processing techniques and so can be combined on wafers to creates microcircuits having high degrees of functionality. The near-lossless nature of interconnecting traces ensures extremely wideband dispersionless behaviour of transmission lines, and in fact the kinetic inductance of the elemental superconductors is used extensively and routinely to produce a variety of miniaturised passive components, such as RF filters, hybrid couplers, and antennas to 1 THz.

Superconducting devices are a very promising approach for a direct determination of the neutrino mass scale via, for example, high resolution and high statistics measurements of low-energy electron capture and beta decay spectra. Although measuring the absolute neutrino mass is extremely challenging, having the aim to detect an extremely tiny spectral distortion in the end-point region of beta and electron capture spectra in an energy scale much less than 1 eV, R&D for quantum sensors is very well motivated given that we know that there is a lower bound for neutrino masses.

Overall the opportunities for creating a new generation of fundamental physics experiments based on superconducting electronics is substantial. Areas such as combining superconducting devices with micro-machined accelerometers and mechanical resonators is largely untouched, but entirely realistic. Combining superconducting devices with single and macroscopic spin systems is an area that is also starting to gain traction, and will inevitably lead to major innovations. It appears that the application of superconducting devices to massive particle detection has not been explored in-depth or indeed exploited, but there is a steady trickle of disconnected papers in the open literature going back for many years. We feel that this is also an area that needs assessing. Finally, to our knowledge there have been no published quantitative studies exploring the application of superconducting devices and electronics to traditional accelerator-based particle physics experiments, and this is clearly a subject of substantial importance.

5.3.3.1 Dark matter searches with 3D microwave cavities

The most sensitive instruments to explore the parameter space of the QCD axion are the haloscopes, which rely on axion to photon conversion within microwave cavities under multi-Tesla fields [Ch5-40]. Since the axion mass is à priori unknown, all possible mass ranges need to be explored, and experimental efforts are made to enhance the speed at which haloscopes can scan through parameter space at some fixed axion to photon coupling g_γ [Ch5-41]. The scan rate R depends on experimental parameters according to $R \propto B^4 V_{\text{eff}}^2 Q_0 / N_{\text{sys}}^2$, with B the magnetic field amplitude, V_{eff} the effective cavity volume and Q_0 its intrinsic quality factor. N_{sys} is the total system noise temperature. In spite of the promising fourth-power dependence, in most advanced haloscopes the magnetic field today does not exceed by more than 25-30% the value it had about 30 years ago. Cylindrical cavity volumes shrink for increasing frequencies[3], and in addition, their quality factors are limited by the anomalous skin effect to less than 10^4 at a few GHz frequency in normal conductors such as copper. Next generation experiments target the challenging 1-10 GHz frequency range by using SC technology to reach quality factors larger than copper by at least an order of magnitude, and by using Josephson junction parametric amplifiers (JJPAs) with total electronic noise very near its quantum limit [Ch5-42] to minimise total system noise, N_{sys}.

Accelerator cavities made of bulk niobium have been demonstrated with quality factors exceeding 10^{10} [Ch5-43]. While this technology is of interest for dark photon

[3] The detection volume goes down with at least the second power of frequency increase.

searches [Ch5-44] or so-called multi-mode axion searches [Ch5-45], it is not applicable to haloscopes as superconductivity in bulk Nb is lost at magnetic fields higher than its critical field (1 T). Metallic cavities coated with films of superconducting materials as YBCO, Nb_3Sn or Nb-Ti promise to largely exceed the performance of copper cavities. As for Nb_3Sn, experiments need to build expertise on different fabrication technologies including magnetron sputtering [Ch5-46] or vapour tin diffusion [Ch5-47] to obtain high quality films. Copper resonators coated with a Nb-Ti film produced by magnetron sputtering have already been obtained with a factor 10 improvement in Q_0 over copper cavities [Ch5-48]. A polygon-shaped cavity with inner walls covered by YBCO tape has been demonstrated with quality factors exceeding 3×10^5 at around 7 GHz, with no considerable degradation in the presence of magnetic fields up to 8 T [Ch5-49].

Even with cavity quality factors matching the axion linewidth, haloscopes relying on quantum limited amplifiers for readout of the cavity signal cannot probe the plausible parameter space within a reasonable amount of time. Squeezing, based on utilisation of two JJPAs, has proven effective in circumventing the standard quantum limit in linear amplification, and doubling the scan rate in the HAYSTAC receiver [Ch5-50], but a real breakthrough in this field could be achieved by switching to photon counting techniques. In the energy eigenbasis, a haloscope receiver would only be limited by dark counts and efficiency. Superconducting quantum circuits provide platforms for measuring microwave photons ($E \sim 10^{-5}$ eV). Recently, following impressive progress made in the fabrication of these devices for circuit QED applications, different schemes for single microwave photon detectors (SMPD) based on transmon qubits have been demonstrated [Ch5-51], [Ch5-52], [Ch5-53], [Ch5-54]. SMPDs are available both for photons confined in resonators and for itinerant (travelling) photons. The first type of detector has already been applied to dark photon searches, where intense magnetic fields are not required, demonstrating acceleration of the search by a factor 1300 compared to quantum-limited amplification [Ch5-55]. Strategies based on itinerant photon detectors appear instead more suited to haloscope searches, even though they are more challenging to develop with the required low dark count, efficiency and bandwidth. Dissipation engineering [Ch5-56], a new paradigm introduced in circuit QED, has allowed unprecedented low dark count rates in this latter type of device [Ch5-51], and might significantly impact future haloscope searches in the 5-15 GHz range.

5.3.4 Optomechanical technologies

Optomechanical detectors have achieved remarkable sensitivity over the past several decades, for example, allowing the detection of the feeble strain on the earth caused by gravitational waves from distant astro-physical sources [Ch5-27]. Optomechanical sensors are also well suited for precision searches of the dark sector, including dark matter and "fifth-force" searches, as well as for fundamental tests of quantum mechanics and gravitation. In this section we highlight several optomechanical sensing technologies that are ripe for development for these purposes.

Ultra-light scalar DM (ULDM): Optical-cavity-based detectors
Scalar ULDM fields can produce a tiny atomic strain and oscillation in the atomic Bohr

radius, by coupling to the fine structure constant and/or the mass of the electron. This signal would cause the dimensions of solid objects to fluctuate at the DM Compton frequency, and can be searched for by tracking the resonance frequency of optical cavities [Ch5-57]. Monolithic reference cavities used for optical frequency standards are a mature technology offering exquisite strain sensitivity at frequencies between 0.1-100 kHz, little explored in the search for ULDM. A differential readout scheme, which is immune to parasitic coupling to the probe laser frequency [Ch5-57] is used. Here the length of a cavity with a rigid spacer can be compared with the length of a cavity with suspended mirrors. The rigid cavity undergoes a measurable strain due to the ULDM while the suspended cavity is unable to respond rapidly enough to see the signal due to the suspension. To achieve the best sensitivity, development of substrate materials with ultra-low mechanical loss and coefficient of thermal expansion (CTE), "supermirror" technology with ppm-absorption dielectric coatings, and mounting and spacer geometries that eliminate coupling to transverse vibrational modes can be employed. Operation at cryogenic temperatures ($< 10\,\mathrm{K}$) enables further reduction of mechanical loss, minimising thermal noise and giving access to shot noise limited readout over a wide range of acoustic frequencies [Ch5-57], limited by the cavity response time. Squeezed light techniques similar to those used in GW observatories [Ch5-58] may further improve sensitivity above the kHz range.

Ultra-light DM: mechanical resonators

Bar detectors have also been proposed as detectors for ultra-light scalar DM in the audio-band [Ch5-59]. The resonant mechanical response of a material object can be harnessed to provide sensitivity to DM-induced strain at the resonance frequencies of a detector, and various readout mechanisms are possible, including optical and electronic. An analysis from data taken by the AURIGA bar detector [Ch5-60], [Ch5-59] provides the current best limit on scalar DM coupled to the electron mass at the frequency near 1 kHz. Vector "dark photon" DM may produce a weak force on atoms e.g. proportional to their neutron charge (B-L), oscillating at the DM Compton frequency. This force would deform an optical cavity or resonator made of two materials with differing (B-L), an effect which can be resonantly enhanced by utilising mechanical resonances at the DM Compton frequency [Ch5-61].

Gravitational wave and axion detection: levitated microspheres

Optically levitated dielectric sensors have been identified as a promising technique for GW searches spanning a wide frequency band from a few kHz to $\sim 300\,\mathrm{kHz}$ [Ch5-31]. A dielectric nano-particle suspended within an optical cavity will experience a force when a passing GW causes a time-varying strain of the physical length of the cavity. The particle will be displaced from the location of the trapping-light anti-node, resulting in a kick on the particle at the frequency of the GW. The sensitivity is limited by Brownian thermal noise and in ultra-high vacuum is quantum-limited by photon-recoil heating from discrete scattering events of individual trap laser photons [Ch5-62], rather than the displacement detection sensitivity. This results in improved sensitivity at higher frequency (unlike traditional interferometer style detectors, which decrease sensitivity at high-frequency due to laser shot noise) [Ch5-31]. The trapping frequency and mechanical resonance line-width are widely tunable based on the laser intensity and laser cooling parameters chosen. Particularly motivated sources in this frequency range are gravitationally bound states of QCD axions with decay constant near the grand unified theory (GUT) scale that form through black hole superradiance and annihilate to GWs. A 1-m meter prototype Michelson-interferometer configuration detector called the Levitated Sensor Detector (LSD) is under construction in the U.S., with a target sensitivity of better than $h \sim 10^{-19}/\sqrt{\text{Hz}}$ at 10 kHz and $h \sim 10^{-21}/\sqrt{\text{Hz}}$ at 100 kHz [Ch5-63]. Fibre-based approaches are being investigated to permit longer cavities without the need for expensive optics [Ch5-64]. A detailed analysis of the search reach for GWs produced by axions via the black hole superradiance process is provided in [Ch5-63].

Particle/extended-object DM: levitated microspheres

A recent search has been performed for composite DM particles scattering from an optically levitated nanogram mass, cooled to an effective temperature $\sim 200\,\mu$K [Ch5-65]. This search placed limits on the interaction strength between DM and neutrons, for DM masses in the range 1–10 TeV. These searches can probe models inaccessible to large WIMP detectors or to approaches aiming to detect single nuclear or electron recoils for DM particles that collectively scatter from multiple targets, and which transfer sufficiently small energy to normal matter that such recoils would not be visible in existing detectors [Ch5-65]. Since the scattering cross section scales as $\sim 1/q^4$, where q is the momentum transferred to the sphere, future searches with lower detection thresholds (or consisting of arrays of many spheres) could further improve sensitivity to these models by many orders of magnitude [Ch5-66]. The LSD is also sensitive to GWs from binary coalescence of sub-solar-mass primordial black holes and as-yet unexplored new physics in the high-frequency GW window (see Figure 5.2).

Particle/extended-object DM: Windchime experiment

The only interaction between SM particles and DM which has been observed is that due to gravity. If DM consists of heavy particles (at the GUT scale to the Planck scale or beyond), it is possible in principle to mechanically detect small signals induced by passing DM particles in a network of accelerometers [Ch5-67], [Ch5-66]. The Windchime collaboration [Ch5-67] aims to develop a proof-of-concept experiment. Apart from lower particle flux at higher masses, a challenge for these schemes is to achieve detection sensitivity below the standard quantum limit as well as low background noise.

Tests of "Fifth-forces" and quantum aspects of gravitation

Mechanical sensors including torsion balances and micro-oscillators have been used for tests of the equivalence principle [Ch5-68] and tests of the Newton inverse square law [Ch5-69], [Ch5-70], [Ch5-71], [Ch5-72] where several BSM theories suggest deviations [Ch5-73], [Ch5-74]. Understanding and eliminating systematic effects and backgrounds in these experiments, for example from surface patch potentials, is a primary challenge [Ch5-75]. Optically levitated particles are also well suited for such investigations [Ch5-76], providing 10^{-21} N force sensitivity [Ch5-77], [Ch5-78] and a different set of systematic effects and backgrounds [Ch5-79]. While probing physics at the Planck scale directly may not be possible in the near future, examining the role that gravity plays in uniquely quantum phenomena such as entanglement can provide insight into the quantum nature of gravity [Ch5-80], [Ch5-81], [Ch5-82]. Recent experimental progress has achieved quantum ground state cooling and quantum control in levitated optomechanical systems [Ch5-83], [Ch5-84]. Proposals have been presented for using macroscopic superpositions of massive nanoparticles to test whether the gravitational field can entangle the states of two masses [Ch5-85], [Ch5-86]. The state of embedded spins in the masses can be used as a witness to probe entanglement (e.g. [Ch5-86]). A significant consideration in these experiments is to avoid non-gravitational interactions due to surface forces, external fields, and other external environmental perturbations. Technologies such as low-vibration cryogenics and ultra-high vacuum are needed to realise the potential physics reach of these methods.

Additional optomechanical techniques
Other mechanical sensors have been employed in fifth force or ultra-light DM searches, including torsion balances [Ch5-87], [Ch5-88], micro-cantilevers [Ch5-71], and superfluid-helium based detectors for gravitational waves and dark matter [Ch5-89]. Fifth-force and equivalence-principle tests using torsion balances for example have produced wide-sweeping limits extending over orders of magnitude of DM Compton frequencies [Ch5-59], [Ch5-88]. Further advances in these technologies may also result in substantial improvements in a number of domains of physics.

5.3.5 Atoms, molecules, ions and atom-interferometric probes

Precision control and manipulation of atomic, molecular and ionic systems lies at the heart of many of the most striking advances in the highly dynamic field of quantum optics and atomic and molecular physics, with a very large international university community having developed over the last decades the commensurate tools and expertise. Extremely well calculable and measurable transitions, correlations and interactions provide extraordinary sensitivity to even the weakest perturbations, and makes these systems particularly well suited to precision tests of fundamental constants, to searches for unknown fields, very weak interactions or deviations from standard interactions.

Atoms, molecules and (possibly highly charged) ions in traps offer extraordinary sensitivity to dark matter-induced shifts or temporal variations of internal energy levels, allow tests of the equivalence principle, or allow searching for violations of fundamental symmetries (e.g. Lorentz- or CPT-invariance). Further areas of application are highly sensitive searches for variations of fundamental constants, tests of QED or searches for non-SM interactions (fifth forces) [Ch5-90], which can also be carried via Ramsey spectroscopy of gravitationally bound quantum states of ultra-cold neutrons [Ch5-91].

Diatomic molecules are the focus of several attempts to improve the limits on the EDM of the electron (ThO, HfF^+, RaF), with first exploration of the potential of polyatomic molecules to improve sensitivity even beyond those systems [Ch5-92]; these systems also provide a window into searches for hadronic T-violation or CP-violation in the nucleus (RaF, $RaOH^+$). Similarly, searches for a neutron EDM via the Ramsey technique probe BSM CP-violating interactions at scales up to 1300 TeV [Ch5-93], with the potential of a further order of magnitude in sensitivity.

To benefit from the potential of these systems, close ties between the AMO and the particle physics communities should be fostered, and technology R&D of mutual interest, e.g. development of VUV, XUV, and soft X-ray frequency combs and lasers to drive them for HCI spectroscopy, should be encouraged in an interdisciplinary manner.

Atom interferometry using macroscopic path lengths is a particularly dynamic and promising approach to search for low frequency (Hz) variations of interaction potentials that an ensemble of atoms is subject to. This opens a specific window (see Figure 5.2) for detection of slowly varying gravitational waves that several groups are working towards using clock atom interferometry based on single-photon transitions between long-lived atomic clock states (AION, MAGIS, MIGA, ZAIGA). The same devices are equally sensitive probes for the existence of a range of dark matter candidates: ultralight wave-like DM (mass $\leq 10^{-14}$ eV) (Figure 5.2), scalar- and vector-coupled DM candidates, or the presence of new interactions (short range 5-th force-like interactions). The sensitivity of individual systems can furthermore be greatly enhanced – in the near future – by combining them in local or global networks of individual atom interferometers focused on high precision fundamental physics. These should operate in tandem (similarly to networked GW detectors) and in collaboration with already existing networks in metrology institutions.

Finally, because of their macroscopic nature (meter-scale wavepacket separation), these systems are excellent probes for studies of decoherence, nonlinear interactions and more generally, of fundamental aspects of quantum mechanics. Long-distance entanglement of individual atomic systems holds further great potential for even greater sensitivity.

The technological challenges to reach the aimed-for sensitivities are numerous, and range from scaling up from table-top devices to the 100 m (ongoing), 1 km (in the development phase) and beyond scale (requiring inter alia appropriate vertical shaft infrastructure and access), to magnetic shielding (passive and possibly active) and implementing photon squeezing (to improve sensitivity), among many others.

While current systems are ground based, reaching ultimate sensitivity will require operating them in space, as proposed in the context of e.g. ESA Voyage 2050; achieving this on time scales of 20 years requires, in addition to the above, sustained R&D focusing on a single atomic species and aiming at high technical readiness level versions of complex and fragile laboratory experiments. Miniaturisation, ruggedisation, and extreme reliability of experimental equipment, as well as redundancy of components, standardised protocols and platforms, and significant cost reductions are all equally essential.

5.3.6 Metamaterials, low-dimensional materials, quantum materials

Materials play a crucial role in quantum sensing through their potential role as sensor but also through their function in transduction and interrogation [Ch5-94]. Materials studies are often characterised by their dimensionality. Bulk properties of materials in three dimensions (3D-materials) are engineered to provide well-defined two-level systems with long coherence times, for example, as we have seen with superconducting devices. Topological materials are being studied broadly given their interesting quantum properties that are determined by topology. Topological insulators, insulating in bulk and conducting at the surface, are quite persistent in the face of disruptions to their physical structures and given their interesting quantum properties, can become an important probe for testing fundamental quantum principles. Properties of topological materials can indicate the existence of Majorana, Weyl and Dirac fermions.

With the advent of advanced technologies, such as molecular beam epitaxy, materials can be engineered as two-dimensional systems of atomically thin layers. Many 2D-materials are under study, such as ultra-thin layers of superconductors, but also graphene, silicene, germanene, stanene, phosphorene, transition metal dichalcogenides (TMDs), black phosphorus, or all-inorganic perovskites, with properties that could lend themselves to act as sensor or detector. Graphene is characterised by high mobility and high responsivity to a broad range of wavelengths, from from the visible (532 nm) up to the mid-infrared ($\sim 10\,\mu$m), but also into the THz band, making this a promising material for measuring low-level THz photons, albeit at low operation speeds ($\mathcal{O}\,(\mathrm{Hz})$) [Ch5-95]. In Chapter 7 emphasis is placed on integration of front-end electronics in CMOS devices. Recently there has been progress on the integration of photonics with CMOS electronic circuits enabling on-chip optical interconnects. The integration of non-silicon electro-optical materials with silicon integrated circuits has been challenging. Graphene and related 2D-materials may provide for a pathway for opto-electronic integration combined with photodetection with speeds up to 80 GHz and extreme broadband photodetection for ultraviolet, visible, infrared and terahertz. In addition to detection of THz photons, 2D-materials may also play roles in more traditional environments, such as in the amplification stages of GEM detectors in HEP, or in photo-detection of UV photons, in the form of graphene quantum dots [Ch5-96]. Of particular relevance to the physics targets covered in this chapter are applications of graphene as a room-temperature bolometer for photons [Ch5-97], specifically graphene nanoelectromechanical systems to detect light via resonant sensing, whose resonant frequency can furthermore be tuned via targeted membrane loading with individual atoms, nanodots (or nanocrystals) or additional mono-layers.

One-dimensional materials are materials that have strong covalent bonds in one direction and weaker bonds in cross-plane directions and are often prepared as crystalline nanowires, that is, atomic chains. Within these chains, often quantum dots are embedded, a 0D-material with special quantum properties. Quantum dots have a tunable bandgap as a result of their size. When the size of a quantum dot approaches the size of the material's exciton Bohr radius, quantum confinement effects become prominent and electron energy levels must be treated as discrete energy levels. Quantum dots thus have an energy level spacing dependent on their size. Generally, the energy bandgap increases with a decrease in size of the quantum dot. The adjustable bandgap of quantum dots, nanodots or nanocrystals (e.g. perovskites) allows the construction of nanostructured materials that can provide significant improvements in the performance of, for example, ultra-rapid frequency-tuneable scintillator materials [Ch5-98].

While the sensor families discussed in this chapter often rely on properties that are inherent to the material being used (superconductivity, energy transitions in bound systems), quantum materials represent a step forward in that systems with specific quantum properties are engineered by fine-tuning these properties. Examples of such materials that rely on fabrication control at the atomic scale (and thus go beyond metamaterials) encompass atomic-layer thin surface coatings (control of the optical properties of a crystal), formation of artificial atoms in two-dimensional materials, or manipulations of trapped neutral systems to form macroscopic, extremely weakly bound Rydberg molecules, but equally topological quantum materials, van der Waals heterostructures based on atomically-thin 2D-crystals, spin torque materials, Moiré materials and many others [Ch5-99].

Materials with quantum mechanically tuneable electronic, magnetic or structural properties (which can furthermore be combined into heterostructures) hold great promise as their emergent properties are highly sensitive to environmental perturbations or transient phenomena, and can greatly amplify, via collective transitions, any interactions related to spin, charge or orbital states in response to external fields.

5.4 Observations and Prospects

Developments in the field of quantum sensing and other emerging technologies are taking place at a very rapid pace. Consequently, extrapolation beyond the next 15 years is fraught with risk. Nonetheless, a number of increasingly ambitious physics targets would clearly benefit from increased, dedicated R&D efforts over the next two decades. In Figure 5.1 the R&D needs for the presented families of quantum sensing approaches was summarised to achieve the science goals in the different categories of evolving physics targets. That representation maps the technologies onto physics targets for different time windows, with the colour code indicating the R&D needs. In Figure 5.3 a different representation is used where the impact of the proposed R&D programme is presented. The quantum and emerging technology categories are indicated again, but under each category the reach of the directed R&D for the different physics targets is quantified, indicating the timeframe within which this could be achieved. Increases in sensitivity or accessible range are highlighted in red.

This representation covers a very wide range of physics targets and technologies, starting from current state-of-the-art small-sized, local setups to networked ensembles to space-based detector systems to address the rapidly expanding explorable parameter space in DM searches, in searches for new interactions, probing fundamental symmetries, measuring the relic neutrino mass or even foundational aspects of quantum mechanics. Long-term prospects include transforming conceptual ideas for HEP detectors based on quantum sensing ideas into prototype or even functional HEP detectors, or even addressing completely novel fields, such as searches for relic neutrinos.

The promise of quantum-enhanced and fundamentally new sensors will have transformational impact with a dedicated R&D programme that is fully complementary, but equally impactful, to the traditional methods of exploration in particle physics.

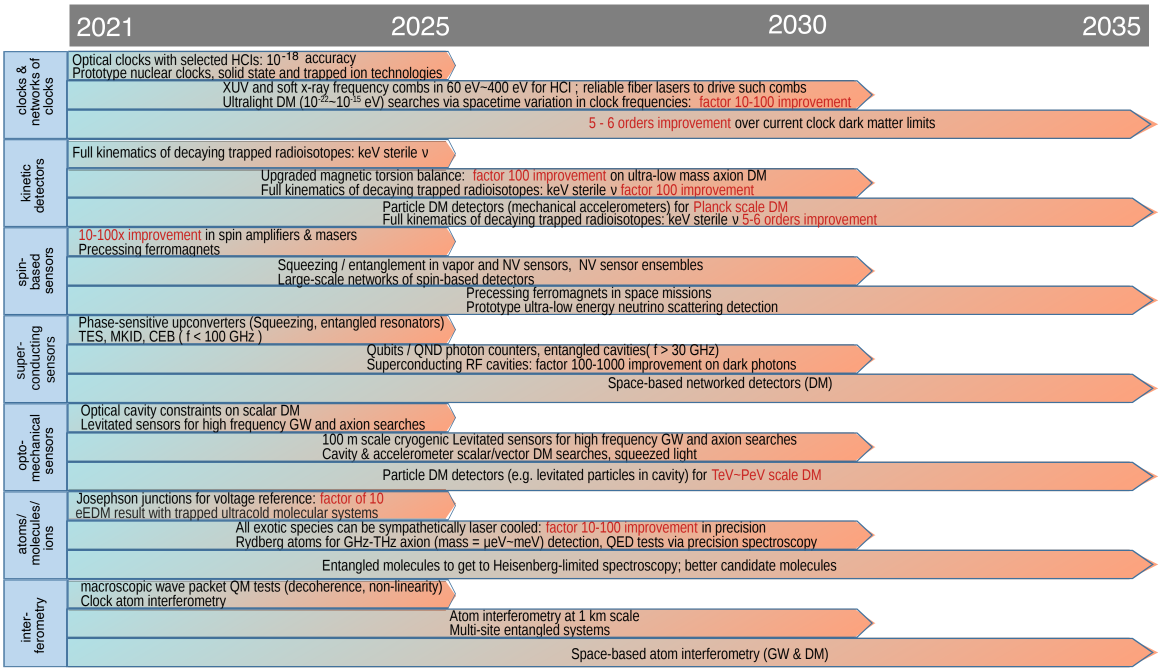

Figure 5.3: Prospective time line for selected developments with a range of quantum and emerging technologies; increases in sensitivity or accessible range are highlighted in red.

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Chapter 6

Calorimetry

6.1 Introduction

During the last decades, the role of calorimeters in High-Energy Physics (HEP) has become more and more important, and complex. Today's detectors are required to:

- Measure energy deposits with high accuracy and precision. Thanks to the statistical nature of showering process(es) and the high number of particles involved, the response is typically linear while the relative precision scales with the inverse square root of the energy;
- Provide highly selective trigger information, in particular in high-rate high-background environments. Calorimeters are in general based on fast processes and can easily provide triggering signals at high rate in correspondence to (high) local energy depositions;
- Provide information for particle identification and final-state identification (through the shower topology and through timing).

Past and present implementations are normally addressing two complementary sets of measurements: the identification and measurement of all energy deposits generated by primary electromagnetic (EM) particles ($e^{\pm}$ and γ-initiated showers), done with EM calorimeters, and the measurement of hadron-initiated showers which are observed in combined systems of an EM calorimeter in the front and a hadronic calorimeter behind.

In addition EM calorimeters are separated into:

- Sampling calorimeters, that allow the realisation of fast and highly granular devices at affordable costs. They can provide an energy resolution of $\mathcal{O}(10\%)/\sqrt{E}$;
- Homogeneous calorimeters, that often have higher costs and a lower granularity (and often a slower response) but a much better energy resolution, $\mathcal{O}(1-3\%)/\sqrt{E}$.

On the other hand, hadronic showers develop both a hadronic component (due to nuclear interacting particles) and an EM one (due to the EM decay of neutral mesons such as π^0 and η) which produce, in almost all detector implementations, a different signal response ($e/h \neq 1$), due to “invisible” contributions to the hadronic energy deposition, such as nuclear excitation. In this case, the calorimeter is said to be “non-compensating”, and the hadronic energy measurements are compromised by the fluctuations in the EM fraction (f_{EM}) and ultimately limited by the fluctuations of the invisible component. Nonetheless, strategies for response equalisation (i.e. compensation) exist and, indeed, hadron calorimeters can be divided into:

- Non-compensating calorimeters, offering higher degrees of freedom to optimise cost or 3D-segmentation;
- Compensating calorimeters, that require a fixed sampling fraction and specific choices of absorber and active medium, but have a much better energy resolution ($\sim 30\%/\sqrt{E}$ compared to $\sim 45 - 60\%/\sqrt{E}$ or worse for non-compensating calorimeters).

For many years, there have been two main lines of research to tackle the problem of optimising the energy resolution for hadronic jets and achieving the best possible overall energy measurement in collision events. The first exploits Particle Flow (PF) Algorithms, employing highly granular systems to disentangle neutral- and (dominating) charged-particle contributions and using the main tracker to precisely measure the latter ones. The highly granular calorimeter information can be used in addition to improve the hadronic energy resolution by equalising the response to EM and hadronic shower components in the reconstruction (“software compensation”). The second approach (Dual Readout, DR) is based on the measurement of all the energy deposits through two different processes, usually scintillation and Čerenkov light emission, the former produced by all ionising particles, the latter only by relativistic charged particles (i.e. mostly $e^{\pm}$ from the EM shower component). After a calibration with electrons, the combination of the two signals allows an event-by-event estimate of f_{EM}, strongly improving the hadron-shower energy measurements. In all cases, new developments target highly granular 5D-(3D-space, E, t)-detectors where timing plays an important role as well.

6.2 Main drivers from the facilities

Broadly speaking the near- and mid-term R&D programme has to meet the needs of the HL-LHC experiments, of the calorimeters for future e^+e^- Higgs-EW-top factories and for an electron-ion collider. For the longer term, strategic R&D to address requirements of muon and hadron colliders, e.g. radiation tolerance significantly beyond today’s standards, must be pursued. This leads to the target definitions and associated required progress in technology that are summarised in Figure 6.1 and described further below.

DRDT 6.1 - Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution.
Priority developments are geared towards the successful completion of R&D programmes for the variety of HL-LHC detector upgrades aiming at much finer spatial granularity

and high accuracy timing while still delivering excellent energy resolution in high radiation environments. LHCb plans an upgrade of the inner part of their EM calorimeter for LHC LS4. The upgrade aims at a time resolution of 50 ps and an EM energy resolution of around $10\%/\sqrt{\mathrm{E[GeV]}} \oplus 1\%$. LHCb shares R&D goals with the fixed target experiment KLEVER [Ch6-1] in terms of sustainable rates and time resolution. An excellent EM energy resolution of a few % over $\sqrt{E}$ is targeted for an EIC Detector, while the ALICE FOCAL (discussed below) primarily targets ultra-high granularity.

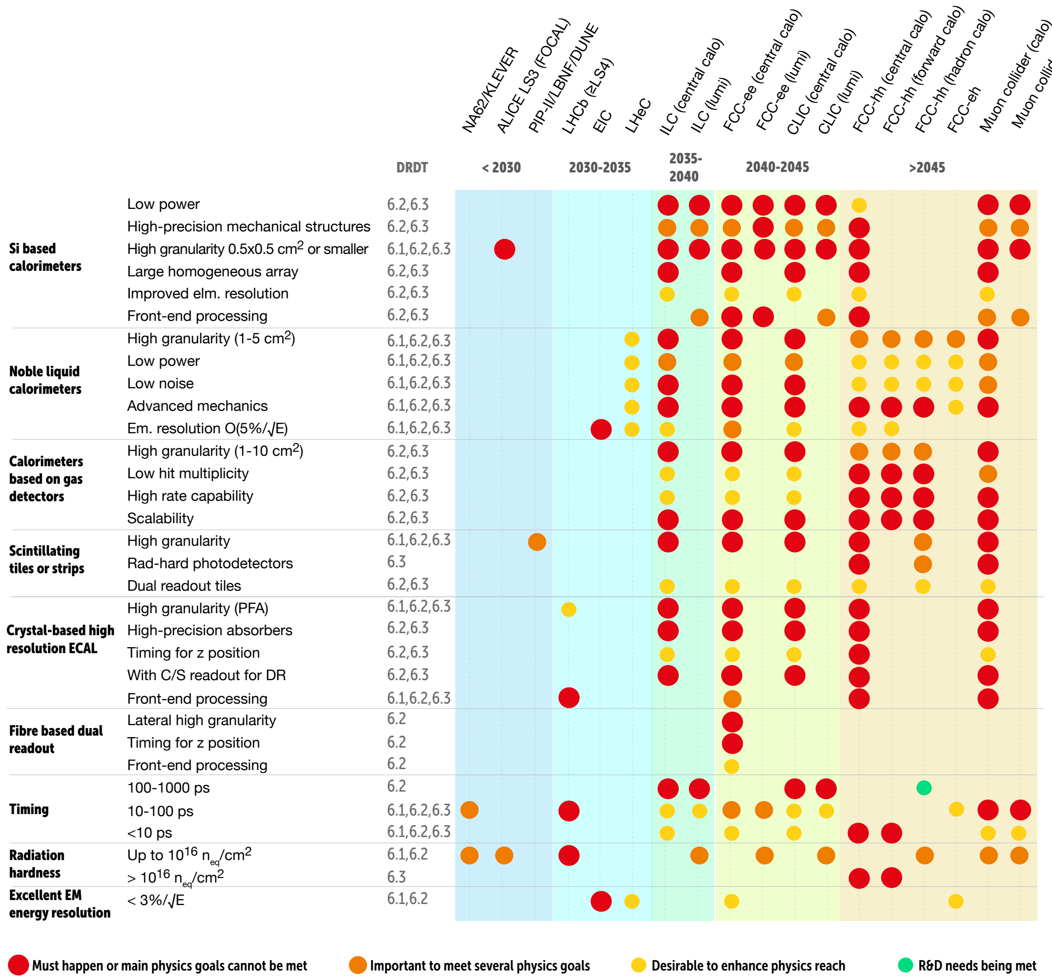

Figure 6.1: Schematic timeline of categories of experiments employing calorimetry together with DRDTs and R&D tasks. The colour coding is linked not to the intensity of the required effort but to the potential impact on the physics programme of the experiment: Must happen or main physics goals cannot be met (red, largest dot); Important to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); No further R&D required or not applicable (blank).

DRDT 6.2 - Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods.
This theme principally addresses calorimeters at future Higgs-EW-Top factories, but a granular EM calorimeter is also an interesting option for the near detector of DUNE. During LS3 ALICE envisages the installation of the FOCAL detector, which introduces CMOS sensors to calorimetry. Typically for a given Higgs-EW-Top factory one aims at a jet-energy resolution of 3%–4% over the entire centre-of-mass range, through PF methods. Developments are focused on combining information from the calorimeter with other detector systems. Capitalising on the experience at the HL-LHC, the objective is to achieve 3D-pixelated calorimetry to measure each particle individually and use of precise tracking information for charged particles. This goal can be achieved using silicon sensors (Chapter 3) or SiPMs (Chapter 4) coupled to scintillator tiles or strips as active medium, as well as gaseous detectors (Chapter 1) in the case of hadronic calorimeters. Liquified noble gas (Chapter 2) may often represent a performant and cost-effective alternative.
Further developments are to be pursued to exploit the different signals produced by the electromagnetic and non-electromagnetic components of hadron showers in a Dual Readout system. Eventually, combining both approaches might lead to an optimised jet energy resolution; for example, using finely-segmented crystals with excellent EM energy resolution to complement a hadronic DR section. In all cases the inclusion of timing at the 10 ps level can significantly improve the quality of the event reconstruction.
A notable difference between linear and circular colliders is the beam structure, with the former allowing for a pulsed operation of the front-end electronics, leading to reduced services (e.g. cooling, powering) and allowing a more compact detector design when compared to that possible at circular machines with continuous operation.

DRDT 6.3 - Develop calorimeters for extreme radiation, rate and pile-up environments.
Long-term R&D is to start for calorimetry systems at a future hadron collider to address up to two orders of magnitude more severe requirements than at the HL-LHC, related to unprecedented radiation hardness, pattern recognition in the presence of severe pile-up and the associated data handling. Radiation levels at a Muon Collider are between that of HL-LHC and the FCC-hh. The Muon Collider also has challenges in pattern recognition and the need for techniques to reduce beam induced backgrounds.

The R&D timelines for the above themes can be found at Figure 11.1 with attached explanation. R&D for calorimetry has a particularly long lead-time due to the duration of the stage for experiment specific final prototyping, procurement, production, assembly, commissioning and installation. For the facilities listed in Figure 3 and Figure 4 in the Introduction, the most demanding requirements associated with DRDT 6.1 include those for next decade further upgrades of ALICE and LHCb. Particle Flow based on high granularity calorimetry (DRDT 6.2) is particularly important for future e^+e^- Higgs-EW-top factories and an option to be seriously considered for the electron-ion-colliders. Beyond the HL-LHC upgrades this decade, the requirement of extreme radiation-hardness and pile-up rejection (DRDT 6.3) becomes critical for the FCC-hh in particular.

6.3 Key technologies

6.3.1 Silicon-based calorimeters

Silicon offers several attractive features for calorimeters in HEP experiments, in particular for highly-granular EM sampling calorimeters. Silicon sensors are highly segmentable, show a robust and stable performance over time and over a wide range of environmental parameters, and are tolerant to high levels of radiation. Silicon has a relatively high density, resulting in suitable sampling fractions for analog energy-based calorimetric measurements also when using relatively thin sensor layers, and enables very compact systems with good shower separation in combination with high-density absorbers such as tungsten. There are two general classes of applications of silicon-based calorimeters in HEP:

Smaller systems with specific applications
Examples include: beam/luminosity calorimeters; dedicated far-forward calorimeters for photon tagging and reconstruction [Ch6-2], [Ch6-3]; and compact calorimeters in satellite borne experiments [Ch6-4].

Main calorimeter systems in collider detectors
Developments of highly-granular calorimeters using Si/W as the main EM calorimeters for collider experiments were pioneered by the CALICE collaboration [Ch6-5], achieving excellent two-particle separation in combination with a highly granular hadron calorimeter [Ch6-6], and an EM energy resolution of approximately $16.5\%/\sqrt{E[GeV]} \oplus 1\%$ [Ch6-7]. A first large-scale highly granular silicon-based calorimeter system, the High Granularity Calorimeter (HGCAL) [Ch6-8] will be implemented for the Phase II upgrade of the CMS endcap calorimeters, with a total silicon area of approximately $600\,\mathrm{m}^2$. ALICE-FOCAL and the ALICE pre-shower detector would be first applications of CMOS based sensors for calorimetry. Systems with sensor areas of up to 2500 m^2 and 10^8 channels and more are being planned for the main calorimeters (barrel and endcap) of detectors at Higgs-EW-Top factories. Spin-off applications of the technology developments for towards these large systems, such as the planned LUXE experiment [Ch6-9] at DESY with a scale of typical prototypes (i.e. silicon area of approximately $1\,\mathrm{m}^2$), will also directly benefit from the further R&D described in this section.

6.3.1.1 Challenges and requirements for future projects

The applications introduced above have overlapping, but also specific technological requirements and challenges, which fall into two broad categories: one related to the system aspects; the other to sensor technology.

On the system side, large Si-based calorimeter systems at colliders require fully embedded electronics with high dynamic range, low noise, low power and maximum compactness, and suitable interconnect technologies between sensors and electronics PCBs, which also address edge effects that arise in particular in circular endcap geometries. An integrated approach for the mechanical and electronic design, as well as for cooling and services is crucial, as are scalability, automation in assembly, and documentation. The large number of channels ($\mathcal{O}(10^8)$ or more), and the large sensor surfaces impose new challenges in operation and calibration, and result in the need for redundancy and complex monitoring.

Smaller Si-based calorimeters typically do not have the same system-level requirements, but target specific applications that require maximum compactness with the smallest possible Molière radius, sensors and front-end systems capable of handling occupancies close to 100%, and extreme mechanical precision. This latter can be a few $10\,\mu$m for luminosity monitoring at linear e^+e^- colliders, and as low as $1\,\mu$m for circular e^+e^- colliders targeting high-precision Z-pole programmes with 10^{12} recorded Z-bosons.

On the sensor side, small dead zones, in particular at the sensor edges, are important for the overall calorimetric performance. Precision timing will gain in importance as requirements increase and the performance in this area improves, as discussed in more detail in Section 6.3.5. Large signals, either through thicker sensors, or via physical gain built-in to the sensor (like e.g. LGADs), can improve the signal-to-noise ratio (SNR) and, consequently, energy and time resolution. Small pads or pixels improve the spatial granularity of the calorimeter systems and can also improve SNR at the expense of more electronic channels. Radiation tolerance significantly beyond the current state of the art becomes relevant for future hadron colliders. Here, sensitivity to minimum-ionising particles also at the end of life of the system is important for a robust calibration scheme. Calorimeter applications are in general significantly more sensitive to sensor cost than tracking detectors, since the required sensor area is typically 30 times larger, up to $2500\,\text{m}^2$ or beyond, for full systems at future electron-positron colliders.

6.3.1.2 Main R&D Directions

Silicon based calorimeters

R&D Need	Main direction	Target facilities	Related DRDT
Reduction of passive space	Larger wafers, smaller guardrings, suited mechanical structures	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3
Increase of signal	Thicker Si sensors, active gain	ILC, FCC-ee, CLIC, Muon Collider	6.2, 6.3
New Techologies	CMOS based sensors, digital SiPMs	HL-LHC, ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.1, 6.2, 6.3
New Materials	GaAs for beam calorimeters, improved radiation hardness	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3

Table 6.1: Overview of main R&D needs and corresponding directions of development for silicon-based calorimeters connected to facilities and DRDTs.

From the requirements outlined above, a few main R&D directions arise for silicon-based calorimeters.

- The *reduction of dead space*, through larger wafers and novel guard-ring designs. For full exploitation novel precise mechanical structures play a key role;

- *Increase of signal*, via increased sensor thickness or physical gain;
- *Control of power consumption:* The high channel density of silicon based calorimeters calls for power economical solutions for the front-end electronics. Power pulsed operation is one approach. For continuous powering a power consumption well below 1 mW/cm^2 should be targeted. Therefore electronics for silicon based calorimeters are particularly challenging use cases for the goals formulated in DRDT 7.1 (see Chapter 7);
- The use of *new technologies*, such as CMOS-based monolithic active pixels sensors. Calorimeters have to cover large areas. This requires large Si wafers and/or reliable stitching techniques. Both are among R&D topics described in Chapter 3 but would need to be adapted to calorimeter needs (coarser granularity than for trackers, miniaturisation of services, signal transport over larger distances). 3D-integration of sensors may lead to reduction of dead space in addition to the means described above. New technologies may have increased intelligence for digital EM calorimeters and possible fully-digital approaches with internal gain for faster response inspired by d-SiPMs, see Section 4.4.3. For low-occupancy applications, additional position sensitivity within pads may yield lower channel counts and reduced power in the electronics;
- *New materials*, which offer higher density and suitable band-gaps may offer performance benefits for specialised applications, as already seen for GaAs in luminosity detectors. Further improved radiation tolerance will become relevant in the more distant future.

These R&D directions are put into the context of future facilities and overarching DRDTs in Table 6.1.

6.3.2 Calorimetry Based on Liquified Noble Gases

Calorimetry based on liquified noble gases was successfully used in many high-energy experiments (e.g. NA48, SLD, H1, D0, ATLAS) due to its energy resolution (a stochastic term of $10\,\%/\sqrt{E}$ can be easily achieved), linearity, stability, uniformity, timing resolution ($\mathcal{O}(100\,\mathrm{ps})$ for highly-energetic showers has been achieved) and radiation tolerance. While the latter is only a concern for future hadron colliders, all other properties are necessary for all future colliders. The granularity, can be adjusted to the needs, with readout cell sizes of $x_\Theta \times x_\phi \times x_{\mathrm{depth}}$ of $5 \times 10 \times 20\,\mathrm{mm}^3$ achievable by carefully designing the readout electrodes. Liquid argon is the most common medium (e.g. ATLAS LAr [Ch6-10]) and a similar design, using either argon or krypton, has been proposed for the FCC-hh baseline detector [Ch6-11] and a design is underway for FCC-ee. The R&D programme will combine the excellent EM energy resolution of noble-liquid based calorimeters with the benefits of high readout granularity, facilitating particle-flow with 4D- and 5D- shower imaging.

6.3.2.1 Challenges and requirements for future projects

The challenges and requirements for calorimeters differ substantially between e^+e^- Higgs-EW-top factories and future hadron colliders. However, there are some commonalities:

- High readout granularity: For pile-up mitigation and particle-flow reconstruction, including techniques using 4D- or 5D-shower images;
- Timing information: Timing precision of order $\mathcal{O}(1\,\text{ns})$ will be crucial for triggering and attributing the energy deposits to the correct bunch crossing. A timing resolution of $\mathcal{O}(30\,\text{ps})$ will be essential for pile-up rejection in future hadron colliders;
- Minimisation of passive material in front of the calorimeter: Cryostats, mechanical support structures and services need to be minimised in terms of material. Heavy calorimeters (100's of tonnes) need to be supported by these "low-material" cryostats.

Specific challenges for the different major collider projects are summarised here:

- Future e^+e^- Higgs-EW-Top factories: The required EM energy resolution (sampling term of 5 to $8\,\%/\sqrt{E}$) and photon-energy measurement down to $\sim 300\,\text{MeV}$ call for low-material-budget cryostats and extremely low-noise readout electronics. Excellent jet-energy resolution is only achievable by particle-flow algorithms relying on high-granularity measurements. Extremely low noise levels, to enable detection of single MIPs in each of the cells, require a careful optimisation of the readout electrodes and the readout electronics. For timing precision the situation is much less clear, and a final requirement will have to take into account the price of better timing information in terms of power and readout noise; but some performance improvement could be expected by completing the 4D-imaging of the particle showers with its time development;
- Future 100 TeV Hadron Colliders: An expected 1 MeV neutron equivalent fluence and total integrated dose in the central calorimeters (forward calorimeters) of $4\times10^{15}\,\text{n}_{\text{eq}}\,\text{cm}^{-2}$ ($5\times10^{18}\,\text{n}_{\text{eq}}\,\text{cm}^{-2}$) and 4 MGy (5 GGy), respectively (for $30\,\text{ab}^{-1}$), will require a careful selection and radiation testing of all materials used. The huge number of up to 1000 simultaneous collisions per bunch crossing will require an efficient pile-up rejection, which will have to rely on precision timing $\mathcal{O}(30\,\text{ps})$, highly-granular calorimeter information and an efficient combination with the tracker measurements.

6.3.2.2 Main R&D Directions

The above listed challenges and requirements lead to the following R&D directions:

- *R&D to achieve high granularity readout*, comprising R&D on low-noise and low cross-talk, finely segmented readout electrodes and dense signal feedthroughs. This requires multi-layer PCB readout electrodes with embedded traces sandwiched between ground layers to prevent cross-talk. These ground layers increase the capacitance of the readout cells and therefore impact the readout noise;

- *R&D on warm (i.e. outside the cryostat) and cold (i.e. inside the cryostat) readout electronics* minimising noise. Cold electronics would improve considerably the signal-over-noise ratio. It faces however technological challenges such as more involved maintenance and potential heat dissipation inside the noble liquid. The R&D carried out for DUNE (see Chapter 2) may give valuable input on this matter. In case of warm electronics, the high granularity of future calorimeters implies an increased signal density at the feedthroughs of up to 20-50 signals/cm^2. This is a factor about five to ten more than in the ATLAS experiment;
- *R&D on low material-budget cryostats*, see also Section 8.3.5. For composite-material cryostats, vacuum-tight junctions between the cryostat and metallic flanges (e.g. for feedthroughs) for warm and cryogenic temperatures will be required;
- *Performance optimisation* addressing the sampling frequency, the sampling fraction, the choice of the active medium (LAr or LKr), the absorber material and the overall geometry;
- *R&D on the limits of timing precision* aiming at $\mathcal{O}(30\,\text{ps})$ for larger energy deposits, as required for the application in future hadron colliders. The precision for timing of MIPs must also be optimised.

In addition it is important to study whether using the scintillation light produced in the noble liquid, following the R&D described in Chapter 2, could be used to improve on any of the above parameters.

These R&D needs are put into the context of future facilities and overarching DRDTs in Table 6.2.

Calorimeters based on Liquified Noble Gases

R&D Need	**Main direction**	**Target facilities**	**Related DRDT**
High granularity for PFA and 4D-imaging	Finely segmented readout electrodes, dense signal feedthroughs	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3
Low noise and low power electronics	Electronics at room temperature or in cryogenic environment minimising the read-out noise	DUNE, ILC, FCC-ee, CLIC, Muon Collider	6.1, 6.2, 6.3
Low material budget	Thin cryostats to maximise calorimeter performance using composite materials or Al honeycomb	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3
Optimisation of calorimeter performance	Choice of sensitive material (e.g. LAr or LKr), absorber material, geometry optimisation, detection and exploitation of scintillation light	DUNE, ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.1, 6.2, 6.3
Timing precision	Timing precision of $\mathcal{O}(30\,\text{ps})$ will be extremely beneficial for pileup rejection	FCC-hh, Muon Collider	6.3

Table 6.2: Overview of main R&D needs and corresponding directions of development for calorimeters based on Liquified Noble Gases connected to facilities and DRDTs.

6.3.3 Calorimetry Based on Gaseous Detectors

Gas detectors as active elements have been proposed mainly for future hadronic calorimeters but could also be options for EM calorimeters (see Chapter1). While the intrinsically-low sampling fraction results in rather modest energy resolution, gas detectors offer some attractive features: adaptability of readout pad sizes (from $1\,\mathrm{cm}^2$ to $10\,\mathrm{cm}^2$) and sampling frequency; high efficiency for single MIPs; excellent spatial resolution of 50 to $100\,\mu$m; and applicability to large cost-effective calorimeter systems. This is especially true for e^+e^- Higgs-EW-top factories with benign radiation environments, modest particle rates and relatively-low particle multiplicity, but where excellent two-jet invariant-mass resolution is needed to classify all relevant final states. Gas detectors are also an interesting option for pre-samplers and tail catchers. Timing on the $\mathcal{O}(5\,\mathrm{ns})$ level can be easily achieved and some configurations can be optimised for $< 100\,\mathrm{ps}$. Still, their integration in a calorimeter would require specific studies. While at e^+e^- Higgs-EW-top factories timing resolution of $\mathcal{O}(10\,\mathrm{ps})$ might be used to improve shower reconstruction through 5D imaging, it is mandatory for pile-up rejection in future 100 TeV hadron colliders.

Calorimeters based on Resistive Plate Chambers (RPCs) or MicroPattern Gas Detectors (MPGDs) have recently been studied by the CALICE collaboration [Ch6-12]. Two full hadronic prototypes using single-gap RPCs have been built and tested in particle beams: one digital HCAL with Fe and W absorber (38 +14 layers $1\,\mathrm{m}^2$) and a semi-digital HCAL with Fe absorber (48 layers $1\,\mathrm{m}^2$). Several layers of Micromegas and prototypes of GEM and of resistive plate WELL detectors have been built and tested. The SCREAM project [Ch6-13] is studying sampling calorimeters with resistive anode MPGDs.

6.3.3.1 R&D needs for Gaseous Calorimeters

While R&D on gas detectors is generally covered in Chapter 1, specific challenges are listed here related to their use in calorimeters for future collider projects.

- Scalability of the technology and the production of large-area detectors with sufficient uniformity and response stability. PCBs of several m^2 with per-cent level flatness are beyond today's industry standards, calling for a close collaboration with industry;
- For future hadron colliders the rate capability has to be improved. R&D on semi-conductive glass RPCs is one way to improve on this parameter;
- Clever solutions to avoid double counting on cell edges have to be developed;
- Dedicated R&D targeted to achieving the required timing precision for particular applications (e^+e^- or hadron collider).

These R&D needs are put into the context of future facilities and overarching DRDTs in Table 6.3.

Calorimeters based on Gaseous Readout

R&D Need	Main direction	Target facilities	Related DRDT
Scalability of technology	Large area PCBs with robust interconnection, large scale precise absorber structures	ILC, FCC-ee, CLIC, FCC-hh	6.2, 6.3
Rate capability	Semi-conductive Glass RPC	FCC-hh	6.3
Control of pad multiplicity	Avoid/reduce double counting on cell edges	ILC, FCC-ee, CLIC, FCC-hh	6.2, 6.3

Table 6.3: Overview of main R&D needs and corresponding directions of development for calorimeters based on gaseous readout connected to facilities and DRDTs.

6.3.4 Calorimeters with light-based readout

6.3.4.1 State-of-the-art

Light-based-readout calorimeters exploit the properties of light-transparent media to emit light either when excited by ionising radiation (scintillators) and/or when crossed by fast charged particles (Čerenkov radiators). The amount of emitted light correlates with the energy absorbed by the medium. The readout is light-based: a photosensitive device is either directly coupled to the medium or through wavelength-shifting (WLS) fibres. Classical readout options exploit vacuum photomultiplier tubes, while advanced configurations – permitting compact designs and high segmentation – include avalanche photodiodes (APDs) and silicon photomultipliers (SiPMs). Light-based-readout calorimeters are well established, with a long record of successful applications in many experiments. Crystals, plastic scintillators and light-emitting fibres are excellent candidates for future calorimeters. These active media can be adopted in compact designs for HEP collider experiments, but also for specific needs of low-energy and fixed target experiments.

High-resolution measurements of photons and electrons down to small particle energies call for crystal-based calorimeters (e.g. L3, Babar, Belle, CMS ECAL, etc.). When the requirements on the EM energy resolution are less stringent, sampling EM calorimeters, consisting of an active medium and a passive absorber (e.g. Pb, Cu, W), are often chosen for cost considerations. Popular solutions include lead with scintillating fibres ("SPACAL"), sandwiches with WLS fibres crossing through the active (and passive) material ("Shashlik"), or tiles with local readout of the light. The actual sampling fraction depends on performance needs, integration and radiation constraints. Both, crystal-based (e.g. LHCb R&D) and plastic-tile options (e.g. DUNE Near Detector R&D, CALICE ScECAL R&D) are under study.

Plastic scintillators (tiles or strips), allowing a cost-effective coverage over large areas, are particularly well suited for hadron sampling calorimeters (e.g., ATLAS TileCal and CMS HCAL). For ultimate precision in PF reconstruction of the jet energy, fine segmentation is paramount, in both, the EM and the hadronic calorimeter compartments (e.g. CMS HGCAL, CALICE AHCAL and ScECAL R&D). Dual readout (DR) of scintillation and Čerenkov light provides a complementary approach for jet-energy precision measurements. Fibre-based calorimeters are the baseline candidate for DR energy reconstruction (DREAM/RD52) in highly granular 4D-detectors [Ch6-14]. An integrally active DR calorimeter is currently tested for the REDTOP/ADRIANO proposal [Ch6-15]. Compact systems combining PF (segmentation in space and potentially in time) and DR (multiple readout) may compound the benefits of either reconstruction method and have a great potential interest for future applications [Ch6-16], [Ch6-17].

6.3.4.2 Challenges and requirements for future projects

Precision EW measurements at future e^+e^- factories require two-jet invariant-mass resolutions of about 3% at the Z-, W-, and Higgs boson mass values for efficient identification of the final state. An EM compartment with enhanced performance ($< 3\%/\sqrt{E}$) would provide access to the reconstruction of exclusive states for precision tests in flavour physics. To match these requirements with light-based-readout calorimeters, several challenges arise related to system aspects, to the validation of the conceptual designs, and to the sensor technology, with significant differences between pure PF and pure DR calorimeter systems. At $\mu^+\mu^-$ and hadron colliders, the performance goals are similar, while beam background and the radiation levels impose further requirements on the time response and radiation tolerance of the system.

At system level, PF calorimeters with fine 3D-segmentation require a significant integration effort with embedded photon detectors and readout electronics with high dynamic range, low noise, and low power. The routing of signals, services and cooling should be compliant with a hermetic design. Complex thermal management, possibly including options for local cooling and in-situ annealing of the photon detectors (e.g. with thermoelectric coolers/heaters), is relevant for future hadron colliders. In DR calorimeters, the complexity of the integration is moved to the back of the calorimeter where the optical fibres exit. Options for longitudinal segmentation are presently focused on timing measurements. Both systems share the need for precision machining of absorbers. The optimisation of a high-performance EM calorimeter compliant with PF and/or DR reconstruction is another challenge. In PF systems, a (crystal-based) EM calorimeter with a high-sampling fraction should be finely longitudinally segmented. In DR systems, crystals with an appropriate spectral difference of the Čerenkov and scintillation light emission are required. Typical EM calorimeters consisting of homogeneous crystal blocks cannot detect the event-by-event fluctuations between the EM and the strong interaction components of hadron showers and have e/h ratios that spoil the hadron energy resolution.

Photodetectors with high photoelectron efficiency and a broad range of spectral responses are needed, to match the emission spectra of a variety of scintillators and Čerenkov materials. Response linearity, B-field immunity, compact devices, and excellent timing are crucial. Radiation hardness significantly beyond the current state of the art is particularly relevant for future hadron colliders. These requirements are common across the different light-based readout calorimeters and are typically similar, if not less stringent, to those for application in particle identification systems.

Challenges in the choice and development of the active media are different for crystals, plastic scintillators, and fibres, but fall into three main categories: the search for novel materials; the optimisation of time measurements; the identification of radiation-tolerant materials or configurations for application at future hadron colliders.

6.3.4.3 Main R&D directions

Development and optimisation of the *photon detectors* is a field of intensive R&D. Close collaboration with industrial partners yielded SiPMs with spectral responses covering a wide range of wavelengths with high quantum efficiency. Further evolution, such as digital SiPMs, appears desirable. Novel SiPM materials, such as high band-gaps semiconductor, hold the promise of higher radiation tolerance. More details about the main R&D directions for photon detectors are covered in the Section 4.4.3.

New material technologies
Novel techniques for crystal growth have broadened the range of potential configurations for crystal-based calorimeters, including crystal-fibre EM calorimeters and multiple-readout calorimeters [Ch6-18], [Ch6-19], [Ch6-20]. A SPACAL calorimeter, using co-doped garnet crystal fibres (GAGG, YAG, GYAGG), is proposed for the upgrade of the LHCb ECAL [Ch6-21], for improved energy resolution, shower timing with ten ps precision, and appropriate radiation hardness. Further improvements in radiation hardness will become relevant for future hadron colliders. Heavy scintillating glasses such as $DSB : Ce^{3+}$ are investigated as a cost effective alternative to e.g. the common $PbWO_4$ crystals [Ch6-22], [Ch6-23]. Beyond, new plastic scintillators will be needed to improve radiation hardness and/or for use in multiple-readout options with Čerenkov and scintillation emission. The exploration of 3D-printing technologies in the production of scintillators [Ch6-24], as well as for mass production of precision absorbers in collaboration with industrial partners are promising R&D lines.

Timing in event or shower reconstruction
The use of timing in event or shower reconstruction is emerging as an interesting new field, with promising potential benefits for the jet-energy resolution. While some precision timing with crystal-based calorimeters has been demonstrated, specific R&D is needed with both, plastic and crystal scintillators for further appraisal of the critical design parameters (e.g. light output, time constants, discrimination threshold, granularity of the time information) for a calorimeter offering intrinsic fast-timing capabilities. Promising new technologies in this area include Nanostructured-Organo-silicon-Luminophores (NOLs) (see Section 4.4.5) due to the innovative transmission of the scintillation light to the wavelength shifting fibre. Chapter 5 also introduces quantum dots. This approach yields a higher transparency since the embedded nanomaterial has a different band structure to that of its surroundings.

These R&D directions are put into the context of future facilities and overarching DRDTs in Table 6.4.

6.3.5 Precision timing in calorimetry

The main use of sub-ns timing precision in calorimeters has been largely focused on in-time pile-up suppression at hadron colliders such as the LHC and HL-LHC. For the latter in particular, with a possible pile-up of 200 simultaneous primary collisions, the new wave of calorimeters is being designed with $\sim 30\,\text{ps}$ precision to allow the many vertices that overlap spatially to be separated in the time domain. Achieving this level of precision

Calorimeters based on Optical Readout

R&D Need	Main Directions	Target facilities	Related DRDT
Optimisation of Photon detectors	Novel SiPMs with large spectral sensitivity and high-band semi-conductors for higher radiation tol-erance, Digital SiPMs	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3
Novel crystal tech-nologies	Co-doped garnet crystal fibres	HL-LHC, ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.1, 6.2, 6.3
Longitudinal infor-mation	Longitudinal segmen-tation of crystals, z-position from timing	HL-LHC, ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.1, 6.2, 6.3
Novel plastic scintil-lators	Radiation hardness, implementa-tion of dual readout	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3

Table 6.4: Overview of main R&D needs and corresponding directions of development for calorimeters based on Optical Readout connected to facilities and DRDTs.

requires fast signal production with a good signal-to-noise ratio, with high-precision TDCs and clock distribution to match. Existing R&D has targeted all these three critical components with excellent results. The ongoing R&D for the LHCb SPACAL has already been introduced in Section 6.3.4.3. R&D on crystals with different dopants is targeting faster decay times. For example, BaF_2 has a decay time of ~ 0.5 ns when doped with yttrium, making it suitable for ultrafast calorimetry for fast-repetition-rate colliders. PbF_2 is investigated for KLEVER and the Muon Collider. Fast sampling can be used for the removal of out-of-time pile-up, as done, for example, for the present CMS ECAL using *template fits* to crystal time samples.

6.3.5.1 Use of timing information for enhanced calorimetric performance

An emerging field is the use of high-precision timing to trace the evolution of EM and hadronic showers and extract information that can be used to enhance the calorimeter performance, see Figure 6.2. It is easily apparent that measurements of the spatial evolution of showers at different times can provide information about the particle type and support particle separation in calorimeters. The inclusion of timing information into convolutional and graph neural networks shows an improvement in energy resolution when compared to simple cluster sums, particularly when shorter time slices are included, see also Ref. [Ch6-25]. Similar studies have shown that the use of time information can improve calorimeter linearity, particularly important for ultra-high-energy colliders such as FCC-hh. Note finally that time stamping of calorimeters hits can be used to search for new long-lived particles.

6.3.5.2 R&D Needs

As described before and sketched in Table 6.1 trends in calorimetry and the challenges of future colliders require timing precision down ~ 10 ps by 2030 and maybe better in the longer term. There are promising developments in fast crystals (including crystal fibres) that can be suitable for e^+e^- and muon colliders (low dose/fluence) but there

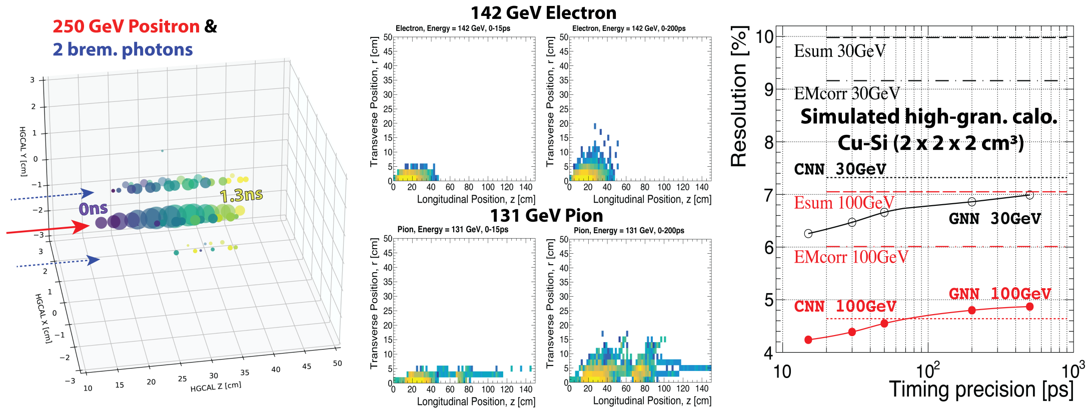

Figure 6.2: Left: Time evolution (0-1.3 ns, shown with a colour scale) of a 250 GeV positron shower (including bremsstrahlung photon showers) as measured with a CMS-HGCAL prototype; Centre: R-Z evolution of electron (top) and charged-pion (bottom) showers for two different time periods; Right: energy resolution of a simulated high-granularity Cu-Si calorimeter, showing the improvement in performance for 30 and 100 GeV pions when using neural networks (CNN), and when including time-slice information (GNN) [Ch6-25].

remains significant R&D to optimise the rise/fall times and scale these systems up to large-volume detectors. Developments of ultra-fast integrated photon detectors, such as digital SiPMs, may provide timing performance to match these new crystals, at the same time negating the need for separate ASICs. The most challenging future collider, on the timescale considered here, will be the FCC-hh, due to its expected pile-up of 1000 events, complex collision topologies and possible bunch-crossing frequency of 200 MHz. A timing precision of $\sim$5 ps will be required to help mitigate these challenging conditions. This will require significant R&D in the domains of active materials, light detectors, front-end ASICs and clock distribution, taking into account signal propagation times over large areas, e.g. in light guides or on PCBs and through cables/connectors. On-ASIC fast digitisation and advanced processing may be beneficial but, as with high-precision TDCs/PLLs, it comes at the price of increased power consumption, so that R&D into low-power ASIC blocks is mandatory.

High-precision timing may be necessary in every layer of a calorimeter, but R&D for its use in dedicated layers, either for preshowers (using e.g. LGADs) or at specific depths in the shower (e.g. at shower-maximum, as proposed by RADiCAL) should be carried out in order to optimise the complete detector performance whilst taking into account cost and integration.

Finally, R&D into advanced software able to exploit the capabilities of the calorimeters needs to be performed. In this context "software" may refer to programmable features on ASICs as well as in back-end processors, and should include the use of neural networks and machine learning.

6.3.6 Readout Systems for Calorimetry

Over the past 40 years calorimeters have mainly grown in size, but not significantly in channel density (with the exception of the silicon-based *Preshower* of CMS). The next-generation calorimeters being developed for the HL-LHC will push the boundaries in terms of both spatial density and timing resolution, to facilitate 5D-reconstruction for particle flow. This requires some major developments of the accompanying electronics. For future colliders, the challenges for calorimeter electronics will be even more extreme, but also heavily collider-dependent. The general prospects for electronics R&D are given in Chapter 7. Aspects specific to calorimeters are outlined in the following.

6.3.6.1 Breadth of challenges for calorimeter readout systems

Linear e^+e^- colliders have a low duty cycle coupled with low occupancy, resulting in rather modest levels of radiation. This means that the available readout bandwidth can be used to stream all data from high-granularity calorimeters and techniques such as power-pulsing can be exploited. The CALICE collaboration has made significant R&D along these lines, with great success so far. At the other end of the spectrum lies the FCC-hh, with a high duty-cycle coupled with extremely high levels of pile-up (in-time and out-of-time). Calorimeters at FCC-hh therefore need to survive extreme levels of radiation, must include high-precision timing information in order to mitigate pile-up (see Section 6.3.5) and, due to bandwidth limitations, will most likely require triggered data flow. There is consequently no "one size fits all" recipe for calorimeter readout systems: they must be tailored to the application.

6.3.6.2 Necessary ASIC developments

Possibly, the most challenging aspect of front-end ASICs specific to calorimeters is the large dynamic range coupled to low noise for small signals (necessary for calibration of most sampling calorimeters). A related aspect is the response linearity over the full dynamic range. For smaller technology nodes, with lower operating voltage than the present generations, this will certainly require dedicated R&D.

The increased granularity of all future calorimeters requires a move to *processing* at all stages, from front-end to back-end, including data compression, encoding/decoding and embedded neural networks. Some recent developments for HL-LHC have included neural-network-based encoders for front-end triggering inside a 130 nm ASIC - i.e. putting "software" into the front-end. Future colliders will need to go much further, with more programmability and functionality built into the ASICs.

6.3.6.3 Discrete components for compact calorimeters

Despite increased integration on ASICs, and notwithstanding MAPS-like developments, there will remain the need for discrete, and sometimes bulky, on-detector components. For example, the power-pulsing methodology for CALICE-like detectors requires large capacitors as close as possible to the front-end, to reduce transient effects; and switched-mode DC-DC converters require high-inductance coils. These components are most challenging for high-density EM calorimeters, but the needs are similar in hadronic calorimeters and quite different from trackers or muon detectors, where space is more readily available. Although industry drives much of the development of passive components, specific R&D into in-PCB coils, small-volume capacitors (including for bias voltages) and high-reliability connectors (a common weak point in all HEP detectors) should be carried out.

6.3.6.4 Connection technologies for large-area solid-state sensors

The move to higher-granularity solid-state calorimeters for present and future collider detectors brings challenges in terms of interconnections between the sensors and the readout boards. This is particularly true for large-area pad sensors, where direct soldering to FR4-based PCBs is not practical due to mismatches of the CTEs[1], even when the detectors are operated at room temperature. For colder and even cryogenic operation, this issue becomes even more serious. Through-hole wire bonding can work for low-density sensors. But R&D into different interconnect technologies should be explored, including such things as Anisotropic Conductive Films/Pastes and PCBs based on materials with the same CTE as silicon. These would allow a move to larger-scale industrialisation necessary, in particular, for the next generation of hadron-collider experiments.

6.3.6.5 Readout integration and the new wave of FPGAs

Pattern recognition through artificial intelligence (AI) could clearly be beneficial, especially in the back-end readout systems, with the complex topologies of showers, for particle identification, energy measurements etc. Indeed it is becoming apparent that the new wave of FPGAs is focusing less on large arrays of programmable logic and more on having many dedicated programmable AI cores. The HEP community must exploit synergies with AI developments in the commercial world, possibly through industrial R&D partnerships, as the manner in which FPGAs can be incorporated into our readout systems will necessarily significantly change.

6.4 Observations

Calorimetry is going through a change of paradigm from integral to differential (5D-) detectors. Therefore the performance metric has to be somewhat rethought. The new metric has to take into account the changing role of calorimeters as a key element in the global event reconstruction of detectors, rather than devices purely for the measurement of single- (or multi-) particle energies.

From the beginning, individual components such as sensitive materials, ASICs and mechanical structures, will have to be considered holistically, as a single system of several

[1] Coefficient of Thermal Expansion

layers, deep enough to absorb highly-energetic particle showers. Large-scale demonstrators are an essential ingredient of the R&D programme. These demonstrators are early applications of novel technologies at system level, including novel materials for precise mechanical structures outlined in Section 8.3.5. Data recorded with these demonstrators validate and constrain the Monte Carlo (e.g. Geant4 [Ch6-26]) predictions, in particular for assessing the relative contributions of the different nuclear models. The validation in the time domain will become important in the coming years. The validation of Monte Carlo predictions has a general interest, even outside the HEP field.

The complexity of calorimeters already at the prototype level calls for the formation of R&D collaborations that include research centres and laboratories with the necessary engineering competences. An important point to take into account is the time needed for the construction of calorimeters. The R&D for calorimeters should finish approximately 8-10 years before the start of data taking. This requires well-conceived demonstrators at an early stage that allow for a smooth transition from the development phase to the construction phase.

Robustness and reproducibility are important factors that have to be developed in collaboration with industry, due to the large number of modules involved in modern calorimeters. It is, however, observed that: (i) in many fields particle physics is not the main technology driver anymore, and (ii) the quantities required for particle-physics detectors are still small compared to today's industrial standards.

Thus, future projects and national and international funding agencies should develop strategies for collaboration with industry, valuing the training opportunities that flow from the construction of calorimeters and their prototypes as well as, of course, the gain in knowledge through the research itself.

Traditionally, calorimeters have strong overlap with other fields such as medicine or earth science. The advent of complex granular devices makes calorimeters also an ideal "playground" for the application of modern pattern recognition technologies.

6.5 Recommendations

In order to implement the research directions the following set of recommendations is formulated.

- Implementation of DRDT 6.1. Support of R&D on novel optical materials and corresponding readout technologies to optimally prepare for the LHCb Upgrade II (in $\geq$LS4). Experiments such as KLEVER could provide an early use case of developments for LHCb. The development of heavy glasses for the Electron-Ion-Collider should be followed closely and European groups are encouraged to join this effort;
- Implementation of DRDT 6.2. In order to meet a start of data taking for a Higgs factory around 2035, the planning should make sure that advanced options can reach maturity in the coming years but should enable also a judgement on alternatives. Therefore, where demonstrators (e.g. CALICE & Dual-Readout prototypes)

are planned or existing, the programme should be fully supported. Where possible one should capitalise on HL-LHC experience to accelerate the process;

  - Where R&D is still at a smaller level (e.g. for MAPS or Noble-liquid devices) or at the beginning, the necessary steps should be supported and the construction of larger-size demonstrators should be assessed in two to three years from now. MAPS based sensors will however already benefit from the planned construction of the ALICE FOCAL detector;
  - Experimental setups in beam tests should be able to validate simulation models of EM and hadronic cascades;

- Implementation of DRDT 6.3. Develop a strategy for calorimeter R&D at a future hadron machine;

  - Test beam and irradiation facilities have to approach the conditions at a future hadron collider as closely as possible. System tests should be combined with suitable computer simulations of the conditions at a high energy hadron collider. The HL-LHC will deliver valuable real-world experience;

- Understand how calorimeters can benefit from progress in terms of precision timing for single particles and showers, including within showers;

  - Section 6.3.5 distinguishes between timing used for pile-up mitigation and for improvement in measurable parameters, such as resolution and linearity. In particular the latter requires systematic simulation studies before a dedicated hardware development for calorimeters. These simulation studies will have to be completed on a time scale of around two years from now;

- Changes in readout architectures need to be followed up and integrated into our planning;

  - The R&D programme must be able to keep up with the rapid development in industry. This concerns in particular the introduction of Artificial Intelligence at the FPGA level;

- The uncertain landscape and the size of demonstrators emphasise the role of R&D Collaborations (or at least open collaborative efforts without a label). These collaborations should take into account that calorimeter R&D is a worldwide effort;

  - R&D collaborations and demonstrators should also be fora/infrastructures to discuss/test new developments at an early stage beyond test-bench level. It is, for example, recommended that the Muon Collider Community integrates into existing R&D structures for calorimeters. The current R&D Collaborations may also be the best route to coordinating contributions to the DUNE Near Detector;

- Present and future calorimetry projects may have a lifetime of about 30 years or even longer. It is therefore important that calorimeters can be upgraded with state-of-the-art technology during the lifetime of a project. This will ensure, on one hand, an optimal scientific output and, on the other hand, is a premise that the field will remain attractive for coming generations of scientists and engineers. Therefore, upgradeability must become a design criterion.

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Chapter 7

Electronics and Data Processing

7.1 Introduction

For fifty years, electronics developments have supported and enabled all aspects of experimental particle physics. Current and near-future detector electronics compares in complexity with the most challenging developments in industry, and is the means by which data and control for many elements come together to constitute an experiment. “Electronic” systems use a wide range of technologies, from nanoscale semiconductors, to high current and voltage power supplies, to optoelectronics. They rely on complex software and firmware. A breadth of skills in engineering, modelling, simulation, software and systems integration is needed to design, deliver and operate them.

The performance of the next generations of electronic systems will be a limiting factor in the scientific reach of future experiments, unless significant R&D, new organisational structures, and a new relationship with industry are put in place. Predicted needs and timescales indicate that this must be done now, building on the lessons from LHC and other current projects. Near-future experiments needing low-power, exceptional granularity, and in some cases very low mass, require focused R&D in the coming years. For further-future collider experiments, today’s technologies lack the necessary combination of performance, power efficiency and radiation hardness, and fundamental R&D is needed. Non-collider experiments with extreme conditions pose a range of challenges, again requiring the use of technologies currently in their infancy.

7.2 Main drivers from the facilities

7.2.1 Technical requirements

The trend in future detectors is for finer granularity, more channels and more data, presenting a challenge in power dissipation. The close coupling of readout ASICs to sensors, improving performance and hermeticity, makes this all the more important. Some applications require ultra-high radiation hardness; all require exceptional reliability for both on- and off-detector electronics. Precise timing information for triggering and reconstruction is a common requirement, and will also increase the amount of data, requiring more and faster links using the smallest possible amount of material. Data selection and reduction will increasingly be addressed by intelligent processors close to the front end, reducing data movement. Here, R&D must identify affordable compromises between performance, complexity, power consumption and flexibility. A summary of requirements is shown in Figure 7.1.

The requirements of future lepton and heavy-ion colliders seem to be mostly within reach of technologies from HL-LHC, but this is not true for FCC-hh or a muon collider, even assuming reasonable progress over the next two decades. Large-scale neutrino and dark matter experiments pose a different set of technical challenges, but have overlaps in areas such as controls, reliability techniques and software. Smaller specialised experiments will continue to pose unique and individual challenges, which may form valuable stepping stones and test-beds for advanced technologies of wider applicability. For the first time, electronics has become an enabling, but potentially also limiting, aspect. The effort required to maintain access to some of the required technologies and tools is so large that a completely new collaborative model must be implemented to focus on a limited set of affordable and targeted R&D lines. The R&D strategy will be dictated by what is feasible and affordable, and not solely by requirements of the experiments.

7.2.2 The inheritance from HL-LHC

The HL-LHC detector projects are currently the largest concentration of advanced electronics developments in HEP. Over 40 front-end ASICs have been developed for readout of silicon pixel and strip sensors, calorimeters, and muon or timing detectors, in 130 and 65 nm CMOS technology. Schemes have been put in place to improve the efficiency of design teams: access to foundry and design tools, run centrally from CERN; common projects for the specific developments (data links [Ch7-1], power conversion [Ch7-2], etc.); and collaborative developments across experiments (RD53 [Ch7-3]) and beyond HEP (Medipix [Ch7-4]). At the back end, HL-LHC will use large, cost-effective data acquisition and processing systems. These systems typically use commercial FPGAs to interface between custom front-end links and online computing, but carry out the majority of data processing using modern computing platforms, including increasing use of co-processors.

7.2.3 Industrial developments

For ASICs, the microelectronics industry has reached nanoscale CMOS nodes, based on new transistor structures (FinFETs, gate-all-around devices, etc.) to improve the speed and power performance of digital systems. EDA tools have simultaneously reached unprecedented performance levels and are essential in the design process. In contrast to most (purely digital) complex commercial ASICs, future readout ASICs will be mixed signal systems, with analogue interfaces to sensors. Achieving the required analogue performance with advanced nodes will be a crucial target of the R&D programme. High-performance commercial CMOS image sensors are based on stacked active layers to

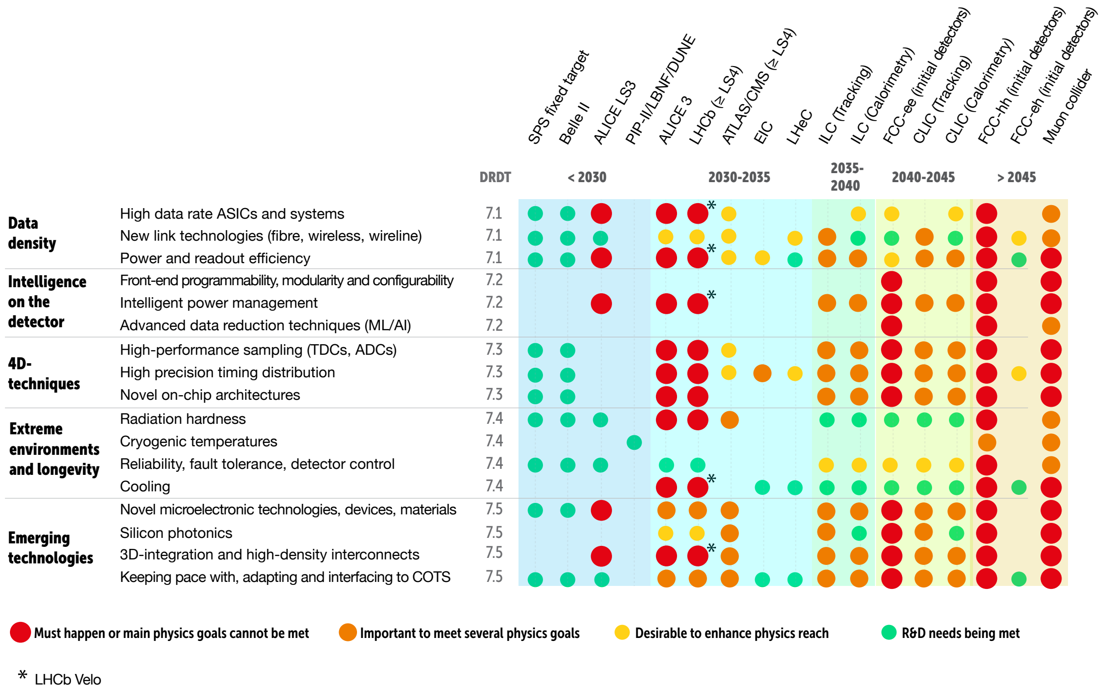

Figure 7.1: Schematic timeline of categories of electronics together with DRDTs and R&D tasks. The colour coding is linked not to the intensity of the required effort but to the potential impact on the physics programme of the experiment: Must happen or main physics goals cannot be met (red, largest dot); Important to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); No further R&D required or not applicable (blank).

reduce pixel pitch and increase functionality. These industrial advances can provide the means to enhance or even revolutionise the performance of future detector readout ASICs and their interconnection to high granularity detectors.

Commercial communications and data processing technologies continue to evolve rapidly. Optical links are now ubiquitous in homes, offices and data centres and enable massive data transfers across the globe. Data-processing technologies are using increasingly specialised co-processing, stream-processing, and multi-processing architectures, as opposed to more powerful single devices. The difficulty in HEP will be in keeping pace with these extremely complex new developments, which unlike today's FPGAs are largely proprietary and not typically available for use in custom developments.

These considerations feed into a number of recommendations discussed in Chapter 10, while the technical R&D themes are detailed later in this section and summarised in Chapter 11. As discussed below, for the timeline illustrated in Figure 11.1 R&D on DRDT 7.1, DRDT 7.2, DRDT 7.3, and DRDT 7.5 is essential to realising the facilities listed in Figure 3 and Figure 4 of the Introduction, all the way through to the FCC-hh/muon collider era. For DRDT 7.4 there is the particular challenge of the two orders of magnitude more extreme radiation hardness requirements for the FCC-hh.

7.2.4 Categorising New Developments

The industry roadmap is driven by commercial imperatives. The particle physics community needs to monitor technology evolution, and put in place structures and relationships providing access to advanced technologies in an affordable and effective way. This is particularly relevant where contracts, licenses or fees are needed to access technologies such as ASIC tool chains and libraries. For other technologies, including high-density interconnects, direct collaboration between industry and research institutes will be needed to gain the necessary access and experience. For yet others (for instance, advanced co-processing or network technology) particle physicists are effectively COTS end-users, and will need to maintain currency through test setups and deployment of new technology into existing experiments.

In some cases, the needs of HEP are far from the industry roadmap. An example is custom ultra-radiation-hard devices. Here, a long-term sustained R&D effort is critical to guarantee that the particle physics community remains abreast of new technologies and their capabilities. An appropriate organisation will need to be put in place to sustain critical mass of a very active but small and scattered community. In particular, the practical use of the most modern technologies may be restricted by cost or licensing, and this is likely to pose a barrier to meeting the needs of future experiments.

7.3 Technical Findings

7.3.1 Front-end ASICs

Over the last three decades, the crucial importance of custom chip design for successful experiments has become increasingly obvious. Microelectronics is likewise key for next-generation experiments, which cannot continue to be performed 'the good old way'. ASIC technologies are evolving rapidly, bringing better performance and functionality, but at the expense of increased complexity and design cost. Design tools are becoming very elaborate, needing experts to handle them, and the specialisation and size of the teams needed to design, simulate and verify the next generations of ASICs will be much larger than in previous projects.

Front-end ASICs have become an integral part of modern detectors, and perform complex functions that determine overall system performance. For most detectors, sensor design is now closely intertwined with its readout electronics and the optimisation of their performance is a joint effort. This is particularly evident in the field of monolithic CMOS pixel sensors (see Section 3.3.1), where the front-end electronics is integrated in the same substrate as the sensing electrodes, setting even more demanding requirements on the design and layout of the pixel cell, which must be compatible with the operation of the sensor and requires similar tools and expertise as needed to design readout ASICs.

7.3.1.1 State-of-the-art

More and more functionality is now integrated inside the front-end ASICs, from low-noise, high-speed pre-amplifiers and discriminators to high-end ADCs and TDCs and digital processing [Ch7-5]. The trend is towards more channels, less power, higher speed, lower noise, and higher radiation-hardness. High-precision timing capability ($< 50\,\text{ps}$) is becoming standard for devices currently in development [Ch7-6]. In addition, devices intended for calorimetry require large dynamic range and excellent linearity [Ch7-7].

7.3.1.2 Technology choice and ASICs evolution

The community currently bases most designs on 65 nm and 130 nm CMOS, which have been qualified by CERN for radiation-hardness. Despite being used for HL-LHC, these technologies are already fifteen to twenty years old, and a 28 nm CMOS technology has now been selected as the next node for highly integrated chips such as pixel readout. This will in particular enable the design of in-pixel precision TDCs. It will also allow for lower power digital processing, advanced programmability and configurability options and high-speed output links, but will come at a much higher cost and complexity, requiring specialised teams dedicated to design and verification tasks. A cheaper process should be preserved for less dense/demanding applications, and a CMOS Imaging Sensors (CIS) variant should be targeted for monolithic pixels. In the longer term, CMOS nodes below 28 nm will also need to be qualified for their potential use in future applications requiring extreme miniaturisation, high speed and low power.

More intelligence can be included in the front end ASICs to allow for data reduction and possibly an overall system power reduction, though there is a trade-off with the needs of software event reconstruction. As with today's trigger systems, complex processing having an irrevocable effect on the recorded data must be adaptable to changing experimental conditions. Ideally the ASICs would be programmable, and either "FPGA-like" or "CPU-like". Such programmability and configurability will ultimately enable the community to develop fewer ASICs of higher complexity and flexibility.

Interconnects represent an important area, where industrial technology now allows the integration of dissimilar technologies for sensor/analogue/digital/photonic functions. R&D in TSVs, ACF and bumpless techniques is needed, noting that 3D-integration is a key process in industry to overcome scaling limitations. CMOS image sensors are a good example, stacking two or three device layers fabricated in different technologies, with high density interconnects between them. Access to advanced interconnect design and fabrication processes is currently limited to selected customers and is a challenge which will need to be addressed.

7.3.1.3 Identified R&D themes

- High-granularity pixel readout chip with 10–100 ps timing and charge measurement capability in 28 nm CMOS, and highly programmable features (DRDT 7.1, DRDT 7.2, DRDT 7.4);

- Integration of "intelligent" signal processing into detector readout chips for data selection / reduction (DRDT 7.1, DRDT 7.2, DRDT 7.5);
- Readout structures for monolithic sensors (DRDT 7.1, DRDT 7.3, DRDT 7.5);
- LGAD/AC LGAD timing chip with 1–10 ps timing capability (DRDT 7.1, DRDT 7.3);
- 3D integration technologies (in collaboration with industry) for high density interconnection of stacked layers of sensors and readout electronics, or for connection of ASICs and specialised PCBs (DRDT 7.1, DRDT 7.5);
- Imaging/dual calorimeter readout chip for Si/SiPM readout (DRDT 7.1, DRDT 7.2, DRDT 7.3);
- Cryogenic readout chip for imaging LAr calorimetry (DRDT 7.1, DRDT 7.4);
- MPGD/RPC timing chip with < 10 ps resolution (DRDT 7.1, DRDT 7.3);
- Integration of readout ASICs with silicon photonics (DRDT 7.5);
- CMOS nodes beyond 28 nm for digital and mixed-signal applications, including characterisation of radiation hardness and analogue performance (DRDT 7.1, DRDT 7.4, DRDT 7.5).

7.3.2 Links, Powering and Interconnects

The raw data rates of modern experiments exceed exabytes per day. With current technologies, only a fraction of the raw data can be transferred from the front-end to the back-end electronics. Electrical data links are unavoidable in innermost detector layers, dictated by space constraints and radiation levels; elsewhere, optical data transmission is the dominant link technology. Tens of thousands of optical fibres are employed in the LHC experiments, and allow the required data throughput at minimum mass while preserving electromagnetic noise immunity and galvanic isolation.

Despite intensive efforts to minimise power, the front-end electronics of LHC subdetectors consumes tens to hundreds of kilowatts. Power distribution and cooling are and will remain major challenges for HEP detectors, particularly for highly granular silicon detectors.

The assembly of sensors, front-end ASICs as well as power conversion and data transmission devices into detector modules, and the combination of modules into larger units, continues to pose severe packaging and interconnect challenges. This is due to: the high density of connections between sensor and ASICs; the need for extremely low-mass assemblies; severe space constraints; and the need to operate sensors at low temperature.

7.3.2.1 State-of-the-art

Almost all HL-LHC optical links will use a common 10 Gbit s^{-1} chipset developed at CERN combining the LpGBT ASIC (65 nm CMOS) with the VTRx+ optoelectronic module (multimode, VCSEL-based). The LpGBT [Ch7-8] aggregates lower-rate datastreams from front-end ASICs to maximise the bandwidth utilisation of the multi-channel optics. 130,000 LpGBTs and 70,000 VTRx+ modules have been ordered by experiments. Tolerable radiation levels reach $2\times10^{15}\,n_{eq}\,cm^{-2}$ and 1 MGy, only just sufficient for HL-LHC.

Innovative powering concepts, DC-DC conversion and serial powering, were developed for the LHC upgrades to minimise losses in cables and minimise material. A key achievement, together with a comprehensive understanding of system reliability and safety, was the development of custom radiation-hard power conversion circuitry and regulators. For DC-DC conversion, dedicated chip sets and power modules were designed at CERN. For serial powering of pixel detectors, most of the circuitry is integrated in the readout chips. The specific requirements of high granularity calorimetry have also required specific developments in miniaturisation of components.

Packaging and interconnect technologies rely on sophisticated flip-chip and wire-bonding processes, fine-pitch flexible circuits, ultra-light high-precision carbon-fibre support structures, highly effective bi-phase cooling techniques, and materials with extreme thermal conductivity. The sophistication of packaging and interconnect technologies is reflected in densities of tens of thousands of pixels per cm^2, sensors and ASICs thinned to 50 µm, and cooling microchannels etched into silicon sensors and silicon modules of as little as 0.05% of a radiation length [Ch7-9].

7.3.2.2 Future challenges

Driven by increasing granularity and the use of precision timing, data rates will increase substantially at future colliders. The links will have to support this while complying with mass, radiation hardness, space, and power constraints, at an affordable cost. If the challenge can be met, advanced links may offer the opportunity to read out a larger fraction of the raw data than today, or even all the raw data, offering benefits for triggering and event selection. This represents an alternative solution to increased front-end data processing. System architectures using front-end data reduction or massive link capacity will thus have to be studied and compared. At the back end of the link, COTS optoelectronics will be used. Custom front-end developments will have to be compatible with COTS standards in terms of signalling rates, modulation formats, error correction schemes, and protocols, while maintaining radiation-hardness. This constraint will grow in importance as the technology gap between front- and back-end widens, and as data transmission and machine clocks may become asynchronous.

At future colliders, power distribution will remain a major concern. Even if the total power does not increase, currents delivered to ASICs will be higher due to reduced supply voltages. This will in turn drive interconnect and cooling specifications and will require packaging and integration studies as well as full scale developments. To reduce power dissipation, ASICs will need intelligent power management and multiple supply voltages, increasing the complexity of DC-DC converters. The power efficiency of converters and regulators will need to remain high, and larger conversion ratios should be realised. Due to increased radiation exposure, and with more modules attached to a single DC-DC converter or a serial powering chain, remote control and monitoring circuits will need to achieve high robustness and reliability. For serial powering and in-chip regulators, circuit designs beyond 65 nm will be required, and this will need specialised expertise and qualification efforts to be sustained. Disruptive and unconventional power distribution approaches like power over fibre or wireless power transfer should be explored. In particular, DC optical power supply modules will become an essential building block for silicon photonics, should this technology become mature.

7.3.2.3 Industry and other fields

The commercial link technologies closest to HEP needs are deployed in data centres over tens of metres to a few kilometres. Data rates follow Ethernet standards from 10 GbE to 800 GbE. Above 25 Gbit s^{-1}, multiplexing over lanes, wavelengths (CWDM) or modulation levels (PAM) is used. VCSEL-based links are still used in the majority of cases, with highly optimised multimode fibres, but a new family of silicon-photonics-based single-mode systems is appearing in the high-rate/long-distance segment. Commercial FPGA IP cores implement these data rates and modulation formats, with corresponding processing and error correction logic. Attempts to co-package optoelectronics with FPGAs are being reported, but most designs still rely on pluggable optoelectronics. Silicon photonics may be a game-changing technology in this context thanks to its good integration density and integration synergies with microelectronics. In this diverse and dynamic environment, HEP will not be short of COTS components meeting its bandwidth needs at the back-end in the foreseeable future; the challenge will however be to develop custom front-end modules compatible with commercial standards.

DC-DC power conversion in HEP is a specialised technology. Commercial converters do not operate in strong magnetic fields or high radiation environments, while serial powering is barely used outside of HEP. Space applications have some commonalities with HEP, but overlapping requirements are difficult to find, and the particle physics community is required to develop its own solutions. However, efficient power distribution and conversion are hot topics everywhere, and promising technologies (GaN, SiC) are being aggressively introduced by industry.

7.3.2.4 Identified R&D themes

- Radiation-tolerant high-speed communication circuit blocks (SerDes, Driver, Receiver, high precision Clock/Timing, etc.) compatible with 25GbE and above, and with FPGA receivers (DRDT 7.1, DRDT 7.3, DRDT 7.4, DRDT 7.5);

- Silicon photonics as the successor to actively modulated VCSEL-based links, facilitating full-custom photonic integrated circuits (PICs) for HEP (DRDT 7.4, DRDT 7.5);

- Co-packaging of electronics and optics through multi-chip-assemblies, fibre-coupling, and cooling techniques compatible with HEP sensors (DRDT 7.4, DRDT 7.5);
- Low-power, low-mass wireline and wireless link technologies to maintain a diverse portfolio of data-transfer solutions adapted to multiple requirements (DRDT 7.1, DRDT 7.4, DRDT 7.5);
- High conversion factor DC-DC converters based on new processes and materials, and associated power management circuit blocks (DRDT 7.1, DRDT 7.2, DRDT 7.4, DRDT 7.5);
- Small form-factor power modules compatible with the HEP environment, including optimised coils, capacitors, cooling interfaces, connectors and packages (DRDT 7.1, DRDT 7.4, DRDT 7.5);
- Optical and wireless power transfer for reduction of cabling mass (DRDT 7.1, DRDT 7.4, DRDT 7.5);
- Low-mass and compact interconnect and assembly techniques, culminating in wafer-scale and 3D integration (DRDT 7.4, DRDT 7.5).

7.3.3 Back-end Systems

7.3.3.1 State-of-the-art

Back-end systems usually comprise "trigger" and "DAQ". The former uses partial information to make a selection decision within a defined maximum latency, during which data need to be buffered at the front-end. Today, triggers are overwhelmingly implemented in FPGAs, sometimes along with ASICs (see for instance [Ch7-10], [Ch7-11]). CPUs and DSPs are not often used due to latency constraints, but there is some adoption of GPGPUs. Specialised chips for "AI" (i.e. inference accelerators) are not yet in use. In some cases, FPGAs are physically near the front end, but for collider experiments this is prevented by radiation levels, and back-end electronics is situated up to several hundred metres from the detector with data transport via custom radiation-hard optolinks. The "DAQ" function typically comprises FPGA-based boards to terminate the optolinks, control and monitor front-end ASICs, distribute high precision clocks, buffer, validate and organise data, and convey them onto a COTS network and thence to commercial computing systems [Ch7-12], [Ch7-13]. Large amounts of buffer storage are used to decouple processing stages and to allow efficient resource usage under varying operational conditions. Large experiments use a dedicated subsystem to distribute clock, synchronisation and "fast" control information [Ch7-14].

7.3.3.2 Future challenges

Power consumption and readout bandwidth will be limiting factors for future experiments. Moving processing traditionally done in the back-end closer to (or integrated with) the front-end can strongly reduce data transmission bandwidth. Standard COTS form-factors (e.g. PCIe cards) cannot be easily used at the front-end, which increases cost and reduces flexibility for long-term hardware maintenance and upgrades. Hard-wiring complex data processing algorithms into ASICs also risks removing the flexibility necessary to address changing detector conditions and physics priorities.

Development of specialised AI and ML hardware in academia and industry is extremely rapid, and it is not clear how this can be reconciled with the extended development cycles for large detector systems. Standardisation and modularisation of front-end electronics and interfaces may offer a solution. It is unlikely that COTS components will be suitable for use in the detector without adaptation, due to power, robustness and radiation hardness constraints. The long-term radiation tolerance of any candidate novel processing technologies must be established.

The FPGA layer connecting front-end links to COTS computing is a major cost driver in large experiments, driven by both hardware and firmware developments. If front-end links use a suitably optimised industry-standard protocol, this cost could be at least partially removed. Today, and for the foreseeable future, this implies the use of Ethernet, PCIe, or other packet-switched standards.

7.3.3.3 Industry and other fields

COTS system performance continues to increase through larger chips, increased power dissipation ($> 300\,\mathrm{W}$ for high-end CPUs and GPUs), integrated memory controller, I/O and auxiliary functions (SoC), and multiple dies per package. Standard elements (CPUs, GPGPUs, FPGAs, ML ASICs, optoelectronics) have the highest volumes, and consequently the best price-performance ratio. They are typically deployed in standardised form-factors and platforms using relatively narrow I/O interfaces. Network backbone link speeds now reach $800\,\mathrm{Gbit\,s^{-1}}$ and credible roadmaps exist for another factor four in the coming years. The complexity of these devices and of their integration into full systems makes it very unlikely that they can be efficiently used outside their intended target platforms and applications, with the possible exception of FPGAs.

For large-scale users capable of the required investment, customisable IP for CPUs and other elements (e.g. ARM architecture) allows development of "application optimised" SoCs. These systems are often quite heterogeneous, which is hidden from the user by sophisticated software. This approach may be a viable route for HEP in the future, although lower-performance open IP (e.g. RISC-V) may be a more practical proposition.

Other fields with large distributed real-time processing systems are also seeking to exploit the processing power of GPGPUs for parallelisable problems, with first-level signal processing also using FPGAs. The largest such systems are for SKA and ESRF. SKA shares power and throughput constraints, but of course has fewer issues related to packaging, radiation, and less stringent requirements for reliability [Ch7-15], [Ch7-16].

7.3.3.4 Identified R&D themes

- Tight integration of front-end and back-end using industry standard protocols and COTS components in extreme environments (DRDT 7.1, DRDT 7.4, DRDT 7.5);

- Integration of AI techniques closer to the front-end using modular, flexible designs using COTS chips or standard IP (DRDT 7.2);
- Use of FPGAs in extreme environments for data transmission and processing (DRDT 7.1, DRDT 7.4);
- Efficient use of modern compute hardware, use of GPGPUs and AI ASICs, cross-platform frameworks, and compatibility with industry standards, connected with high-speed software defined networks (DRDT 7.2, DRDT 7.5);
- Large-scale and realistic technology demonstrators, tracking relevant industry developments, with permanent integration and test-facilities (DRDT 7.1, DRDT 7.2, DRDT 7.5);
- Next-generation pico-second precision timing distribution systems to enable 4D detectors (DRDT 7.3, DRDT 7.4).

7.4 Observations

7.4.1 Organisation and Collaboration

The increasing cost, complexity and specialisation of developments (particularly in ASICs) will require changes in organisation, akin to past initiatives in computing and accelerators, as also discussed in Chapter 10. One model, extending arrangements for HL-LHC and emulating the organisation of large-scale computing developments, would be to organise design work around a number of well-resourced centres (e.g. CERN as "Tier-0" and national laboratories as "'Tier-1"), directly supporting the more exploratory work of university groups ("Tier-2"). Larger centres can maintain the critical mass, access to tools and industry, and verification infrastructure, that are essential for successful distributed development. The full design and verification of a complex ASIC now exceeds the capacity of any single group, so means will be needed to recognise contribution and ownership of sub-components and circuit blocks, and to solve legal and practical issues of collaboration. Long-term positions and career paths for staff with specialised skills are vital, so that knowledge can be maintained (see Chapter 9). Young people will play a key role in generating ideas and providing design effort, as will subcontractors, but success will also rely on the supporting efforts of experienced people with familiarity with HEP-specific challenges. The same issues also apply in other areas of complex collaborative design such as firmware, embedded software and custom board design, as also picked up on in Chapter 11.

7.4.2 Systems Engineering

Intelligent and configurable systems will benefit from the rapid progress of commercial developments. In the future both front- and back-end parts, as well as any intermediate layers, will have to be designed in unison to ensure optimal performance. Contrary to current practices where groups drive developments quasi-independently, this will require top level trade-offs in distribution of intelligence, power, storage, and data bandwidth between layers. System-level analysis, modelling, and simulation will become central themes for future R&D, and will form the starting point for future detector electronics developments, before a conceptual design is adopted. This crucial point applies even to the very next generation of detectors, where designs already exist.

7.4.3 Tools and Technologies

Access to advanced design tool kits and design technologies is crucial. Rising engineering costs dictate that tools and procedures must reach a level of sophistication such that the risk of failing a submission is kept extremely low. This is currently only achievable with commercial packages, with the issues of vendor lock-in and license costs, which can be prohibitive for certain EDA tools. The Europractice initiative is a very valuable facility in this area, underpinning almost every development; it must be supported, continued and if possible extended. A common support service should also provide and train the community with pre-configured design flows and kits so that every development centre uses a similar environment (see Chapter 10).

In parallel, there should be a new emphasis on open-source tools, which have had profound impact on software development. Such open-source projects benefit the entire community. Similarly, the *OpenHW* initiative provides IP blocks free of license constraints, ideal for quick or smaller projects. These approaches support those who cannot access commercial licenses, and are used outside HEP. However, open-source tools are not free, or even of lower short-term cost than commercial tools: development, maintenance and support time needs to be invested. Nonetheless, this is a potentially valuable way of reducing long-term risk, and may provide a route to new innovation in design optimisation.

7.4.4 Interactions outside HEP

HEP instrumentation has similarities to that in astro-particle and astrophysics, hadron and heavy-ion physics, nuclear physics, photon science, space, and medical fields. All seek an increasing channel count, and higher data rates and bandwidths. The take-up of HEP-developed microelectronics is often hampered by lack of documentation and support, non-use of common standards, and lack of open designs with clear licensing conditions. However, there are very successful examples demonstrating that it is possible to break the HEP bubble and develop ASIC families of interest for multiple fields (Medipix, Timepix, Velopix, etc.). Working more closely with projects targeting other applications may help designers to maintain and develop expertise and know-how on advanced technologies and design techniques. This may then provide innovative solutions applicable to HEP.

7.4.5 Skills, Training and Careers

Advanced electronics development relies on well-trained specialists and engineers who are highly sought-after in industry, and who must cope with ever-more-complex tools and designs. They also need a mature understanding of physics requirements and experimental conditions. While the community continually educates and trains highly skilled people, the availability of advanced electronics skills in the field is now clearly insufficient. As in other areas, the non-specialist will find it increasingly difficult to make a satisfactory professional contribution without a large investment of time. It is vital to maintain a specialist talent pool in academia, perhaps attracting them with the multi-disciplinary and "grand challenge" nature of the task compared to industry. Collaboration with electrical engineering departments, early recruitment into attractive graduate programmes in HEP and later into permanent posts with competitive salaries, plus a significantly larger number of technical positions at national research centres and universities, along with a visible career path leading to senior positions, are required (see Chapter 9, Chapter 10 and Chapter 11).

7.4.6 Common infrastructure

Access to radiation-test facilities remains vital, is a current bottleneck, and if anything will become only more important as radiation-hardness requirements increase. However, increasingly complex and costly developments call also for other shared and expensive facilities. For instance, testing very fast and high-timing-precision optical and electrical circuits requires test-equipment and laboratory facilities beyond the reach of most institutes, as do specialised developments in optoelectronics and wireless technology. Also, large and complex systems require sophisticated test infrastructure which will increasingly need to be shared (see Chapter 10).

7.5 Recommendations

7.5.1 Themes for future R&D

The future R&D topics for electronics have been organised into a small number of coherent, but necessarily overlapping, themes. Each of these themes could form the basis of one or more focused RD collaborations.

DRDT 7.1 - Advance technologies to deal with greatly increased data density.

- High data rate ASICs and systems:
  More channels and more bits per sample require higher data rates inside and outside the ASIC. Low noise, low power, high speed ADCs and TDCs, high speed serialisers / deserialisers, PLLs, NRZ and PAM driver blocks need to be developed in advanced technology nodes. Data rates, FEC and modulation formats must be selected at system level, in line with available COTS at the back-end;

- New link technologies (fibre, wireless, wireline, etc.):
  Novel link technologies must be developed to cope with higher data rates, to connect neighbouring detector layers for advanced data reduction techniques, and to

do so with reduced mass and power. Critical technologies include radiation-hard optical links, wireline, wireless, and free-space optics;

- Power and readout efficiency:
  Low-power design techniques are needed at the front-end, including novel architectures. Efficient power distribution, power converter and regulator devices, and protection circuits are required to minimise detector mass and heating. Efficient readout controllers must work in concert with DAQ to optimally aggregate, buffer and transmit data to maximise the utilisation factor of very high bandwidth off-detector links.

DRDT 7.2 - Develop technologies for increased intelligence on the detector.

- Front-end programmability, modularity and configurability:
  Radiation-tolerant processors and programmable logic elements must be made available as circuit blocks in order to allow fewer, more versatile front-end ASICs. Common interfaces and protocols must allow re-use of modules;

- Intelligent power management:
  Increased ASIC power-performance ratio must be achieved by developing improved power management schemes. Clock gating, power pulsing, dynamic voltage supply and other techniques will be key to efficiency;

- Advanced data reduction techniques (ML/AI):
  COTS AI circuits cannot easily be integrated into the front-end, and will not be radiation hard. Standardised, shareable blocks for AI functions, implementable in ASICs or FPGAs, can leverage the enormous intellectual investment in the AI/ML revolution for intelligent data reduction.

DRDT 7.3 - Develop technologies in support of 4D-and 5D-techniques.

High 4D-(timing as well as spatial) resolution requires developing solutions to improve the noise-speed-resolution trade-offs in advanced technologies with low supply voltage and high transistor density, along with achieving an unprecedented precision for the distribution of frequency and time references. Combination with accurate measurement of the energy deposited gives the additional possibility of "5D"-capabilities.

- High-performance sampling (TDC, ADC):
  High-4D resolution requires a solution to the difficult noise-speed-resolution trade-offs in advanced technologies with low supply voltage and high transistor density;

- High-precision timing distribution:
  Distribution of precise frequency and time references remains vital for all readout-systems. The performance of these systems will be pushed to unprecedented levels by 4D sensors, for which they are a limiting factor. There are no ready-made solutions at hand, and the challenge is even bigger in radiation environments;

- Novel on-chip architectures:
  Adding per-hit timing information to high channel count ASICs results in a large increase in complexity. Novel architectures must be developed to manage this challenge as circuit size increases to cover larger detector areas.

DRDT 7.4 - Develop novel technologies to cope with extreme environments and required longevity.

- Radiation-hardness:
  In future particle physics experiments, particularly at energy-frontier colliders, particle fluences are extreme. ASICs, optoelectronics, powering devices, and on- or near-detector FPGAs must be designed and qualified for radiation-hardness;

- Cryogenic conditions:
  Cryogenic detectors offer high sensitivity and resolution for future neutrino and dark matter experiments, but are challenging for the operation of microelectronics. Readout of new sensor types (some operating at mK) requires thorough characterisation and modelling of ASIC technologies, exploration of new data transfer concepts, development of multiplexing technologies, and novel readout and control;

- Reliability, fault tolerance, detector control:
  Excellent monitoring and reliable control are crucial for detector performance and long-term stability. In harsh environments it is an open problem to achieve reliable control and monitoring in inaccessible areas without violating power, cooling or space constraints. Wireless communication may be a solution, but reliability in extreme temperatures, radiation and/or magnetic fields will be a challenge;

- Cooling:
  Sub-detector systems may consume tens or hundreds of kilowatts, predominantly in the front-end ASICs. At the same time sensors must be cooled to minimise leakage current and noise and to avoid thermal runaway. Critical technologies are micro-channels in silicon and novel heat-conducting materials.

DRDT 7.5 - Evaluate and adapt to emerging electronics and data processing technologies.

- Novel microelectronic technologies, devices, materials:
  A rolling R&D campaign is necessary to keep up with fast-moving and emerging technologies. Over the long timescales of HEP developments, one must not lose track of commercial evolution. For example, transistor structures in advanced nodes (FinFETs, Gate-all-around devices) will require thorough study of their behaviour and of the techniques for designing high performance circuits;

- Silicon photonics:
  Silicon photonics is at an early stage of maturity and is new to the HEP community. A robust R&D programme is required to qualify the technology. In case of success

an entire design ecosystem must be put in place to enable its coordinated use across institutes and laboratories;

- 3D integration and high density interconnects:
  Increasing channel density combined with enhanced functionality per pixel can only be managed with sophisticated 3D integration and interconnect technologies. 3D stacking must urgently be explored to combine analogue, digital and photonic functions. 3D integration of sensors with ASICs is critical and even more demanding. Access to reliable and affordable flip-chip processes, redistribution layers, stitching and ACF / ACP will also be important;

- Keeping pace with, adapting, and interfacing with COTS:
  COTS computing (CPUs, GPGPUs, FPGAs, AI accelerators) and networking equipment increases performance at breathtaking pace. Since it is targeted mostly at cloud data centres, use in HEP requires adaptation and integration both at the hardware and software level. This is challenging work which needs to be repeated for every new generation of COTS.

7.5.2 Approach to R&D

7.5.2.1 Novel Developments

An R&D roadmap by definition must provide a planned and prioritised route to produce well-understood deliverables. As indicated throughout, the increasing costs and complexity of HEP microelectronics and computing mandate such an approach. However, transformational "blue-sky" R&D must not be lost from the field of particle physics. Excessive planning and rigidity in the allocation of resources therefore also poses risks. A strong point in the particle physics community always has been tolerance and relative freedom for bottom-up initiatives including "crazy ideas" pursued quickly using the expertise, infrastructure and resources of well-equipped institutes. Scientific as well as technical staff have throughout the decades been highly motivated to find solutions for impossible tasks, or simplifications and cost savings for overly complex and expensive plans, and this has led to success. The Roadmap must provide sufficient freedom for new developments to be pursued as they arise, for rapid solutions to be found to urgent problems, and for clever ideas that have been promoted for many years, but never sufficiently prioritised, to be followed up (as also emphasised in Chapter 10).

7.5.2.2 Horizon-Scanning

Even established technologies are never static, and emerging ones can quickly become mainstream. It is therefore important to maintain a rolling survey of the technological environment and constantly question particle physics R&D directions. This naturally starts with attending conferences and workshops inside and outside HEP, but does not stop there. Building concrete hardware and software demonstrators to evaluate new proposals and assess their relevance to the field of particle physics is a mandatory part of the Roadmap.

7.5.2.3 Software

In industry, software frequently drives innovation. Many impressive recent chip developments are made to run specific software, e.g. matrix / tensor operations required by ML frameworks. Conversely, good software is crucial for the market success of hardware. Since skilled developer resources are scarce and expensive, software frameworks that increase productivity and allow harnessing of full hardware potential have a tremendous advantage, and this will usually trump notionally better hardware. There are obvious improvements to be made in HEP software development: in training, in component re-use, and in avoidance of duplication. Most importantly, the importance of long-term software support must be recognised and funded. Making software re-usable beyond a specific experiment or project is a significant extra effort. However, re-use of software within and outside HEP (e.g. as for ROOT or Geant4) is a tremendous gain for the whole scientific community. This trade-off and long-term model must be taken into account when resourcing larger software projects.

7.5.3 Practical and Organisational Issues

7.5.3.1 Collaborative Model

The Roadmap encompasses significant new short- and long-term activities, requiring concentration of investment and expertise. The international working model must be improved to avoid dispersed, uncoordinated, and parallel activities. An emphasis on open common developments, which can be implemented and specialised in the context of particular projects, is needed. This approach has sometimes been in tension with other drivers: a focus on specific projects as opposed to R&D; a wish to pursue "important" or "sole supplier" projects as opposed to shared or incremental work; and a desire to re-use private in-house IP and tools across projects. While understandable, these issues have sometimes led to grossly inefficient use of resources, redundant work, and even failure of developments. In the worst cases, effectively identical developments arise even within single experiments, implying a weaker effort by all parties, and a multiplication of ongoing support and maintenance load. This will not be tenable in the future (as also discussed in Chapter 10).

The community worked together to address the huge challenges of LHC via the CERN RD programme. The structure of long-lived semi-formal R&D collaborations, self-organised but with governance and support (financial and technical) from large laboratories, is still relevant: RD53 has demonstrated success for the most significant technical challenges posed by HL-LHC. This "RD nouveau" approach must encompass the full spectrum: not just for near-term collider projects, but for non-collider experiments and (crucially) long-term projects where basic feasibility has to be demonstrated. CERN has a central role, but in the "Tier" model, not as main sponsor of every development.

Developments in the coming decade will exceed the capabilities of even the largest groups, using entirely new technologies. An open collaborative model is vital. This will depend on the establishment of trust, best achieved within RD collaborations, and on a collaborative framework for open hardware, firmware, software and documentation, including a common licensing strategy. A key aspect, with a long and successful tradition in HEP, is the definition of common standards, implying adoption of relevant commercial standards (e.g. the use of xTCA hardware) and definition of standards for custom developments. Examples of the latter include: upper-layer readout and control link protocols; interfaces between ASICs; interface definitions and design rules for circuit blocks; and common interfaces to control software.

7.5.3.2 Demonstrators and Common Developments

Tracking industry developments and advancing the state-of-the-art requires an incremental, continuous approach, where demonstrators and proof-of-concept systems are regularly developed. It is important to continuously learn and gain experience, as it is very difficult to skip generations of technologies, when important changes accumulate. Resources must be provided to allow this, even outside the upgrade cycles of major experiments, and without firm commitments of experiments to use the exact same product. For such developments, documentation, support and dissemination are even more important than for projects directly targeting a specific facility.

In this context, common developments (i.e. joint work undertaken with intended application to a number of projects) have obvious advantages: they can rely on a broader base of resources, both material and human; they can leverage more expertise; and they have a larger potential user-base for testing. On the other hand, common developments are not without risk. Broader applicability leads to more generic and flexible designs, which can increase cost and complexity. Re-usability also requires that projects follow well-defined development practices, so that information can be understood, updated and maintained outside the immediate team. A common development calls for a substantial long-term support effort since an entire community may rely on it. This is a frequently forgotten dimension that in the past has led to failure of such developments after initial enthusiasm. Involving larger laboratories can help, but such maintenance effort always needs to be justified and funded. This implies measurement of take-up and added value in the community. Conversely, and yet more dangerously, several common projects for LHC upgrades have ended up with only one institute carrying the projects to completion. The optical links and DC-DC converter projects for the LHC are an example, depending entirely on a single CERN group. It is important to spread the load, risk and expertise better across the community in the future, and to fairly support and acknowledge the invested effort. A "tiered" model may help in this respect.

7.5.3.3 Infrastructure Needs

HEP electronics R&D depends on the availability of well-funded and extremely well-equipped laboratories, and the field is fortunate to have many institutes which have historically made such investments. However, the cost (both purchase and maintenance) of very-high-end test equipment and assembly facilities now presents a challenge even at national laboratories and CERN. This will become yet more significant as HEP embraces new technologies in photonics, wireless, etc. It is essential to ensure that, where such investments are made, facilities are available for a wide range of users and developments.

It would also be beneficial to ensure that investments in large-scale facilities are made in a coordinated way, reflecting the specialisms of institutes, such that good coverage is obtained collectively. A prominent example of the above is the availability of ASIC high end test, verification and radiation exposure facilities. These are barely sufficient to support the collective development effort on ASICs at the present time, leading to delays and compromises across projects, and this problem will soon become even more acute.

Distributed common projects also need well-supported IT infrastructure, including services for collaboration support, source code repositories, and infrastructure for continuous integration and testing. These systems need software licenses and massive CPU capacity for the simulation of ASIC and FPGA designs, and are most easily hosted in large laboratories with full-time IT teams.

7.5.3.4 Interaction with Industry

HEP laboratories and experiments are rarely a commercially important customer for industry. However, industry is often willing to engage in collaboration based on the intrinsic technical interest of particle physics problems, the reputation of the field, and access to highly talented young people for recruitment. Large laboratories such as CERN are clearly well-placed here, and have an important "door-opening" function with industry. In offline computing, the CERN OpenLab [Ch7-17] is a good example of how this can benefit the community when multi-party projects are hosted, and most of the academic work is done by institutes other than CERN. When dealing with global industrial partners, it is important that the HEP community speaks with a single coordinated voice.

While key components like chips, optical fibres, and back-end electronics are produced commercially, access to industry know-how and proprietary information is critical for obtaining optimum performance in extreme experimental conditions. Some specific packaging and interconnect requirements of HEP (e.g. ultra-compact or very-low-mass assemblies), are however not a focus for the microelectronics industry, and progress in these fields relies on close and continuous collaboration with a limited number of specialised research institutions.

Co-design with industry is attractive and important, but it has to be kept in mind that industry's market focus and short time cycles also induce the risk that technologies can be obsoleted at very short notice. Since particle physics developments often need to be aligned with long-term schedules, it is important to have a long-term forward view of industry developments. This is usually only possible through long-term partnerships and in most cases requires legal agreements such as non-disclosure agreements (NDA) with relevant firms. Due to the distributed nature of particle physics collaborations, it would be very useful to define a legal framework where only a single point of contact engages with firms and then audits its collaborating members internally to make information available, without the need for multi-lateral NDAs or individual negotiation of licenses, NDAs and SLAs, thus avoiding much of the repetitive legal work.

References Chapter 7

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Chapter 8

Integration

8.1 Introduction

This chapter is concerned with R&D topics of integration, including tracker mechanics and general detector mechanics topics, cooling systems and on-detector cooling contacts, detector magnets, machine detector interface, monitoring systems of all sorts as well as purification systems for liquids and robotic systems.

Here, a clear distinction is made between “R&D topics” and “engineering challenges and prototyping”. The R&D topics listed in this section focuses on items that need major development before deciding whether and how to implement them in a given system. Many other items of future detectors represent significant engineering challenges and need extensive prototyping, but the state of the art is sufficiently mature that extensive further R&D is not required to allow implementation at the time of detector realisation. Examples are dry gas supply, e.g. membrane plant from industry to provide oxygen depleted air, dewpoint measurement - sniff and measure with commercial dewpoint meters outside volume, leak cables, survey, 3D laser scanning, virtual/augmented reality, neutron moderators, cooling transfer lines (triple-jacketed vacuum pipes, capillaries), thermal shields, thermal insulation, large movement systems for the neutrino near detectors, safety systems and gas chromatographs, sonar systems to measure gas mixtures.

Gas recuperation systems closely coupled to the specific detector gases are discussed in Chapter 1. Accessibility, repair and partial exchange capability have to be thoroughly taken into account at early stages of specific system design/engineering and also studied at early mock-ups. Also cables, especially low impedance and micro-cables/flexes and their respective connectors should be engineered and prototyped from the beginning but no genuine common R&D is proposed. 3D printing enters the particle physics field at many places and should be exploited for R&D and early prototyping and access to such facilities will be largely beneficial.

The main Detector Research and Development Themes DRDTs for the integration aspects are:

DRDT 8.1 - Develop novel magnet systems.

DRDT 8.2 - Develop improved technologies and systems for cooling.

DRDT 8.3 - Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.

DRDT 8.4 - Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects.

The timelines for the above themes can be found at Figure 11.1 showing that for all the half-decade blocks shown in Figure 3 and Figure 4 of the Introduction, there are facilities requiring R&D in each of these areas. Indeed, these are the four key research developments without which future experiments cannot function and which are in need of major development effort. Interfaces to cold detectors and purification systems are further demanding necessary developments, as particularly emphasised in Chapter 2.

8.2 Main drivers from the facilities

The main drivers for developments in the near future are the existing and approved facilities like the HL-LHC, Belle II and EIC. The requirements for detectors at these facilities fall broadly into two categories, namely "radiation dominated" experiments like ATLAS, CMS, LHCb where radiation hardness dominates most of the choices and "lower radiation exposed" experiments like ALICE, Belle II, Mu3e and EIC where luminosity levels are moderate and precision vertexing and PID are key elements. The detector developments for the HL-LHC hence form a preparation for a future high-energy hadron collider, while ALICE, EIC, Belle II and Mu3e are natural stepping stones for R&D towards a future e^+e^- "Higgs factory" collider.

Figure 8.1 puts these developments into perspective of the future facilities.

8.3 Key technologies

8.3.1 Novel magnet systems

The LHC detectors ATLAS and CMS are currently operating large scale superconducting magnets that are important references for the development of future experiment magnets. Table 8.1 lists some examples of future magnet systems that represent the spectrum of engineering challenges and R&D needs for this topic. Detector proposals at future colliders like ILC, FCC-ee, CLIC, FCC-hh or Muon colliders use superconducting solenoids for the momentum spectroscopy. In addition to the choice of size and magnetic field for these solenoids there is the principle choice of whether to place the coil in front of the calorimeter system or behind the electromagnetic or hadronic calorimeter. Proposed detector systems placing the coil behind the calorimeter result in very large magnets of 3-

Accelerator	Detector	B [T]	R[m]	L[m]	I [kA]	E [GJ]	comment
LHC	CMS	4	3	13	20	2.7	scaling up
LHC	ATLAS solenoid	2	1.2	5.3	7.8	0.04	scaling up
FCC-ee [Ch8-1]	CLD	2	3.7	7.4	20-30	0.5	scaling up
	IDEA	2	2.1	6	20	0.2	ultra light
CLIC [Ch8-2]	CLIC-detector	4	3.5	7.8	20	2.5	scaling up
FCC-hh [Ch8-3]	main solenoid	4	5	19	30	12.5	new scaling up
	forward solenoid	4	2.6	3.4	30	0.4	scaling up
IAXO [Ch8-4]	8 coil toroid	2.5	8x0.6	22	10	0.7	new toroid
MadMax [Ch8-5]	dipole	9	1.3	6.9	25	0.6	large volume

Table 8.1: Examples of magnets for future experiments that represent the engineering and R&D challenges. The dimensions and fields refer to the free bore. The magnets for ATLAS and CMS are given for reference.

5 m bore radius and they represent scaled versions of the CMS coil, the largest ones being the FCC-hh coil. The development of next generation Al-stabilised high yield-strength Rutherford cable conductors for 30-40 kA and prototyping are needed for realising these magnets. Coils placed in front of the calorimeters have to be ultra-thin and represent $< 1\,X_0$. Preliminary designs show that thin conductors based on Al/Cu/NbTi together with a cryostat made from an Al honeycomb structure can achieve this goal for a coil of 4 m bore diameter and 2 T field. R&D on dedicated conductors and prototyping is needed to achieve these goals. In the long term, the development of high temperature superconductors for coils and current leads would remove the need for He temperatures and allow operation at 30-40 K. Some detector proposals use dual solenoids instead of iron yokes for shielding of the magnetic field and the R&D for assemblies of this size still has to be performed.

The magnets for non-collider experiments are mainly related to axion searches that either make use of existing accelerator magnets or propose dedicated large volume magnets, the largest one being MadMAX with a 9 T/1.3 m bore magnet, which requires extensive R&D.

Development of quench protection, energy extraction and high voltage designs for coils with high energy/mass ratios is also needed.

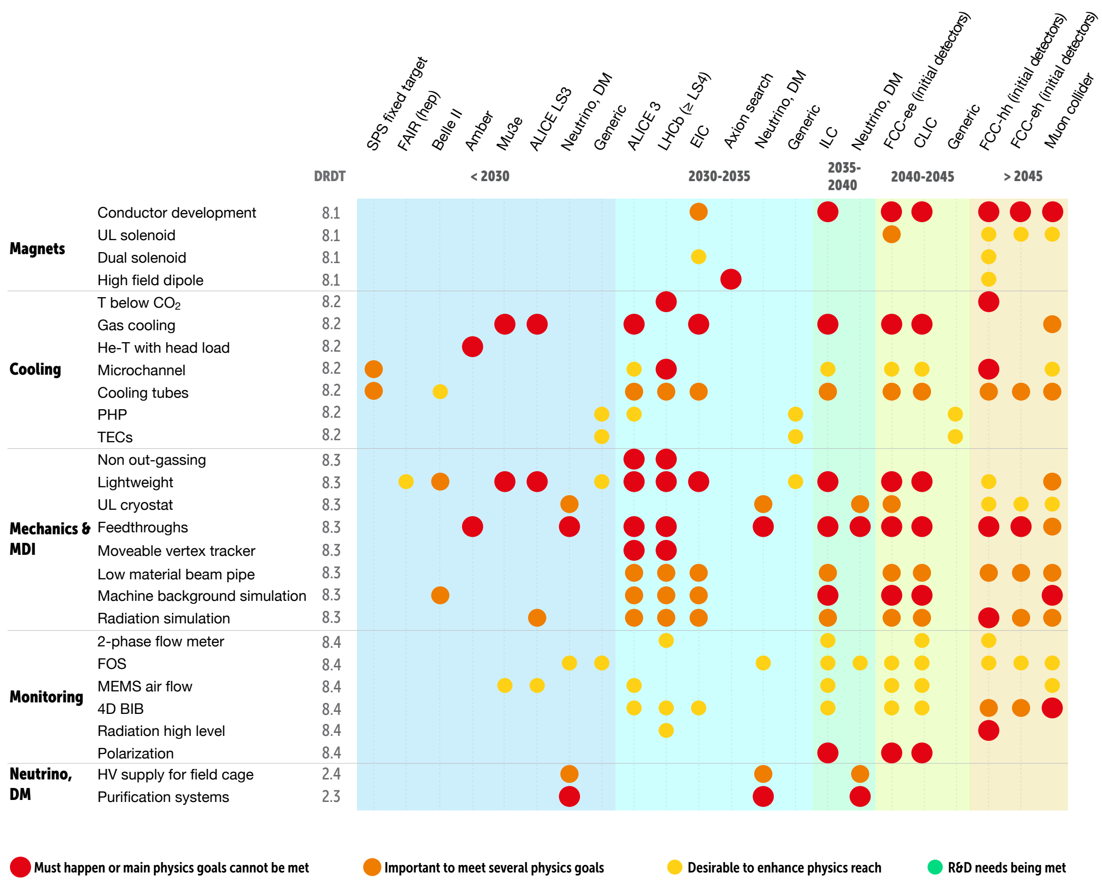

Figure 8.1: Schematic timeline of categories of diverse R&D topics of integration together with DRDTs and R&D tasks. The colour coding is linked not to the intensity of the required effort but to the potential impact on the physics programme of the experiment: Must happen or main physics goals cannot be met (red, largest dot); Important to meet several physics goals (orange, large dot); Desirable to enhance physics reach (yellow, medium dot); R&D needs being met (green, small dot); No further R&D required or not applicable (blank).

8.3.2 Improved technologies and systems for cooling

Cooling is a central topic for all future detectors with very different requirements. Scaling up of current cooling systems will work for some applications, but others need long-term R&D for refrigeration systems, detector intrinsic cooling contacts and transfer/distribution lines. Cooling needs to be applied to electronics (Chapter 7), irradiated semiconductor sensors to avoid thermal runaway (Chapter 3) and to silicon photomultipliers (SiPMs) decreasing dark count rate and in general sensor noise (Chapter 4). Cryogenic systems without significant heat load are typical examples where industrial solutions exist and engineering scale-up is possible, e.g. for liquid calorimeter, Neutrino and dark matter detectors (Chapter 2). No R&D is advised for any fluorocarbon or other greenhouse cooling liquid.

Transfer lines and detector internal capillaries must be considered at early stages of system design but, as long heat insulation and pressure can be accommodated, this is considered an engineering challenge and triple-jacketed vacuum pipes can run long and complicated paths.

8.3.2.1 Cooling systems

The key parameters are minimum temperature (operation), highest expected temperature (annealing/start-up/commissioning) and especially power density. Expertise in standard mono-phase and bi-phase operation exists in the community, while operation in supercritical mode (special monophase cooling with favourable properties for heat and mass transfer due to very high heat capacity and very low viscosity) has been less explored so far.

Above heat loads $> 0.15\ W/\text{cm}^2$ bi-phase cooling is the preferred choice and in HEP, temperatures down to -45°C are today's standard with CO_2 scaled to several hundreds of kilowatts – 2PACL [Ch8-6], [Ch8-7] and adapted industrial R744 systems [Ch8-8], [Ch8-9]. For CO_2 additional R&D would be necessary to go above 1 W/cm^2 or to higher temperatures (above 20°C). For temperatures lower than -45°C different cooling media and cycling technologies needs to be explored. Figure 8.2 gives an overview of the different temperature regimes, potential use cases and promising liquids.

LHCb is seriously looking into this regime for VELO-3 during LS4 and FCC-hh is interested in this as well. For cooling systems using Krypton (evaporative and supercritical) a new cycle technology is needed as cool down starts from gas phase. Mixtures of N_2O/CO_2 could be considered for lower heat fluxes, e.g. for SiPM applications, as N_2O has the same properties as CO_2 but at lower freezing point (100% CO_2 > -55 °C / 100% N_2O > at -90 °C).

For low heat loads below $0.15\ W/\text{cm}^2$, standard monophase, supercritical or even air flow cooling can be considered. In addition, Lepton and Ion collider are less affected by radiation thus can be cooled to only moderate temperatures. Monophase water or Novec[1] cooling with ultrathin pipes could be engineered. Warm evaporative or supercritical CO_2 cooling systems would need dedicated R&D.

[1] Fluid with thermo-physical properties similar to C_6F_14 and a very low global warming potential.

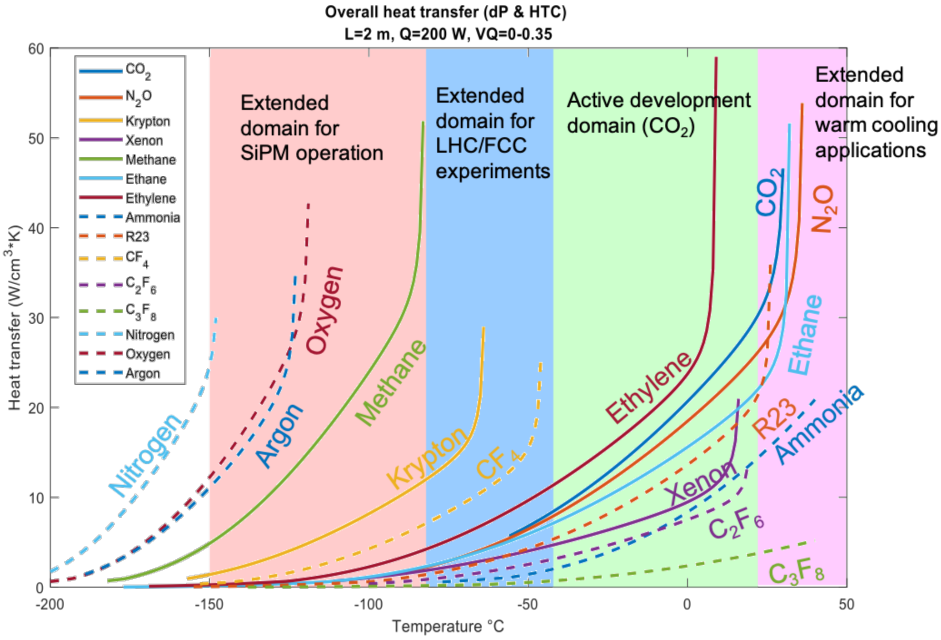

Figure 8.2: Potential liquids for the different temperature and power density regimes.

Another very promising path is air cooling (or e.g. Helium gas cooling) where the full geometrical design of the structure must be entirely designed to this goal from the very beginning, to guarantee that the cooling flow reaches all relevant surfaces in the detector. Collider detectors with moderate radiation load like ALICE, EIC can be stepping stones to inform later lepton experiments. The development of early small-scale generic systems will be useful to inform later dedicated engineering prototypes – a good use case for 3D printing. In addition, dedicated R&D is necessary for the cryogenic tracker in the AMBER experiment [Ch8-10] to achieve temperatures below 1.8 K with power dissipation of 10 W.

8.3.2.2 Local Cooling / Cooling contacts

Thermal management within the detector, tying in with the requirement to minimise material budget, is one of the biggest challenges for tracking detectors. The key parameters are heat produced at the source, maximum temperature of the source, uniformity and stability, thermal interface/contact, space and material budget considerations, reliability and lifespan. The important factor to minimise is the Thermal Figure of Merit $TFM = \frac{\Delta T_{sensor-fluid}}{SurfacePowerDensity}$ competing with the amount of contact material (radiation length X_0).

As discussed in the previous section for air cooling the aerodynamic systems properties are important. With substantial R&D these can be improved by liquid assisted air cooling, guiding micro-fluid (e.g. CO_2 or Novec) through porous carbon foam as radiator/heat exchanger. Development on cooling to foam interface and miniaturisation seems important as well as choice of the foam itself.

In dense environments Polyimide or Carbon Tubes embedded in light-weight support structures, e.g. high conductivity carbon plates are an established concept to be engineered to the specific system. A common database of tubes properties (material, diameter, wall thermal resistance, deformation under pressure, heat transfer coefficient, cooling compatibility bending, radiation tolerance, possible connections, 3D printable, source, etc.) as well as thermal interface materials is important and should be systematically realised and continuously updated.

Three more complex concepts of thermal interfaces need to be further developed, Thermo Electric Coolers (TECs), micro-Pulsating Heat Pipes (PHPs) and microchannel cooling, the probably ultimate low TFM. Examples of these concepts are displayed in Figure 8.3.

TECs, micro-Peltier elements, are available in industry, and are useful to locally decrease the temperature further. Advantages include: no moving parts, precise temperature control, radiation tolerance, no maintenance. Disadvantages include: low efficiency, high X_0 and the need of an additional heat sink. Improvement on efficiency and more miniaturisation would be beneficial. They are the baseline choice for the Phase-II CMS Barrel Timing Detector cooling SiPMs.

PHPs work without wick/capillaries and need no return flow but need power at the source. PHPs have potential as secondary cooling circuits, pre-integrated into an ultra-light support structure, potentially also 3D printed, e.g. connected directly to pixel sensors [Ch8-11], [Ch8-12], [Ch8-13].

Microchannel cooling [Ch8-14], [Ch8-12] comes in a large variety and seems to have the potential to minimise the TFM but R&D is necessary to overcome current drawbacks and to develop standard solutions which can then be highly customised. Microchannel cooling is already applied in NA62 (liquid FC-72) [Ch8-15] and LHCb-VELO (bi-phase CO_2) [Ch8-16]. In general, the micro hydraulic connectors are fundamental bottlenecks. Current thermo-mechanical structures can be realised in silicon (potentially integrated/etched directly into sensor/CMOS wafer), ceramic composites, metal alloys or ultra-thin polymer pipes in carbon/graphite matrices but future developments should not be limited to these. It should be investigated how far 3D printing can be exploited here. The concept allows monophase, bi-phase or supercritical operation directly connected to the full heat source surface. For silicon microchannel cooling, well established in MEMS technology, the brittleness, cost and size limitations should be overcome.

8.3.3 Novel materials to achieve ultra-light, high precision mechanical structures

Ultra-lightweight support mechanics are the big challenges for tracking detectors and cryostats for calorimeters and magnets in all collider experiments to minimise multiple scattering of particles, brems-strahlung, photon conversions and nuclear interactions. Aspects to be taken into account are a high radiation environment, dynamic stability under external vibration, stability under temperature and humidity variations, high

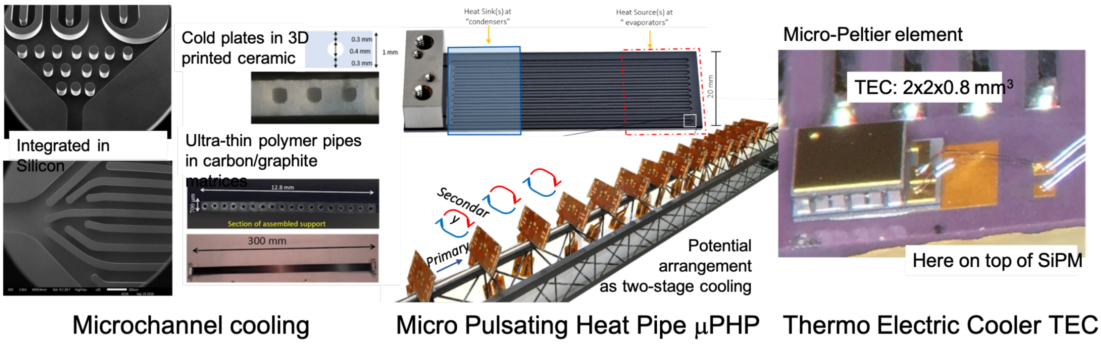

Figure 8.3: Local Cooling Concepts to develop further: Microchannel, micro-Pulsating Heat Pipe and Thermo Electric Coolers.

required thermal conductivity, non-flammability, minimum mass (low X/X_0), non-out-gassing and sometimes the need for electrical insulation, and all inherently linked to the cooling requirements to minimise TFM. Low X/X_0 is even more important for lepton (ILC, FCC-ee, CLIC) and ion experiments compared to hadron experiments (HL-LHC, FCC-hh). References [Ch8-17], [Ch8-18], [Ch8-19], [Ch8-1] give examples of requirements and provide perspective for this section.

Also here, a common updated database with full characterisation of all potential materials; being it for support or cooling tubes, or microchannels (Thermoplastics, Polyimides, ceramic composites, CF sheets, Carbon foams, Graphene, etc.) but also resins and potting or insulation material; is key to success. The database should also cross reference which materials can be easily connected/embedded together. R&D improvements on lighter thin pipes and channels, carbon microvascular plates, CF plates, thermal pyrolytic graphite and carbon foam is encouraged. Novel materials like nano-material, thermal conductive carbon nanotubes fibres should be investigated profiting from industrial advances. For resin systems, thermoplastics and nano filled resins (nano composites) seem promising. Carbon foams can be used as radiators in gas cooling applications and many foams are available from Aerospace to be characterised.

Easy access to wind tunnel testing facilities seem necessary to validate gas cooling on mock-ups, checking mechanical stability and oscillations for optimisation and final validation. Another aspect to explore is light weight mechanics that can be partially transparent to gas flow, as specifically needed for self-supporting silicon devices, e.g. DEPFET in Belle II and bent sensors for the ALICE upgrade during LS3.

Entry windows for fixed target experiments and inner detectors walls in front of the first layer should be minimised. Studies on very thin Beryllium, Aluminium, AlBeMet, etc. should be conducted, and also carbon composites should be investigated. Studies on non-out-gassing material for devices within vacuum applications is mandatory.

R&D on fabrication methods should be pursued together with standardisation; key considerations include micro-fabrication, additive manufacturing, and inter-connectivity. As of today, modules are attached to long cooling pipes while a "LEGO" concept, with partial cooling pipes embedded and then attached together, would facilitate large systems in a leak tight fashion.

Lighter and thinner cryostats for superconducting magnets and calorimeters must be investigated, as well as lightweight coils themselves. This is also relevant for some neutrino detectors, i.e. in between sensitive volume and downstream (muon) detectors. Aluminium honeycomb panels represent an attractive solution. Potential advances in industry and aerospace can be exploited, e.g. of developments for liquid oxygen and hydrogen tanks. Aluminium could potentially be replaced by Ti, carbon composites, high and ultra-high modulus Carbon Fibre Reinforced Polymer (CFRP) or carbon sandwich structures thereof. R&D in industry on sandwich/flute designs, thin plies, out of autoclave materials and winding/tape deposition as well as Ultra-High Vacuum (UHV) seal joints should be evaluated and tested. Figure 8.4 shows state-of-art examples of cooling pipes, new materials and cryostats.

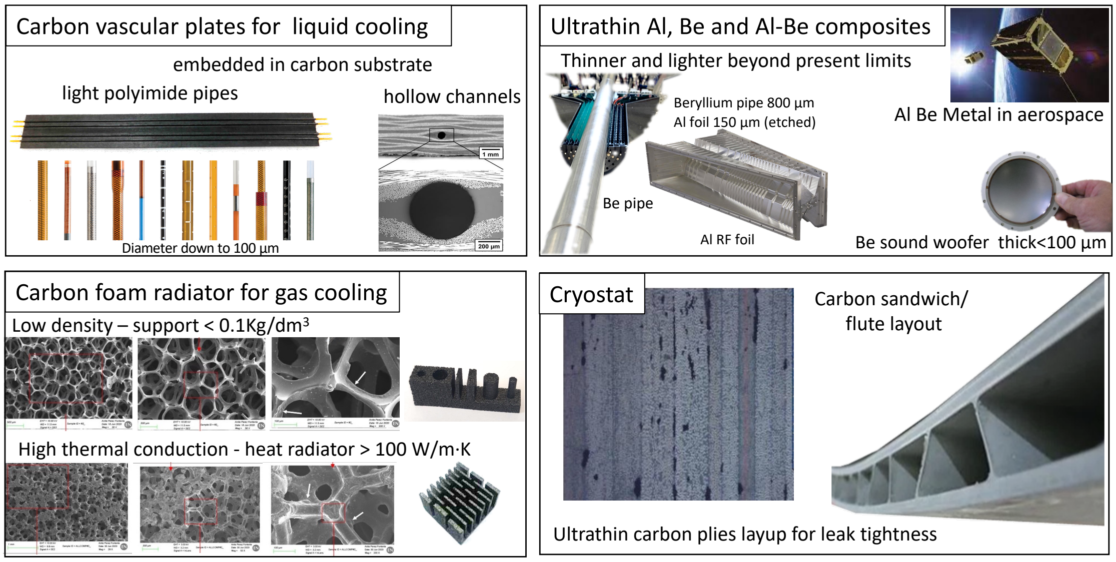

Figure 8.4: State-of-art examples of pipes, embedding, new materials for beampipes, entry windows and support structures and also cryostats systems.

8.3.3.1 Machine-detector interface (MDI)

Machine-detector interfaces differ significantly between the different accelerator types as indicated in Tables 8.2 and 8.3. An important difference between hadron machines and e^+e^- machines concerns the position of the last machine elements i.e. the final focusing magnets, that determines the space for detector elements. For the FCC-hh these magnets are placed at a distance of 40 m from the IP, while for the FCC-ee this distance is just 2.2 m. For e^+e^- accelerators the integration of detector and machine elements is therefore a prime challenge. For circular e^+e^- machines the synchrotron radiation hitting these machine and detector elements is a significant source of background and is therefore strongly interleaved with this integration question. The further development and application of reliable simulation tools for background simulations and benchmarking at existing facilities are therefore of utmost importance.

The central beampipe is the most direct interface between accelerator and detector. Beampipes with minimum amount of material as well as the smallest possible radius are key elements for the physics exploitation at all machines. Impedance and vacuum quality are key parameters for the machine performance. In addition, for e^+e^- machines these beampipes have to be cooled. Engineering, simulation of background, impedance and vacuum as well as prototyping are key R&D topics in this context. Vertex trackers in secondary vacuum vessels that are dynamically moved close to the beam after injection are a very effective possibility for significant improvement of the tracking and vertexing performance. LHCb is exploiting this already at the LHC and future proposals like the ALICE 3 detector are planning for such installations. While the development of the focusing magnets and other machine elements is typically part of the accelerator project, the support and alignment of these is an integration challenge that concerns the detector, and topics like remote vacuum connection have to be designed together.

		LHC	HL-LHC	FCC-hh	EIC	LHeC
E	GeV	7000	7000	50000	10/275	49.19/7000
L	$10^{34}\text{cm}^{-2}s^{-1}$	2.1	5	5-30	1	23
Angle	mrad	0.26	0.5		25	0
Bunch	ns	25	25	25	10	50
L^*	m	23	23	40	4.5	10
B det	T	2/4	2/4	4	1.4	3.5
r_{pipe}	cm	2.35/2.1	2.35/2.1	2.5	ell.	ell.

Table 8.2: Examples of accelerator parameters for future hadron accelerators machines that represent the MDI R&D challenges [Ch8-20], [Ch8-3], [Ch8-21], [Ch8-22].

		KEKB	FCC-ee	ILC	CLIC
E	GeV	4/7	45.5/120/182.5	125/250	190/1500
L	$10^{34}\text{cm}^{-2}s^{-1}$	80	230/8.5/1.6	1.4/1.8	1.5/6
Angle	mrad	83	30	14	16.5/20
Bunch	ns	4	20	554, 5Hz	0.5, 50Hz 231
L^*	m	0.77/1.11	2.2	4.1	6
B det	T	1.5	2	5	3.5-5
r_{pipe}	cm	1	1.5(1)	1	3

Table 8.3: Examples of accelerator parameters for future e^+e^- machines that represent the MDI R&D challenges [Ch8-23], [Ch8-1], [Ch8-24], [Ch8-2].

Radiation simulations are crucial for the following MDI topics: for e^+e^- machines, shielding is key for suppression of synchrotron radiation background. For hadron colliders the shielding is key for suppression of neutron background in the experiment cavern and for minimisation of energy deposit in the superconducting magnets. The activation of the elements has an important impact on access and detector maintenance. For muon colliders the shielding cones on both sides of the detector that are absorbing the muon decay electrons and positrons are a key MDI element that has to be optimised and simulated in detail. Multi-turn tracking of IP collision debris for optimisation of collimation schemes is important as well.

8.3.4 Monitoring

8.3.4.1 Environmental Monitoring

The community has established significant experience with environmental sensors and existing solutions can be scaled-up and engineered to the specific use case. Still there is room for improvement and standardisation, especially for radiation tolerant and small package devices. As safety systems must be simple and reliable, it is argued here that the usual overheating/-voltage/-current protection, RTDs (Resistance Temperature Detector) plus commercial dewpoint meters checking inlet gas quality and gas sniffed/pumped from the volume is adequate and no further R&D is recommended.

As many sensors, including radiation tolerant ones, exist and are in use at different experiments, a database with full characterisation and specification of sensors seems mandatory to avoid duplication of developments and characterisation. This is especially true for MEMS (Micro-Electro-Mechanical Systems), as they are available in industry but not systematically designed/tested for radiation tolerance [Ch8-25], e.g. pressure-, vibration- and flow sensors.

Opportunities are recognised for further embedding and for increased granularity of such sensors, eventually implemented in 3D printed metal tubes/tanks/feedthroughs, and for heat exchangers which could also be realised in carbon fibres (CF) structures. Fibre-Optical Sensors (FOS), e.g. Fibre-Bragg Grating Sensors (FBGS) are a well-established technology to measure e.g. temperature, deformation, stability and relative humidity [Ch8-26] if the correct coating is used. These sensors are established to be sufficiently radiation tolerant [Ch8-27] for the HL-LHC environment. There is ample development opportunity to standardise FOS and to provide templates for later custom solutions. The following challenges merit further development: increased precision, e.g. 0.1°C and utilisation in cryogenic environments, and increased sampling rate to achieve dynamic measurements, e.g. oscillations but maybe also flow and pressure measurements. A key target would be the embedding in CF to achieve real-time information on structure deformation/vibration at sub-μm level.

No adequate sensors for flow and vapour quality measurement in 2-phase cooling systems exist and these should therefore be developed. Also miniaturised gas flow meters embedded in the detector for gas cooled systems would be very useful, e.g. MEMS with vanes or sense hairs.

Position survey tools are mature and industry standard. The development of an easy to use and fast to deploy system for maintenance and re-assembly procedures would be very useful, as well as radiation tolerant and miniaturised distance measurement devices/cameras for opening/closing systems. It has to be mentioned that some systems e.g. the BEAMCAL luminometer [Ch8-28] have severe requirements on placement precision, i.e. $50\,\mu$m for linear and $1\,\mu$m for circular colliders.

8.3.4.2 Beam and Radiation Monitoring

Beam Loss, Beam Induced Background, Luminosity

Beam loss protection devices exist and should continue to be improved and adapted to specific use cases. Beam loss monitors need to be radiation tolerant and of small size as they must be located in the inner detector. They must be 100% available and reliable, fast enough to provide beam aborts/interlocks, and neither sensors nor electronics should be susceptible to saturation. Diamond and sapphire detectors are good candidates.

Beam condition/background monitors must be radiation hard and small due to the preferred closeness to the beampipe and high-rate capable to allow bunch-by-bunch information. 4D-tracking (time & space) as well as directional measurement devices able to discriminate between collision and Beam Induced Background (BIB) should be developed. BIB measurements with timing capability seem especially important for a future Muon collider with $\sim 10^8$ BIB particles in a single event.

Luminosity determination is a key challenge at all collider experiments and merits further development to achieve a bunch-by-bunch error below 1% (goal for HL-LHC). Individual luminometers need at least a 0.7% precision on calibration and linearity with good stability and an understanding of systematic errors at the per mille level. Linearity is key to calibrate with Van-der-Meers scans from multiple interaction per bunch crossing of 0.5 to 200 (HL-LHC) or even 1000 (FCC-hh). R&D addressing the system level must either produce fast analogue front-end electronics or a low occupancy, thus high granularity, system or both. A specific calometeric luminometer BEAMCal is described in Chapter 6.

Polarisation measurement at ILC, FCC-ee and CLIC

The polarisation measurement of the up- and downstream e^+e^- beams is an essential combined experiment and accelerator R&D endeavour. The complete systems (magnet, laser, alignment system, vacuum guiding, position sensitive Compton electron detector, e.g. quartz Čerenkov) has to be developed as a package. Specification and radiation tolerance of the system has to be defined by the experiments. More details can be found [Ch8-29] for FCC-ee and [Ch8-30] for ILC.

Radiation Monitoring

The community has a vast experience with radiation monitoring and this needs to be continuously improved, especially in view of the future higher levels (HL-LHC and FCC-hh) and higher energies. The challenge is threefold: improve simulation, measurement devices and cross-calibration of irradiation facilities.

There is an important need to maintain and improve the code for simulations of the underlying physics processes, e.g. cross sections, event generation at higher energies, etc. These tools are of utmost importance to understand longevity of detectors, remaining activation during maintenance periods but also to understand particle rates in systems or effectiveness of shielding, etc.

Further R&D on spectroscopic particle detectors should be supported, e.g. Medipix based detectors with specialised conversion targets. Also radiation-hard, small devices with low power consumption or on-chip dosimetry and fluence measurement is very interesting. Long term there is the need for devices to measure integrated values of $1{\times}10^{18}\,\mathrm{n_{eq}\,cm^{-2}}$ and 300 MGy Total ionising Dose (TID) not achievable with conventional p-in-n diodes. Radiation dependent resistors as NIEL monitor or Fibre based dosimeters (RaDFOS) [Ch8-31] might be candidates to explore further. For any new detector material NIEL (Non Ionising Energy Loss) studies (spectra) for different particle types and energy and interpolated to the mixed fields of future experiments are of the utmost importance.

To allow the thorough evaluation of such devices as well as other sensors, the network of radiation facilities should be fully utilised and improving standard methods, e.g. fluence measurements, cross-calibration and exchange of information (database) is strongly recommended (see also Chapter 10).

8.3.5 Calorimetry, Neutrino and Dark Matter Detectors

8.3.5.1 Calorimetry

The integration challenge for calorimeters has many aspects that are often tied to the specific detector design and that are therefore part of the project prototyping and construction effort (see Chapter 6). Many topics will also profit from progress in industry like e.g. 3D printing techniques. Collaboration on this technology will allow highly optimised absorber structures. There are however some general items that require R&D in order to be able to make specific choices for next generation calorimeters. Calorimeters using cryogenic liquids (see also Chapter 2) require cryostats that need to support the heavy weights but at the same time have to represent a minimum amount of material, as discussed in the previous section. The need of high granularity in future calorimeters also requires a large number of signals and services which calls for the development of compact data concentration and powering solutions and, for cryogenic detectors, of high-density signal feedthroughs. Access to cryo-laboratory facilities for generic testing and development is essential (see Chapter 10). Another topic that differs from industry needs is the radiation load, specifically for the FCC-hh with hadron fluence numbers up to $1{\times}10^{18}\,\mathrm{n_{eq}\,cm^{-2}}$. Radiation hard insulators, glues and other relevant materials have therefore to be identified and characterised.

8.3.5.2 Neutrino Detectors and Dark Matter Detectors

The next generation large scale neutrino detectors like DUNE or HYPER-K represent significant engineering challenges that are specific to the detector design. The large scale components for these facilities are developed together with industry. For prototyping of these detectors, facilities like the CERN neutrino platform are essential. Common R&D needs refer to purifiers for the production of ultra pure noble liquids with $< 30\,\text{ppt}$ of O_2-equivalent impurities and purifiers for ultra-pure water. Radio purity of these systems is essential to enable low energy physics studies (see Chapter 2). Reliable programmes for CFT calculations for evaluation of the distribution of ions, impurities and dopants have to be developed. R&D on scaled up HV systems, electrical insulation and cryostat feedthroughs for supply of the field-cage potentials is also needed. 3D printing of e.g. scintillator cubes or optical components like Winston cones are an interesting option for affordable large scale applications.

Radio purity is also a key topic for dark matter detectors. Access to radon free cleanroom facilities is therefore essential. The assembly of photosensors into highly efficient large area arrays is a crucial engineering challenge for dark matter detectors (see Chapter 4).

8.3.6 Robotic Systems, Survey

Robotic systems as well as positioning systems and sensors are being used and developed in industry at a large scale and the R&D efforts relate to their customisation for application in high energy physics. Integration of systems for heavy mass movement can make use of industrial solutions and the R&D is related to the development of the interfaces to the detector structures. Positioning systems and positioning sensors are available on the market and have to be customised in collaboration with industry. For magnetic field mapping and radiation mapping, R&D is required to allow the use of drones or blimps in the presence of magnetic fields and radiation. The development of robotic systems is certainly also driven by industry and the R&D is on the adaption to the radiation and magnetic field environment. A potential use-case would be regular inspection and fault detection in very confined, inaccessible and highly radioactive areas. Robotic systems for cryogenics environments, like the large Liquid Argon TPCs, are not available on the market and dedicated R&D is needed.
Finally, the significant radiation levels at future hadron colliders are calling for automated detector opening systems and automated insertion of radiation shields to allow the safe access of personnel for maintenance.

8.4 Observations and Recommendations

Many integration aspects require continuous R&D and the synergies unfold for the different detectors, e.g. local cooling contacts DRDT 8.2, lightweight mechanics DRDT 8.3 and all aspects of monitoring DRDT 8.4. Magnets DRDT 8.1 are very specific with some crucial R&D but long lead time items, e.g. the conductors.

There is a general sequence of use cases for LHCb Upgrade II, CMS/ATLAS partial pixels replacement in LS5 leading towards FCC-hh and on the other hand Belle II, ALICE 3 and EIC experiments clearly spearhead needs for future e^+e^- “Higgs factories”.

Discussions during and around the symposium showed the usefulness of 3D-printing for many aspects, especially for prototyping, and there is the need to continuously monitor and exploit advances in industry.

All aspects of integration are in high demand of continuous access to engineering resources and close collaboration with industry during R&D and also later design and realisation of the experiments.

Ultra-light cryostats are mandatory for noble liquid calorimeters, thin magnets in front of the calorimeters, and possibly for Neutrino experiments. Depending on the success on these in combinations with ultra-light solenoids, one could later reconsider experiment configurations toward smaller bore magnets.

Many developments will profit from central collections of information (databases) on items including their properties, e.g. glue, resin, lightweight materials, sensors, radiation monitors, cables, etc. Also all items from industry, characterised by the particle physics community must enter here.

Another crucial aspect is to continuously maintain and improve simulation tools, e.g. for detector development [Ch8-32], [Ch8-33], [Ch8-34], radiation, background simulation, activation [Ch8-35], [Ch8-36], gas flow dynamics and thermal management.

The necessity to have regular and easy access to test beams [Ch8-37] and radiation facilities [Ch8-38] cannot be emphasised enough. But also more generic access to wind tunnel experimental areas, cryogenic facilities and radon free clean rooms are essential.

It is mandatory to establish and maintain fora with regular intellectual exchange on these topics, e.g. the "Forum on Tracking Detector Mechanics", as such gatherings and exchanges are less common than sensor conferences.

It should be emphasised that aspects of detector integration cannot be done in isolation. There must be strong cohesion and collaboration with all detector Task Forces and technologies and especially with the second horizontal Task Force 7 Electronics (Chapter 7). For mechanics and cooling (DRDT 8.2 and DRDT 8.3 combining) effort with Task Force 3 Solid state detectors (Chapter 3) is especially important. Obviously, this becomes mandatory as soon as concrete system designs and their realisation starts.

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Chapter 9

Training

9.1 Relevance of instrumentation training

Particle physics experiments demand technology well beyond the state-of-the-art, with ever increasing complexity. Establishing novel technologies requires decades from conception to application. The detector development programme of particle physics experiments must be accompanied by a well balanced training programme aimed at preparing the next generations of detector developers required by the field and by industry. This should also contribute to train and motivate those who commit to the continuity in operation of existing complex detector systems. A successful training concept needs to be based on the following key points:

- Stimulate and recognise the field of instrumentation in particle physics and specifically the importance of innovation, detector development and operation;
- Attract and train outstanding talented individuals in physics and engineering;
- Recognise the diversity of skills needed in the field;
- Find an appropriate balance between specialisation and breadth.

Detector instrumentation training spans all career levels, from university courses, to (post-)graduate programmes, to specialised courses for professionals. An adequate and well structured programme needs to be developed which is well balanced between classroom, online and hands-on courses. It must provide access to modern infrastructures and also address geographic, nationality and gender diversity.

Scientists pursuing a career in instrumentation should be able to count on: recognition at all stages, e.g. dedicated scholarships, stipends, awards; opportunity for publications in high-ranked journals of technology and experimental methods; and attractive career prospects. Particularly this last point is of great importance for Early Career Researchers (ECRs) and has not been sufficiently addressed.

Establishing a successful long-term training programme in instrumentation is crucial for particle physics, since it ensures the continuity of highly qualified detector experts from R&D to construction and to operation of HEP detectors. It has also benefits for society, by providing a talent pool for industry and other sectors.

9.1.1 Junior ECFA input

As training is primarily dedicated to the education of less senior physicists, it was recognised that the input and opinions of Early Career Researchers (ECRs) were key elements in appreciating their perception of the existing provision, as well as to identifying improvements to better meet their needs. The ECFA - Early Career Researchers Panel was thus approached to provide direct input to the symposium. A working group was formed, and a survey was distributed about training in instrumentation and related issues. In total, 473 answers were collected in a very limited time, showing the strong interest of the ECRs in this topic. 80% of the participants were from Europe. A complete analysis document was produced [Ch9-1]. Here only a brief account of the most significant outcomes is possible.

A first message from the ECRs survey and the symposium debate is related to the general recognition and perception of instrumentation work by the community. Many junior physicists think that work in instrumentation, although of prime interest to them and moreover to their experiments, is not sufficiently recognised and could even be detrimental to their career. This negative perception needs to be further investigated by ECFA. If confirmed, corrective measures should be taken, and recommendations made. ECRs need to be deeply convinced that if they engage in instrumentation training and related subsequent commitments, this is not against their prime career interests. The same also prevails for ECRs who participate as trainers in instrumentation programmes. There is a wide belief among ECRs (with the exception perhaps of assistant professors - yet at a later career stage) that acting as trainers in instrumentation is not sufficiently rewarded. Unless this is addressed, it will be difficult to justify involving more ECRs in designing and implementing training programmes, which is one of the very fruitful measures to make such training more attractive (as horizontal training - ECRs to ECRs).

Out of the 473 respondents, more than 70% indicated that they are active in instrumentation (more than 20% of their time spent working on instrumentation). This is a very significant fraction that makes the survey findings quite relevant for planning training evolution. There were apparently no perceived differences between respondents based at universities compared to those at laboratories, which is contrary to the expectations expressed by some in the symposium.

Only 40% of the respondents felt that they had access to sufficient training in instrumentation, and in general ECRs feel that they are insufficiently informed of what is available. The global satisfaction of those who took instrumentation training, in all its diverse forms, is rather high. It is interesting to note that 60% of those who followed remote training were positive about it. Apparently, many feel that they lack training in the use of Open Source software tools that are frequently deployed for operating experiments. The same is true with respect to networking opportunities in instrumentation. This is one of the areas where ECRs working on instrumentation would benefit from significant improvements, as only 20% of the respondents felt satisfied with the networking opportunities. Developing networks or forums in instrumentation as well as training ECRs on "how to network" could be considered.

The ECR Panel report also mentions difficulty reaching young engineers who were not included in the initial discussions. It was highlighted in the ECR Panel's town-hall meeting that those involved in instrumentation can have a range of backgrounds involving physics and engineering, but the number of engineers responding to the survey was relatively low. A subsequent survey with an adapted questionnaire could be undertaken to collect their inputs on the issues discussed here.

Human and geographic diversity and inclusion issues are serious concerns in the ECR community that need to be properly addressed especially at the training level. Many of the respondents called for a wider inclusivity in training opportunities to help further improve diversity in the experimental community.

Last but not least, it is interesting to note the apparent division between analysis and detector physicists, which is perceived as a particularly pronounced feature of the LHC experiments, is really disapproved of by many ECRs. ECFA should take actions to remind the community that experimental particle physics is a highly varied activity that includes many career profiles, and ensure that the opportunities and recognition for training and work in instrumentation are appropriate in light of this variety.

In summary, the survey revealed that there is much interest and enthusiasm in the ECR community for instrumentation work, however there are also barriers. The ECR community is eager to work with ECFA and the rest of the community to improve accessibility to training and networks in instrumentation, and on better recognition for those who design and deliver training programmes.

9.2 Status of instrumentation training in Europe

The design and delivery of detector instrumentation and accelerator projects in high energy physics relies heavily on the expertise and experience of senior scientists, a specialised technical workforce, cutting edge facilities and a large number of students, postdoctoral researchers and early career scientists.

In addition to the main HEP instrumentation fields, such as: detector science, electronics, mechanics, materials science, programming (including that of FPGAs and for DAQ) and accelerators; scientists require continuous training in emerging topics. Examples include: quantum computing, detectors at the quantum limit, condensed matter, quantum dots, novel methods of acceleration and cryogenic detectors.

In order to attract young people to the field, early recruitment has to happen, starting with programmes designed for high schools, and then through instrumentation studentships and detector schools, or through graduate training and dedicated schools in the case of accelerators. In this section, the existing landscape of instrumentation and accelerators is reviewed in terms of: university courses (Section 9.2.1); dedicated graduate schools for HEP instrumentation in Europe and worldwide (Section 9.2.2); and specific programmes offered by the major European laboratories (Section 9.2.3). The status of accelerator training is reviewed in Section 9.2.4.

9.2.1 University programmes dedicated to HEP instrumentation training

Future instrumentalist in HEP typically enter the field through two main paths: Bachelor/Master in physics or in engineering. The challenges are different for the two paths. Typically, the physics students do not have sufficient access to training on detectors and technology, while the engineering students have limited knowledge of HEP to be attracted to this domain. To begin with, students need to be attracted to physics studies. Here, instrumentation activities at universities and visits to see local, national or international research infrastructures is highly valuable. It is important to have early opportunities for high school students to get in touch with experimental work. In the programme "Beamline 4 Schools" offered by CERN, high school classes may collaborate with local universities in preparation of the bids or experiments for the programme.

Once students have started physics studies opportunities for training in instrumentation vary between universities within each country and even more between countries.

To provide hands-on experience in instrumentation to students is one of the major challenges for university programmes. Few groups have access to infrastructure for hands-on training. Equipment used in nuclear physics laboratory courses can be used to give the first basic experience in instrumentation. Some universities have access to accelerator and state-of-the-art equipment on site that can be used in a coordinated way by a cluster of universities in the region. Bigger infrastructures at national and international laboratories should in particular be more intensively used for training.

Instrumentation has to be introduced already at bachelor level, if one wants to efficiently attract students to this area. There are many advantages with hands-on training compared to teaching in a classroom. Instrumentation is by nature multi-disciplinary, connecting theory with experiments, and where progress at the technology frontier requires teamwork amongst experts from differing backgrounds. Working on instrumentation also stimulates creativity and a healthy teamwork spirit. The successful experience of problem solving is often contagious and helps attract bright minds to particle physics.

At the ECFA symposium, a number of good examples of training programmes at undergraduate level were presented. In Germany there are several examples like those at the Karlsruhe Institute of Technology and at Heidelberg University, where the masters in physics offers an optional track towards instrumentation. These programmes integrate the students with the local research infrastructures and activities. In the Netherlands, instrumentation programmes connect to a broad range of application ranging from medical to cosmology. This clearly emphasises the multidisciplinary reach of the instrumentation field for the students. In Paris, an inter-university master is offered in the field of large instruments, plasmas, accelerators, etc. A programme called "Excellence by Experiments" provides eight experimental platforms in fields of nuclear physics, particle physics, astro-particle physics and astrophysics. Three of the platforms utilise the local 4 MeV accelerator. More examples certainly exist, but a clear overview is missing. Also, as far is known, an exchange between these programmes similar to the Erasmus initiative, but dedicated to instrumentation courses is not foreseen at present. This is why it is proposed to create and maintained a list of master programmes and schools

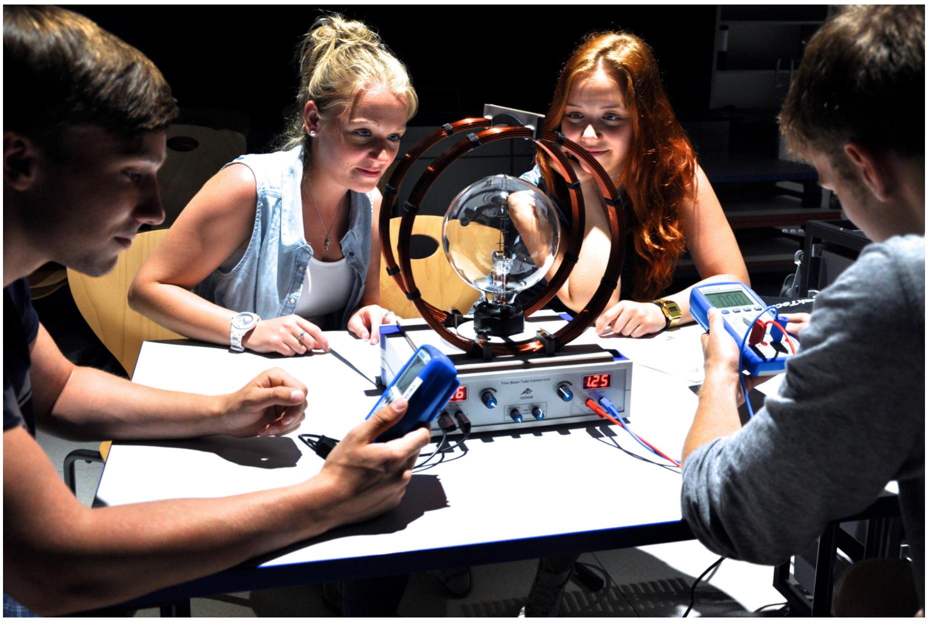

Figure 9.1: Students at CERN's S'Cool LAB [Ch9-2].

dedicated to instrumentation training. When compiled, this list will become accessible via the ECFA Detector Panel web pages at https://ecfa-dp.desy.de/public_documents/.

9.2.2 Graduate schools, doctoral and post-doctoral programmes dedicated to HEP instrumentation training

The content of this section draws heavily from the presentation of A. S. Navarro at the Symposium of Task Force 9 Training (see Appendix C), as well as input from the ECFA appointed National Contacts (as discussed in the Introduction).

Instrumentation schools play a fundamental role in the training of Masters/PhD students, postdoctoral researchers and ECRs, with Europe being at the forefront of organising such programmes. Many international and national schools exist, ranging from those with a very specialised focus, through to those with a more broad and/or interdisciplinary remit, which can also serve as an opening for students to access other fields and related synergies. Table 9.1 lists selected examples of detector international schools, illustrating some of the variations on offer, in terms of format, target audience and breadth versus specificity. The corresponding information for accelerator schools, which form a key part of the education of the personnel in the field, can be seen in Table 9.2 in Section 9.2.4.

The available schools typically offer a balance of theoretical (e.g. via lectures, classes, tutorials) and experimental (e.g. via laboratory experiments) learning, with both elements considered essential to fully train future instrumentalists. The schools are typically one to two weeks in duration, though some are longer and extend to periods of several weeks, e.g. ESIPAP. A few also include a dedicated period of pre-school preparation, in order to maximise the efficiency of learning during the school itself. Participant numbers generally range from about 30 to 100, which is primarily limited by hands-on laboratory capacity and/or available staff. Several schools also offer awards and/or academic accreditation to participants. In contrast, as far as is known, there is little or no routine recognition of training-staff and organisers. Experience during the recent COVID-19 pandemic has shown that, in some cases, virtual schools can be effective (e.g. those with a strong software focus), and can widen participation, but should be used appropriately and in moderation, due to the importance of hands-on experience.

A point of note is that, while a variety of examples of international schools exist, they tend to be independently organised and not sufficiently publicised to ECRs. A better international coordination and a wider advertising effort would greatly improve that situation. In addition to the international and European-wide opportunities, there are a variety of national programmes that offer graduate-level training. For instance, some countries offer doctoral programmes in which instrumentation is key, for example: INFN funding for ~ 60 PhD studentships per year, most on instrumentation topics; KSETA (Karlsruhe School of Particle and Astroparticle Physics) [Ch9-3]; the German-Norwegian PhD research school [Ch9-4]; and the UK STFC centres for postdoctoral training [Ch9-5], which include industrial or major laboratory placements. The "Terascale Detector Workshop" [Ch9-6] is a specific example of a national workshop targeted at PhD students and postdocs from German groups who are active in the area of detector development. National schools are also on offer in several countries, such as: the INFN school on detectors for graduate students [Ch9-7]; the Mainz biennial school on instrumentation for Masters/PhD students [Ch9-8]; and the Spanish "Phy6cool" school on particle, astro-particle physics and cosmology [Ch9-9]. Many countries also benefit from traditionally close collaborations with large national or international laboratories, which serve as a hub for training opportunities, for instance in the form of short visits or extended stays, and/or via shared studentships between those laboratories and university groups that strategically target R&D and detector construction projects (e.g. INFN in Italy, DESY in Germany, RAL in the UK). Overall, it is nevertheless apparent that the programmes on offer vary widely from country to country.

9.2.3 Contribution of major laboratories

Major laboratories act as hubs of scientific activity for a diverse international community. As such, they have well-established research infrastructures that allow for specialised training in instrumentation work. At the ECFA symposium, CERN and DESY were identified as two prominent examples in Europe. Both play a crucial role in training the next generation by providing ample training opportunities in instrumentation that complement programmes at universities.

To some extent, access to these programmes already starts at the high school level. For instance, "S'Cool LAB" (see Figure 9.1), CERN's hands-on laboratory, offers highly popular workshops through which high-school students are introduced to fundamental principles of particle detectors and particle accelerators [Ch9-18]. In addition, "Beamline 4 Schools", an international competition for high-school students from all around the

Block	School	Target audience	Focus
a	ESIPAP [Ch9-10]	Master/PhD/ ECR	Instrumentation for Particle and Astroparticle Physics
	ESI [Ch9-11]	PhD/PostDoc physics/engineering	Basic principles of instrumentation
	EDIT [Ch9-12]	PhD/1^{st} year PostDoc	Detector and Instrumentation Technologies
b	INFIERI [Ch9-13]	Master/PhD/ ECR physics/engineering	Advanced technologies in the fields of semiconductors, very deep sub-micron and 3D-technologies, nanotechnology, interconnects, data transmission, big data, HPC, AI, quantum technology
	ISOTDAQ [Ch9-14]	Master/PhD/ PostDoc physics/engineering/computing	Triggering and acquiring data
	CRYOCOURSE [Ch9-15]	PhD/PostDoc physics/engineering	Cryogenics, microwave measurements and low temperature engineering for quantum technology
c	International School of Nuclear Physics, Erice [Ch9-16]	PhD/PostDoc/ ECR physics	Networking school and seminars between young scientists and highly recognised experts in nuclear, particle and astro-particle physics
	ISAPP [Ch9-17]	PhD/PostDoc/ ECR physics	Networking school and seminars between young scientists and highly recognised experts in nuclear, particle and astro-particle physics

Table 9.1: List of exemplary international instrumentation-related schools. Only schools which have a significant European contribution, are open to students world-wide, and are considered to be an ongoing series (have been repeated at least two times, most recently within the last three years), are included. Block a) are instrumentation specific schools ordered by ever increasing complexity. Block b) are examples of highly specialised schools on a given topic in the instrumentation field. Block c) are broader schools of particle physics and neighbouring fields which sometime include dedicated instrumentation programmes. This list is a snapshot of the situation in 2021. An updated list is intended to be maintained on the ECFA Detector Panel web pages at https://ecfa-dp.desy.de/public_documents/.

world, encourages students to submit a scientific research proposal for an experiment to be conducted at a beamline either at CERN or DESY. Furthermore, CERN currently runs the High School Students Internship Programmes aimed at high school students from CERN's Member States. Through these programmes, groups of students come to CERN for two weeks to gain practical experience in science, technology, and innovation. These are prominent examples of raising awareness of instrumentation careers in high school students and encouraging the next generation of instrumentation scientists and engineers.

At the undergraduate and graduate level, both CERN and DESY offer long-running summer student programmes. Besides these, CERN provides training opportunities through the technical and the doctoral studentship programmes. Here, graduate engineering (mechanical, electronic, software) programmes also exist for students from selected Member States, for example Portugal (FCT), Spain (FTEC), and France (VI). Furthermore, specific programmes are in place for doctoral students from selected Member States, who wish to undertake a PhD based at CERN. For example, the German Wolfgang-Gentner-Programme, the Austrian Doctoral Student Programme, or the Norwegian Doctoral Student Programme. At the post-doctoral level, both CERN and DESY offer large well-established fellowship programmes. CERN also runs regular Academic Training programmes, including coverage of instrumentation and related topics (eg. statistics), and organises seminar series on instrumentation, data science and software, which are open to international participants via video connections.

In terms of instrumentation training, test beam facilities are essential. At CERN, test beam facilities are available in the East Area and the North Area. DESY has three independent beamlines available. To make best use of these test beam facilities, dedicated travel support, for instance from official EU sources, is essential.

9.2.4 Status of accelerator training in Europe

The training and skills needed for the design and delivery of accelerator projects is complex due to the diverse needs of the projects and the range of skills required. The community is broad, including PhD students, university staff, laboratory staff, engineers and technicians and the R&D frontiers on particle accelerators are diversified and extremely specialised. Across Europe and before the 1990s, the major accelerator physics and engineering training effort was done at national and international accelerator laboratories. This training included the physics and engineering of accelerators, and the provision of technician skill development needed for accelerator project delivery. The CAS schools provide intensive accelerator training across all key areas accessible to students and staff across Europe and these started in 1983 (and USPAS in 1981). Since the mid 1990s, there has been a steady expansion of accelerator physics at major research universities, moving the centre of mass of accelerator skills development partially into the university sector. The JUAS programme, with a strong university involvement, started in 1994. However, despite an increasing large economic and intellectual impact, only a small fraction of universities in the world offer a formal graduate education in Accelerator Science and its core technologies. At the present time (2021) the accelerator training in Europe is split between institutional training (carried out directly in institutes) and accelerator schools, with the main international schools used by European personnel shown in Table 9.2. In recent years several EU-funded projects have explicitly addressed the provision of accelerator training in Europe: TIARA [Ch9-19], ARIES [Ch9-20], AMICI [Ch9-21], I.FAST [Ch9-22], EJADE [Ch9-23] and some of these (TIARA, ARIES, I.FAST) include dedicated WPs on training coordination. TIARA WP5 in 2012 made a survey of training and courses across Europe (88 institutes) evaluated the market for trained accelerator scientists and developed a plan of action for promoting accelerator science and technology. This gives a snapshot of the accelerator training across Europe which is still valid today, giving a feel of current status and what needs to improve. They also give a framework for sharing of best practice. The survey found, in 2011, that there is "Superb training provided via universities, laboratories, accelerator schools" and that the development of training across Europe has received serious levels of investment in the early 2000s. Overall, in 2011, there were 3060 personnel involved in accelerator science, 75 institutes (85% of those surveyed) providing training themselves and 12 institutes planning to train in the future (sum of 87/88). The survey found 1371 people receiving training in 2011, 35% undergraduate, 26% Masters, 14% Postgraduate researchers and 17% staff of universities and laboratories.

In terms of accelerator schools (CAS, JUAS, USPAS, LC-school, WILGA and others) 83 institutes sent their people to these schools in 2011, with a total of 339 people in 2011 trained this way. Finally the survey gave an idea of destinations of accelerator-trained personnel in 2011. At each educational stage, about 1/3 of trainees go to industry, finance, medicine, with 2/3 of undergraduates going into further study. A similar survey was made by ARIES in WP2, who also attempted an e-learning initiative (MOOC) on accelerators, which is seen as a useful direction of centralised training material.

To get a feeling for the demand and needs of accelerator training, TIARA WP5 in 2011 also investigated the "needs" for accelerator-trained personnel. 70 research institutes were surveyed, 44 companies and some X-ray and hadron facilities. The survey concluded a projected growth in personnel to train of 18–20% in five years, largely engineers and technicians and an annual recruitment of personnel of 9% in institutes and 18% in companies. The survey reported difficulties in recruiting trained personnel, especially engineers (70%), a skill shortages of RF engineering, vacuum, beam dynamics, instrumentation and controls, and significant need (60%) for external training. This survey proved extremely valuable and should be repeated in the near future.

9.3 The future of instrumentation training

The future of our field depends on the availability of well-trained experts for research and development, construction and operation of detectors for the next generation of HEP facilities.

In the next years it is essential that instrumentation work receives broader recognition and support by the HEP community. Career prospects for excellent detector physicists and engineers should be well identified.

School	Target audience	Focus
The CERN accelerator school (CAS [Ch9-24])	MSc/PhD/ECR/Staff	A range of schools offered, from introductory to more specialist topics
The Joint Universities Accelerator School (JUAS [Ch9-25])	MSc/PhD/ECR	An intensive school for the fundamentals of accelerator physics and engineering
The Linear Collider School (LINK [Ch9-26])	MSc/PhD/ECR/Staff	A dedicated school for the physics and engineering of the International Linear Collider
The US Particle Accelerator School (USPAS [Ch9-27])	MSc/PhD/ECR	Education in Beam Physics and Accelerator technology

Table 9.2: List of international accelerator schools. Only schools which have a significant EU contribution, are open to students world-wide, and are considered to be an ongoing series (have been repeated at least two times, most recently within the last three years), are included.

The following sections elaborate on the key aspects, which are needed to implement a successful coordinated programme for training in instrumentation (DCT 1, see Figure 11.1). Existing and additional training opportunities need to be developed and strategically coordinated on a European level, including virtual reality as a novel tool for remote training. In addition, worldwide cooperation in training should be sought, and a dedicated programme for underprivileged countries should be put in place. Exchange and synergy with industry should be expanded and intensified.

9.3.1 A coordinated European training programme

The level of training largely varies between countries in Europe. The instrumentation community, supported by ECFA, should formulate a recommendation for a curriculum in instrumentation. An example of a possible structured training programme is given in Figure 9.2, where the "knowledge block" at each career level indicate the recommended stage at which a training should be accessible to individuals who intend to pursue a career in HEP instrumentation. A structured training programme shall support the scientists in their career. First, they gain an increasingly broader overview during their bachelor-master studies. Then, they deepen their knowledge into a specific field during their PhD studies. They acquire the right skills for project management and system engineering at the post-doctoral level. Finally, they reach the broad overview necessary to seek synergies with other fields of research and to develop interdisciplinary projects.

The limited number of students interested in the field of instrumentation at each university demands sharing of equipment, knowledge and expertise through European programmes. This would be facilitated by an accredited European master degree in instrumentation (DCT 2, see Figure 11.1). This includes the development and running of

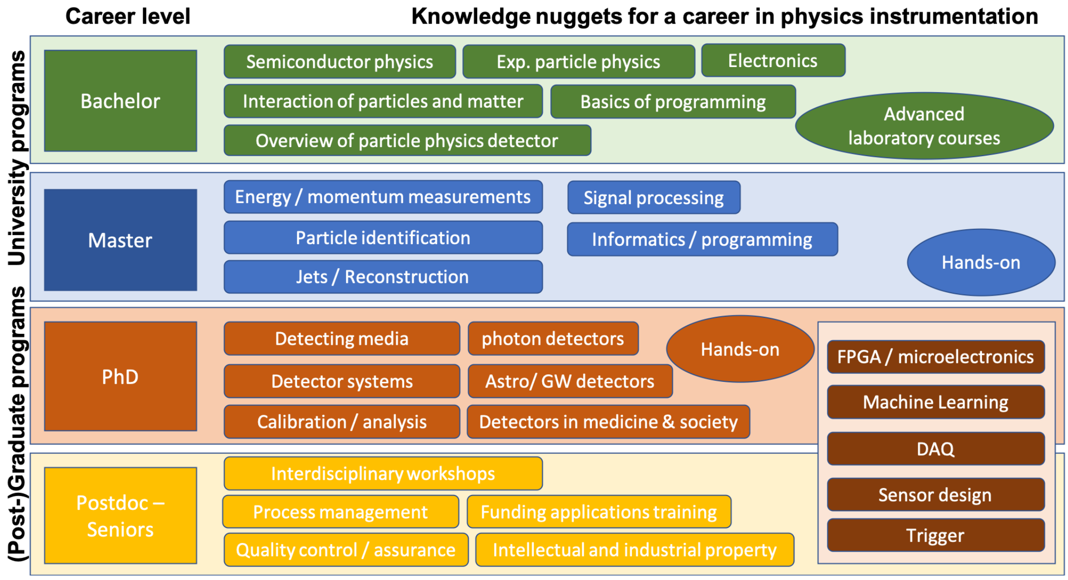

Figure 9.2: Possible structure of a training plan recommendation. The knowledge expected at different levels for a career in HEP instrumentation are shown.

a bank of online courses to complement local university training; the integration of European instrumentation schools in master courses via a compatible accreditation system; the establishment of a European inter-university specialised master degree. Adjacent fields such as nuclear and astro-particle physics could be invited to participate to this action.

A large fraction of the instrumentation training runs in the form of "learning by doing". Whereas this is recognised as an essential part of the training of instrumentation experts, dedicated courses addressing the complex issues of debugging and problem solving should be developed.

Interdisciplinary training, particularly for established researchers is essential to generate novel ideas, and experimental methods. Emblematic for this is the fast developing field of quantum technologies, where "novel" materials such as meta-materials, quantum dots, structural and photonic materials open possibilities for new fundamental physics experiments. Those can usually be carried out within the time of a PhD thesis, and serve as a unique training ground for HEP experimental physicists. Interdisciplinary training profits from an open-minded and yet opportunistic attitude to identify developments happening elsewhere in physics or industry as potentially interesting for HEP. This is typically easier at a later stage in the scientific career.

Researchers require continuous specialised training to develop new competences, e.g. on cryogenic systems, FPGA programming, specific COMSOL packages, etc., to enter emerging fields. Such specialised training is often provided by industry and is expensive. A coordinated programme offered via e.g. the major laboratories, may help to reduce the costs and increase accessibility. To this end, a list of the most relevant or requested courses needs to be compiled, and these should be made available to the instrumentation community in a coordinated manner at a European level.

Finally, it is vital to recognise that soft skills like communication, project management, applying for funds, etc. are essential for a career in instrumentation, and need to be provided in dedicated courses.

The organisation of courses, hands-on training and schools is time consuming, and it is mostly done on a voluntary basis. Individuals who engage actively in training should receive the adequate recognition in the form of attestation and possibly awards.

9.3.2 The role of virtual laboratories

Virtual reality (VR) tools are becoming widely used in many fields. For instrumentation training, they offer unique possibilities of gaining virtual access to equipment and infrastructures, that would normally not be available. Examples of virtual reality laboratories exist, which are mainly used for outreach purposes. The crucial next step is to implement the exact physics of the experiments and their instrumentation into VR set-ups. This step is not easy, and calls for tight cooperation between physicists and informatics experts to allow the usage of VR laboratories for training. One successful example is the advanced laboratory course "Femtosecond X-ray experiment", offered to bachelor students at the University of Hamburg [Ch9-28]. This novel VR experiment provides a detailed introduction to the operation of very complex equipment in modern large-scale research facilities such as the European XFEL. Students have the unique chance to experiment with state-of-the-art equipment, controlling and learning all levels of technical details involved. This and other similar examples show that VR projects are a possible and successful extension of instrumentation training. They provide a significantly increased continuous access to large-scale facilities. Thus, VR experiments can help to overcome the geographical and economic limitations of training at the European level and worldwide.

9.3.3 The role of major laboratories

Major laboratories will continue and intensify their essential contribution to instrumentation training.

Specifically, in light of the long term demands of the field, an increased amount of dedicated training programmes for (under-)graduate students will be required to complement their university education.

Here, innovative offers, such as VR experiments and remote participation in beam tests, will be significant additional assets to provide training opportunities to all students, particularly to those who cannot easily travel to facilities directly. The role of major laboratories should be to coordinate and develop a network of virtual laboratory experiments.

Given their geographical proximity and their common interests, Europe and Africa are in the ideal position to further develop their collaboration in training programmes, through existing schools or new initiatives. Given the difficulty to access major facilities, the network of virtual laboratory experiments should be extended and adapted in a coordinated project with African countries.

Major laboratories should support the development and distribution of table-top instrumentation set-ups (including training of future tutors), such as transient current technique or Medipix-based set-ups, to modernise on-site training opportunities at universities. Furthermore, the currently running "Beamline 4 Schools" competition should be scaled up by expanding to additional major laboratories, and running dedicated competitions for undergraduate students. At the graduate level, major laboratories need to implement other training opportunities for ECRs who want to gain experience working in instrumentation. This will encourage and support junior scientists to enter the field at a later stage. In turn, this will also lead to an improved recognition of instrumentation work and skills.

All these initiatives should be coordinated at the European level, in cooperation between major laboratories and universities, and could be funded through EU projects. A scheme for recognition is necessary to engage excellent scientists in high quality training.

9.3.4 Industry meets academia

Collaboration between academia and industry has benefits for both. Students get trained to work with industry: building advanced Big Science instrumentation requires collaboration with industry. Advanced technologies are only available in or through high-tech industry and that is why fabrication of detector components is often outsourced. Building a detector system requires skills in project management and system engineering, where particle physics can learn from industry. Working with industry may attract engineers to undertake a PhD or career in Big Science. In addition, it enlarges the career perspectives and network for HEP PhDs and postdoctoral researchers (PostDocs).
Industry also faces fundamental and challenging research. Bringing together diverse disciplines in hackathons, where students work on R&D problems in industry or on societal problems, often generates innovative solutions. A few successful examples are: the yearly event in The Netherlands [Ch9-29]; the HEP technical events initiated by CERN [Ch9-30]; the Industrial CASE Studentships in the UK [Ch9-5] industrial-case-studentships; and the series "AIDA-2020 Industry Academia".

Training students on the newest technologies developed in industry and technical universities enables the early implementation of these technologies in HEP instrumentation. It also serves the purpose to get industry interested in the HEP challenges, and in working together with academia on solutions. An existing implementation of such training are organised hands-on events like IdeaSquare@CERN, where physicists and engineers from academia and industry work together on early-stage detector Research, Development & Innovation initiatives.

Young researchers are interested in learning about the newest digital technology. Facilitating the exchange with industry via commonly organised hands-on laboratories and demonstrators enables instrumentation minded academics to get experience with these new technologies. This could be part of PhD curricula at universities. The exchange of dedicated measurement set-ups and techniques can be beneficial for both parties.

9.4 Recommendations

The goal for the next five years and beyond is to increase participation of young scientists, in particular graduate students, in leading-edge instrumentation R&D, and to foster growth of future HEP instrumentation experts who can compete for permanent positions. This needs to be achieved by coherently implementing in Europe three clearly defined measures: improve recognition and career perspectives for instrumentation experts; establish a coordinated and structured instrumentation training programme; overcome geographical and economical limitations of training at the European level and worldwide. Some of these key messages are also picked up again in Chapter 10 and Chapter 11 below.

To improve the recognition of the instrumentation field requires establishing more PhD programmes based solely on instrumentation research, as well as research staff scientists and faculty positions in this field. The creation of prestigious instrumentation studentships, providing extended internships at laboratories or universities with excellent technical capabilities, is a key element. New awards could also be a way to recognise the excellence of instrumentation work. When creating awards it is essential not to forget the fundamental role of team spirit for the particle physics field. Recognition of individuals and teams engaged in training is equally important.

To better coordinate and structure instrumentation training in Europe, the European coordinated programme for training in instrumentation (**DCT 1**) should provide courses for all career levels, with particular emphasis towards hands-on opportunities. It will need to promote summer student positions and internships to provide a flow of personnel entering the field and joining instrumentation training. The possibility to establish an accredited master's degree programme in instrumentation (**DCT 2**) needs to be investigated. This would offer access to excellent training, specialised laboratories and state-of-the-art technologies throughout Europe, enhancing mobility and networking possibilities.

Existing European graduate and post-graduate schools for physicists and engineers must be supported and better coordinated. ECFA should establish a panel to coordinate the synergies between HEP instrumentation and accelerator diagnostics training. The same panel ought to also coordinate accelerator training between laboratories and universities. To improve training synergies with adjacent fields, members of the nuclear and astro-particle communities could be invited to participate to this panel.

A better coordination with training programmes worldwide would be advantageous to broaden the researchers perspectives and networks. International instrumentation schools following the example of EDIT, need to be supported. Networking events, hackathons and industry-academia schools with significant hands-on character, should complement the proposed training programme. Such interdisciplinary exchanges and access to novel technologies are important for a career in instrumentation, and stimulate the development of communication, project management, and teamwork skills.

The ultimate goal is to extend the national programmes globally, to countries without a major laboratory or suitable university facilities. It is recommended that large-scale facilities, with the support of universities, invest in creating and coordinating a virtual laboratory platform for training. Virtual reality can help in overcoming both geographical and economic limitations to training opportunities.

In the next five years ECFA should:

- engage in promoting and advertising instrumentation training programmes;
- facilitate worldwide access to the training offered while improving inclusion;
- help attract funds to implement these measures, e.g. via EU projects.

The goal for the next 20 years is to maintain a well trained community of detector experts, along with a sufficient number of trainers for the instrumentation programme, and improve academic career prospects in instrumentation. To bridge the gap between the HL-LHC upgrades and the experiments at future facilities, along with experiments sharing common instrumentation with particle physics in neighbouring fields and others, the major laboratories must play a central role in creating and supporting dedicated training programmes on accelerator and instrumentation physics.

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Chapter 10

General Observations and Considerations

In this chapter a number of more general topics common to several of the areas discussed previously are considered. These also reflect common themes that emerged in the community feedback, particularly during the Symposia and from the various surveys. General Strategic Recommendations derived from these are presented in Chapter 11 along with a discussion of the recommendations linked to the DRDTs outlined in the earlier chapters.

Supporting R&D facilities

Here a number of essential common infrastructure requirements, not described in the preceding chapters are outlined [Ch10-1]. Firstly, coordinated access to **test-beam facilities** should be continued and enhanced to meet the needs of next generation detector development. A small number of world leading facilities at major laboratories support access to test beams [Ch10-2], [Ch10-3], where detectors and detector systems can be tested under realistic conditions and their response to a range of particle types can be evaluated. Given the different functions of different sub-detector systems, beams of charged hadrons, electrons and muons at different momenta and rates are vital. The cryogenics, gases, cooling, magnets, electrical services and readout, along with provision of the beams themselves, represent a considerable annual cost that host laboratories supply to the community. In addition, further detector systems ("beam hodoscopes") are required to provide increasingly accurate tracking and timing information of the individual incoming particles, and further instrumentation is required to determine particle energies, monitor particle fluxes and determine beam compositions. For large scale system tests, the engineering and other infrastructure required can approach the cost and complexity of a small scale experiment.

The second area of infrastructure provision, which is typically available only at a few larger laboratories in Europe, is that of supporting **large scale generic prototype assembly and characterisation**. This support should be continued and enhanced to meet the needs of next generation detector development. Specialist equipment is often required to provide R&D demonstrators for a proposed technology targeting a large area or large volume detector system. Specialist resources in terms of services (gas distribution systems, cryogenics, radio-purity, sensor post-processing, micro-electronic interconnection technologies, dedicated fast readout) are often required which are costly and wasteful to duplicate across many sites. Issues which do not impact small area devices can be shown to represent major limitations when larger arrays are built, and mitigating strategies for these can be developed at an early stage before industrial partners are engaged in prototype manufacture and significant costs associated with redesign and reassembly are encountered. Major infrastructure and engineering resources are required to even build adequate proof-of-principle prototypes for some of the largest volume detector concepts, such as those targeting neutrino experiments for example. In other cases, the highly specialist infrastructure even for small test detectors (for example targeting dark matter searches or neutrino-less double beta decay) can only be supported at dedicated laboratories. The model with centralised specialist infrastructure at a small number of larger centres can only function properly as long as there is also a support network of equally active smaller sized academic centres associated with it.

Finally, many applications call for **radiation testing** because all components which are expected to receive any appreciable dose have to be shown not to degrade too severely over the lifetime of an experiment or mitigation strategies have to be implemented. Support for radiation testing should be continued and enhanced to meet the needs of next generation detector development. In many experiments, even modest levels of radiation exceed those to which any commercially available equipment has been designed to withstand. Unless fully customised components can be afforded, the impact of this is that sample (batch) testing of all commercially sourced equipment is needed to check that no design or process changes (which would typically be commercially confidential) could have resulted in reductions in the radiation tolerance properties and to be able to track such changes over time. Even fully customised designs targeting radiation hardness still typically involve commercial partners whose detailed device processing may vary. Establishing a design and a process to the most extreme levels of radiation hardness requires both a high degree of testing at irradiation facilities [Ch10-3], [Ch10-4] and a deep understanding of the physics of the radiation damage mechanisms themselves, often requiring a major simulation effort to model the measured macroscopic degradation with irradiation in terms of the microscopic changes in the heavily exposed materials. Facilities are needed to allow irradiation at a range of energies with neutrons, photons, protons and (ideally) pions (since the latter dominate the actual particle mix for sensors closest to the collision point in many experiments with the most severe requirements). Reactors, x-ray and gamma-ray sources, low energy cyclotrons and beams at accelerator laboratories are all needed, with a wide range of instantaneous particle fluxes and achievable integrated fluences, for these studies.

In addition, the challenges of some future facilities go very far beyond even the radiation levels studied for the HL-LHC, raising special challenges in terms of the facility capabilities in terms of ultimate particle flux capabilities and issues of handling plus testing of highly irradiated sensors and electronics. The need for devices to be operating while being irradiated adds further challenges of installing readout and other services (gas, cooling etc) at the irradiation facility. In this context, Europe benefits from a wide range of facilities in different countries, which thanks to the support of EU-funded initiatives have formed a network, with common schemes for access, common data bases and inter-calibrated dosimetry, that serves the community at large.

Engineering support for R&D

Modern detector systems require an increasingly higher level of integration than in the past, where the readout electronics, sometimes even the front-end electronics, were often external to the detector volume. Thus, for example, active elements or sensors, mechanical structures, and electronic systems could be developed largely independently and also on decoupled time-scales. Nowadays, the front-end electronics and often also first stages of digital data processing are integrated into the detector volume. At the same time, more and more functionality is transferred from off-detector to on-detector systems, and in monolithic architectures the front-end even moves into the sensor substrate. These trends require, already at the conceptual stage, a holistic approach to the design, which keeps the close interdependence between electronics architectures and mechanical constraints in perspective from the beginning. With advancing electronics miniaturisation, also more and more granular systems, with ever increasing counts of individual components, become possible, such that scalability towards automated or even industrialised production and quality control procedures has to be considered early on in the conceptual design.

These developments can only be achieved in close collaborations of physicists and engineers, who bring expertise in state-of-the-art analogue and digital microelectronics and in advanced and novel materials and manufacturing techniques. On the other hand, many of the integration challenges are of generic nature and can be conceptually tackled independently of the implementation into a specific experiment, as the development of highly granular calorimeters, for example, has shown. Therefore, in contrast to the earlier situation where components were developed by a small academic team and engineering effort was injected only after initial approval of an experiment, the development of cutting-edge detector technologies relies on strong engineering support already at the R&D stage. This requires greater cooperation among institutes and the adoption a much more coordinated approach.

Specific software for instrumentation

In addition to physical infrastructure, **software infrastructures** have been stressed by many experts as equally vital and requiring an internationally coordinated approach. Topics included here range from negotiating European licences for essential design and simulation packages through to ensuring key packages developed within the particle physics community (many of which now find wide application in other science areas) are continuously maintained, updated and improved [Ch10-5], [Ch10-6], [Ch10-7]. There are a wide range of non-experiment specific software tools and resources which underpin both detector design and the interpretation of results from testing. For example, the development of simulation tools for the interaction of energetic particles with matter and the evolution of particle showers needs to keep pace with that of the detectors. Showers can now be modelled in much greater detail than at the time LHC detectors were built, but the trends to exploit additional information such as dual read-out or timing for calorimetric measurements will require continuous refinement of the simulation tools in parallel. The same is true for sophisticated pattern reconstruction algorithms, which are also to a large extent experiment or even detector independent, as evidenced by the use of generic particle tracking algorithms and particle flow reconstruction techniques for cryogenic neutrino detectors. Furthermore, a number of commercial packages have been adopted and adapted (for example to model effects of radiation damage [Ch10-8]) which are in widespread use to design microelectronics, trigger and data acquisition, sensors, mechanics and cooling. Users at individual institutes can often only access these affordably and reliably because both national and/or Europe-wide initiatives have enabled the community to organise coherently [Ch10-5]. The use of common tools is also of significant benefit in terms of collaborative detector R&D including synergies with adjacent fields and the pool of expertise this creates provides a vibrant training environment for early career researchers, some of whom will take these highly transferable skills into other science areas or into more commercial settings.

International coordination and organisation of R&D activities

Another general theme which emerges is the desire for greater international coordination of R&D activities across Europe and beyond. A model which is widely admired was the organisation set up by CERN as the Detector Research & Development Committee (DRDC) [Ch10-9] to assess proposals from the community to address the then unprecedented challenges of building detectors for operation at the LHC. Some of the R&D collaborations (RD programmes) established as a result of this initiative are still very vibrant and proposals for others still arise from time to time. The LHC Experiments Committee (LHCC) still reviews the progress of these collaborations, even though some also are very active in developments that go beyond requirements even for the upcoming HL-LHC programme. In parallel, a number of community organised R&D initiatives have grown up to address general R&D needs for different detectors at future facilities and EU-funded R&D initiatives have further provided additional community-led collaborative R&D programmes. The major international laboratories also undertake their own major targeted R&D programmes in collaboration with their user communities and there are a multitude of national and more local initiatives. All of the above are subject to a wide variety of reviewing mechanisms.

The degree of coordination in Europe is perceived from outside as a major success but there is a general feeling that this is to some extent based on past achievements and that it could anyway be more streamlined. There do exist a number of similar initiatives that could be better aligned although successful programmes should clearly not be disrupted. The high value attached by funders to expert independent peer review of programmes is appreciated and this aspect should be strengthened, and would benefit from significantly greater coordination. The reviewing load (particularly if new projects come forward) and who undertakes this should be revisited with more recognition given to those who carry out such reviews. Potentially a greater role could be envisaged here for the ECFA Detector Panel (which already organises such reviews on request) but this would probably require its mandate and membership to be adapted to better fit this purpose.

Key to the recommendations of the EPPSU is "taking into account progress with emerging technologies in adjacent fields". Greater international coordination of particle physics detector R&D can also ease communications with neighbouring fields. Several of the existing R&D Collaborations already have informal mechanisms to engage with other fields using the same technologies. Structures which further encourage such interchange would be beneficial as can be flexibility of individuals in terms of the science areas with which they engage.

Distributed R&D activities with centralised facilities

In some areas (such as for microelectronics, many solid-state sensor developments and larger-scale generic detector R&D), growing complexity, required specialisation, need for engineering teams and prototyping costs mean that current funding models are often found to be no longer fully appropriate. Centralisation at CERN and national/international laboratories eases the burden of keeping pace with rapidly evolving commercial developments and can make capital investments more effective, but this approach brings a number of risks. There is broad recognition of a tension between more centralised R&D to achieve a critical mass and the need to retain scope for individual initiatives at smaller institutes. The ways that computing resources were reorganised for the LHC era with both distributed and centrally coordinated resources (the "Tier Model") may be of relevance for some R&D areas [Ch10-10]. Having distributed activity but with national and international hubs can allow teams of sufficient strength to be assembled while maintaining efficient activity distributed among different institutes where the expertise is based. The importance of cutting-edge local R&D activities in university groups is particularly critical as this is where the bulk of training and recruitment for the next generation of experts in this field is most likely to be based. However, participation in more nationally and internationally connected R&D programmes also enriches the local environment and enhances the visibility and recognition of those involved. Such R&D collaborations should also be eligible to apply for programme funding at national or European levels in similar ways to more focused projects or experiments.

Long-term funding programmes

The need for programme as opposed to project funding for detector R&D has been emphasised in many areas with many national R&D schemes more suited for proof-of-principle R&D, rather than sustained development. Where more long-term strategic investment is needed, a more coordinated European approach could be very beneficial. In some areas, the issue is also that R&D costs have significantly grown, often in addition to requiring a more tier-ed organisational approach. Neither the duration, nor the maximum allowed amounts in many available funding schemes fit the needs of the strategic investments required for a number of key detector R&D areas. The methods whereby accelerator R&D are funded in Europe could provide a better model for supporting R&D on these topics. It should be noted that such programmes, if funded, would be able to sustain developments for multiple experiments over a significant period, supporting intermediate requirement applications on shorter timescales if appropriate and grant continuity in the development. Specific R&D funds for dedicated system engineering would evolve when facilities become approved. A related issue is that such programmes would allow much closer partnerships to be developed with commercial partners, leading to better engagement of European industry in the cutting-edge developments needed for next generation experiments. It is also noted that up-front costs for companies to engage in novel areas of instrumentation can be considerable and a more secure funding environment will encourage the necessary commercial investment.

“Blue-sky” R&D

Innovative instrumentation research is one of the defining characteristics of the field of particle physics. As emphasised in the introduction, more “blue-sky” (more explorative, without addressing immediate detector specifications) R&D has often resulted in game-changing developments which could not even have been anticipated even a decade in advance.“Blue-sky” developments have often been of broad application and had immense societal benefit. For example the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science. The invention of micro-pattern gas detectors is another example (with very large-scale systems now being installed), as are the more recent new technologies for very fast (10 ps) timing coupled with accurate spatial information (“4D”-detectors) which offer the potential to revolutionise tracking in dense environments due to superimposed collisions or high levels of background hits. Many of the challenges of neutrino or non-accelerator based experiments (particularly those searching for the full-range of possible dark matter candidates) are benefiting from developments once perceived as “blue-sky”. As particle physics knowledge improves, the requirements for the next generation experiments also evolve, such that capabilities once thought not to be relevant can become essential. This is also an area where familiarity with the latest developments for neighbouring fields and the commercial state of the art pays significant dividends.

In some of the earlier chapters it can be seen that for several fast evolving fields, involving smaller scale experiments, it is often not possible to plan more than two decades ahead. Here parallel R&D programmes, such as those for quantum computers as an example, can so rapidly change the technology landscape that long-term predictions of the direction of likely research are not sensible. The need to foster less directly goal-driven R&D should also be recognised and funding lines to support this and the individuals carrying out such work also require support if transformative opportunities are not to be missed.

Attract, nurture, recognise and sustain the careers of R&D talents

As commented in the introduction, highly skilled personnel are in general key to the delivery of the ambitious programme outlined in this document. For the technicians, engineers and scientists on which this programme relies, a number of issues have been identified around recognition and career development that cut across many of the R&D topics discussed above [Ch10-11], [Ch10-12]. Chapter 9 is dedicated to detailing a number of these concerns which will not be repeated here. However, the topic is of such importance that these points also deserve to be emphasised in the summary.

The challenge across R&D programmes and running experiments to attract or retain people with key skills in specialised instrumentation and firmware is a specific issue that needs to be better addressed within the particle physics community. These skills are highly marketable outside academia, but are vital to keep many research activities going. A more strategic approach to recognising mission critical personnel, in whom significant training investment has been made, needs to be found if international research programmes are not to be compromised. Methods need to be found to provide appropriate investment where the costs of not doing so at a programme level far outstrip those of the required additional support. Of course producing highly trained experts who end up deploying the skills learnt in particle physics instrumentation development in industry is a significant contribution that the field makes to wider society.

Another issue which relates to a number of specialist personnel (for example ASIC designers) is that high energy physics detector activity can have a very pronounced time varying demand. One mitigation for this is typically that skilled personnel can be redeployed at many institutes, during periods of reduced demand, on projects for other scientific activities, which further enhances the transfer of expertise between disciplines. The individuals concerned will then also benefit from developing a broader range of skills through having to tackle state-of-the-art challenges in a range of science areas, further deepening their knowledge base and skill set. A more strategic approach is needed relating to career prospects, competitive remuneration, recognition and more guaranteed continuity of employment for such personnel.

Industrial partnerships

The quest for ultimate particle detector performance continuously drives available or emerging technologies beyond their limits, and the almost industrial scale at which this happens, is one of the roots of its broader societal and economic impact. Developments are driven by the close collaboration between physicists, engineers and industrial partners. The role of industry is rapidly increasing, due to the requirement of advanced technologies calling for highly specialised equipment, for example in microelectronics integration, and due to the scale of the installations, where thousands or millions of components need industrial-scale production and quality control infrastructure. Intensifying the cooperation between academic and industrial partners will be a key challenge for the future of the instrumentation field, but strategic partnerships need substantial financial support and have to overcome obstacles in organisational or legal questions, such as management of intellectual property, as well as the cultural differences between these communities.

Collaborative work on common detector projects should strengthen the competence and competitiveness of the industrial partners for other markets. Such direct collaboration can also help to identify, at an early stage in the research process, the potential for commercial spin-off applications of originally science-driven technological developments. Supporting promising cooperation and highlighting emerging successes will be key towards establishing such collaboration as a more standard mode of research in the future. Frameworks for forward-looking topical exchanges should be established (e.g. focused on photo-sensors) between industrial and academic players. These should complement instrumentation conferences by concentrating on commercially relevant drivers, anticipated trends and emerging markets, as well as foreseeable needs and scientific ambitions.

Open Science

The importance of Open Science is already stressed in the main documents of the Update of the European Strategy for Particle Physics [Ch10-13], [Ch10-14] where it is recommended that “The particle physics community should work with the relevant authorities to help shape the emerging consensus on Open Science to be adopted for publicly-funded research, and should then implement a policy of Open Science for the field.” Open Science, as defined there, not only includes the sharing of research findings but also facilities and infrastructure with a view to promoting their contribution to training, knowledge and innovation to maximise the benefits to other disciplines and wider society. Crucially it comprises open access to scientific publications and research results.

In the area of instrumentation there are issues around publications, particularly of conference proceedings where many results are presented, and results obtained which have potential commercial applications (either in collaboration with industry or where institutes may wish to protect their intellectual property). In the case of the relevant journals, one route could be to cover these along with other Particle Physics journals within the SCOAP^3 partnership [Ch10-15]. In the case of commercial confidentiality, the needs of industrial partners in particular have to be respected to foster greater collaboration with the commercial sector; but the need for publicly funded research to strive towards to the highest standard of open access should remain an important priority.

References Observations

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Chapter 11

Conclusions

This document presents the outcome of the European Detector Roadmap Process, recommended by the recent European Particle Physics Strategy Update (EPPSU). The goal of the Roadmap is to draw a landscape of future Detector R&D Themes, starting from the present state of the art and anticipated potential towards the creation of the technological basis needed to construct performant detectors at envisaged future facilities. Its particular strength is to highlight the correspondence between technological directions and the needs of each of the future projects prioritised in the EPPSU, thereby encompassing the full set of future options for colliders and experiments, and taking the technically determined timelines of these into account. A first conclusion is that the European Strategy, whilst still pursuing different options for the next big collider projects, through its identification of physics priorities and taking the most aggressive but technically realistic schedule for possible new facilities, provides guidance on the required developments at the instrumentation frontier. Altogether, the principal key challenges can be summarised as follows:

- Develop cost-effective detectors matching the precision physics potential of a next-decade Higgs factory with beyond state-of-the-art performance, optimised granularity, resolution and timing, and with ultimate compactness and minimised material budgets;

- Push the limitations in radiation tolerance, rate capabilities and pile-up rejection power to meet the unprecedented requirements of future hadron collider and fixed target experiments;

- Enhance the sensitivity and affordably expand the scales of both accelerator and non-accelerator experiments searching for rarest phenomena and faintest signals of new physics;

- Vigorously expand the technological basis, capitalise on progress in microelectronics, novel materials, quantum sensors and other innovative trends, maintain a nourishing environment for new ideas and concepts, attract the brightest minds and train the next generation of instrumentation scientists.

In the Roadmap as presented, a picture emerges that unveils potential synergies between concurrent projects pursued by separate communities, as well as between consecutive projects, thus exhibiting the role of the earlier ones as a stepping stone for the later. This opens the possibility to evaluate and to organise R&D efforts in a much broader strategic context than that of a single future project. It is the ambition of this Roadmap to propose a more coherent approach to guide European and National funding schemes across Europe, and, together with similar processes in other regions, to also suggest greater coordination on a worldwide scale.

The relationships between the proposed R&D directions and future projects are graphically displayed at the start of each chapter. The key challenges outlined above summarise the broad R&D drivers to be addressed by the recommendations listed here. To further condense the findings of each Task Force for their respective technological area or cross-cutting activity, two to five major Detector R&D Themes (DRDTs) per instrumentation topic and two Detector Community Themes (DCTs) have been identified. These are shown as time arrows in Figure 11.1, representing the range of targeted applications which may incorporate one or more "stepping stones" where possibly relaxed requirements must be met on shorter timescales. The timelines are driven by the identified earliest technically achievable experiment or facility start dates as explained in the introduction but making clear that the R&D period finishes when experiment-specific prototyping, assembly, construction and commissioning takes over (the lighter shaded region in each bar). The significance of when arrows finish is therefore linked to where there are known future experiments or facilities whose start dates can be estimated today, as further explained in the caption. The caption also defines the meaning of the dotted lines in the DCT case.

A number of further requirements across detector technologies are captured in the General Strategic Recommendations (GSRs) below.

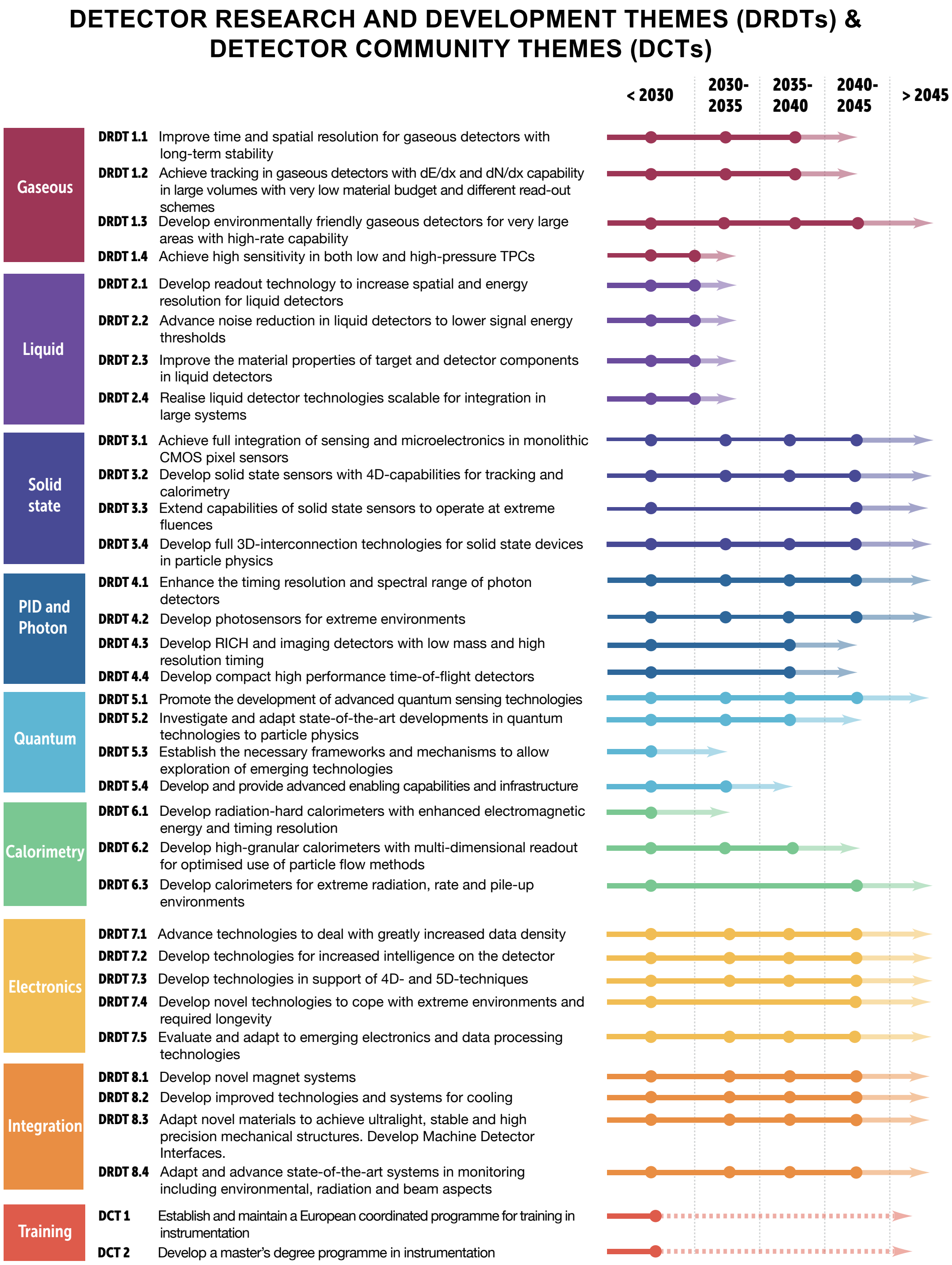

Figure 11.1: Detector R&D Themes (DRDTs) and Detector Community Themes (DCTs). Here, except in the DCT case, the final dot position represents the target date for completion of the R&D required by the latest known future facility/experiment for which an R&D programme would still be needed in that area. The time from that dot to the end of the arrow represents the further time to be anticipated for experiment-specific prototyping, procurement, construction, installation and commissioning. Earlier dots represent the time-frame of intermediate "stepping stone" projects where dates for the corresponding facilities/experiments are known. (Note that R&D for Liquid Detectors will be needed far into the future, however the DRDT lines for these end in the period 2030-35 because developments in that field are rapid and it is not possible today to reasonably estimate the dates for projects requiring longer-term R&D. Similarly, dotted lines for the DCT case indicate that beyond the initial programmes, the activities will need to be sustained going forward in support of the instrumentation R&D activities).

Gaseous Detectors (Task Force 1)

DRDT 1.1 - Improve time and spatial resolution for gaseous detectors with long-term stability.
Future experiments require large areas to be instrumented with unprecedented timing capabilities both for time of flight particle identification and to aid track association to the correct event. Their physics programmes demand an improved momentum resolution and performance needs to be maintained over decades with minimal intervention.

DRDT 1.2 - Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different readout schemes.
Different readout methodologies are required for large volume tracking detectors including micro-pattern gas detector systems, optical readout and direct interfacing to ASICs. Low multiple scattering is essential as is enhanced particle identification through accurate determination of ionisation (either deposited energy or number of clusters) per unit length.

DRDT 1.3 - Develop environmentally friendly gaseous detectors for very large areas with high-rate capability.
The largest area detector systems in an experiment are typically gaseous detectors, often as part of an outer muon spectrometer. Ease of maintenance, stable operation and, for some applications, the ability to cope with very large fluxes of charged particles are required. Key to future applications is the development of more ecologically friendly gas mixtures for gaseous detectors and mitigation procedures for use of greenhouse gases when this is unavoidable.

DRDT 1.4 - Achieve high sensitivity in both low and high-pressure TPCs.
Large volume gaseous detectors provide a key technology for high efficiency searches for rare events with differing readout for optimising the signal-to-noise ratio and reducing detector backgrounds.

Further recommendations
Progress on the following topics is critical to achieve the main research goals defined above. Readout granularity needs to be further increased while ageing, discharge issues and rate capabilities are simultaneously improved. Detector assemblies should avoid gas leaks and offer ease of accessibility and replaceability while still achieving high spatial stability. For the largest arrays, the required absolute positional accuracy also demands highly sophisticated alignment strategies. Prototyping work needs dedicated electronics, particularly where high-speed readout capabilities are being developed. Developments of novel optical and hybrid readout electrodes are to be pursued. The limiting factor for operation at high rates due to avalanche-induced ion back-flow to the photocathode is to be addressed with further detailed studies including exploring alternative designs for photocathodes, such as solid state photoconverters or solutions based on nanotechnology.

Liquid Detectors (Task Force 2)

DRDT 2.1 - Develop readout technology to increase spatial and energy resolution for liquid detectors.
Developments should achieve readout of more highly pixellated detectors with greater photon collection capabilities. Advancing liquid detector readout technologies towards greater quantum efficiency while still offering much higher granularity is a further objective.

DRDT 2.2 - Advance noise reduction in liquid detectors to lower signal energy thresholds.
The expected performance of future liquid detectors requires R&D to achieve lower sensor and electronics noise, as well as developments to measure simultaneously more components of the energy partition: for example light, charge and heat.

DRDT 2.3 - Improve the material properties of target and detector components in liquid detectors.
The R&D on material properties for liquid detectors aim to improve the emission properties of the target, for example through doping of Xe in Ar, H in Xe, Gd in H_20, and to achieve lower radiogenic backgrounds from the detector components, via target purification, material radioassay, and cryogenic distillation to change isotopic content.

DRDT 2.4 - Realise liquid detector technologies scalable for integration in large systems.
Dedicated developments should achieve applications of the previous DRDTs in future detectors ten to a hundred times larger, compared to the current state of the art, and allow coping with increased noise hit rates from detectors with sensor areas reaching 10, 100 and ultimately 1000 m^2. This will have to proceed while addressing the step change in complexity, with decade-long construction, in underground or undersea environments, with handling of heat load, value engineering and industrial production.

Further recommendations:
Near-term R&D should facilitate ten times scale increase of dark matter and neutrino experiments over the next decade, with issues of the number of electronics channels (particularly in terms of cost and heat) and requiring orders of magnitude radiopurity reductions and improvement in purification of target materials. This necessitates fostering industry-academia collaborations from an early stage given the scale of the enterprise. In addition to structural and funding issues captured in the GSRs, links with neighbouring disciplines are needed in the areas of: chemistry, quantum technologies, optics and photonics and engineering/materials science, as well as with industry, particularly around extending the capabilities of commercial photosensor systems. Studies should be pursued on how to combine detection of different modalities, for example the full light spectrum (from near infrared to ultraviolet) with simultaneous Čerenkov-scintillation light detection and the readout of both electromagnetic and acoustic detection.

Solid State Detectors (Task Force 3)

DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.
Developments of Monolithic Active Pixel Sensors (MAPS) should achieve very high spatial resolution and very low mass, aiming to also perform in high fluence environments. For tracking and calorimetry applications MAPS arrays of very large areas, but reduced granularity, are required for which cost and power aspects are critical R&D drivers. Passive CMOS designs are to be explored as a complement to standard sensors towards hybrid solutions (for pixels, strips and pads). State-of-the-art commercial CMOS imaging sensor technology should be studied for suitability in tracking and vertex detectors.

DRDT 3.2 - Develop solid state sensors with 4D-capabilities for tracking and calorimetry.
Understanding of the ultimate limit of precision timing in sensors, with and without internal multiplication, requires extensive research together with the developments to increase radiation tolerance and achieve 100% fill factors. Investigation is encouraged on the use of BiCMOS MAPS, exploiting SiGe properties.

DRDT 3.3 - Extend capabilities of solid state sensors to operate at extreme fluences.
To evolve the design of solid state sensors to cope with extreme fluences it is essential to measure the properties of silicon and diamond sensors in the fluence range $10^{16}\, n_{eq}\, cm^{-2}$ to $10^{18}\, n_{eq}\, cm^{-2}$ and to develop simulation models correspondingly including microscopic measurements of point and cluster defects. A specific concern to address is the associated activation of all the components in the detector. Exploration is desirable on alternative semiconductors and 2D materials to further push radiation tolerance.

DRDT 3.4 - Develop full 3D-interconnection technologies for solid state devices in particle physics.
A demonstrator programme is to be established to develop suitable silicon sensors, cost effective and reliable chip-to-wafer and/or wafer-to-wafer bonding technologies and to use these to build multi-layer prototypes with vertically stacking layers of electronics, interconnected by through-silicon vias and integrating silicon photonics capabilities.

Further recommendations:
Given the large demands of solid state sensors for future experiments, a major challenge relates to industrialisation where R&D funds are currently provided through experiments without concerted efforts devoted to building the industrial capability of producing the large areas of sensors in Europe. Although these are large orders by particle physics standards these are not by those of most semiconductor foundries. CERN and other national laboratories should promote greater strategic coordination to achieve a stronger negotiating position with commercial partners and to provide them with relationships of greater continuity and depth.

Particle Identification and Photon Detectors (Task Force 4)

DRDT 4.1 - Enhance the timing resolution and spectral range of photon detectors.
Fast timing is required for Čerenkov and time-of-flight detectors, while additional sensitivity is also needed at the typical wavelengths of Čerenkov photons and those from scintillation in noble gases. In addition, light collection systems for SiPM arrays (quartz based, micro-lenses, meta-materials) are needed, while for MCP-PMTs improved quantum and collection efficiencies, granularity and larger areas are required. Finer granularity and faster timing are needed in large-area gaseous photon detectors.

DRDT 4.2 - Develop photosensors for extreme environments.
Advances are needed in the radiation hardness of SiPM technology and other solid state photo-sensors, given the high particle fluxes and pile-up conditions at future facilities. Also, for high-sensitivity experiments, radio-pure SiPM technology and operation in cryogenic systems must be realised. For MCP-PMTs, significant improvement is needed in detector ageing and high-rate performance. For gaseous photon detectors issues of photocathode ageing and rate capability should be addressed. Increased light yield and shorter decay times are emphasised for scintillating fibres.

DRDT 4.3 - Develop RICH and imaging detectors with low mass and high resolution timing.
Advanced particle identification capabilities require novel compact low X_0 RICH based systems with few tens of picosecond timing. Greenhouse-friendly radiator gases (including pressurised systems) will be necessary, together with quartz having $\lesssim$nm surface roughness, and high transparency customised refractive index aerogels.

DRDT 4.4 - Develop compact high performance time-of-flight detectors.
For lower momenta, long flight-path TOF systems offer excellent complementary particle identification performance, but to push the momentum range covered requires few picosecond timing to be achieved at a system level.

Further recommendations:
It is suggested that a number of additional, more “blue-sky” R&D activities, should be pursued in this area. The development of solid state photon detectors from novel materials is an important future line of research, as is the development of cryogenic superconducting photon sensors for accelerator-based experiments. Regarding advances in PID techniques, gaseous photon detectors with high sensitivity to visible light would be highly desirable. Meta-materials such as photonic crystals should be developed, as these would provide tunable refractive indices for PID at high momentum. Finally, for TRD imaging detectors, the detection of transition radiation with silicon sensors would be an important line of future research.

Quantum and Emerging Technologies Detectors (Task Force 5)

DRDT 5.1 - Promote the development of advanced quantum sensing technologies.
Promote and capitalise on the development of advanced quantum sensing technologies, their application in particle physics as well as in foundational physics, and exploration of their potential benefits to accelerator-based particle physics.

DRDT 5.2 - Investigate and adapt state-of-the-art developments in quantum technologies to particle physics.
Explore and adopt methodologies and technologies from quantum sensing, quantum materials, quantum computing and quantum communication to develop new probes for the investigation of matter and fields.

DRDT 5.3 - Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies.
Put in place funding opportunities for rapid exploration of the potential of novel approaches as well as for consolidating longer term experimental efforts that build on and expand the initial proof-of-principle investigations.

DRDT 5.4 - Develop and provide advanced enabling capabilities and infrastructure.
Develop key enabling capabilities, such as cryogenic electronics, tailored coatings or dedicated developments in material science for quantum sensing devices, and provide access to common infrastructures at the national and supranational levels for testing and evaluating the suitability of specific quantum technologies for their use in probing fundamental physics.

Further recommendations:
The current rapid growth of quantum technologies holds the promise for significant further advances for fundamental physics at the individual sensor and array level. On a time scale of ten years, the use of networks of quantum sensors could bring transformational advances to the study of matter-energy in the universe. Focus on miniaturisation and reducing costs will enable scaling of experiments with corresponding increase in sensitivity and furthermore could facilitate experiments to be deployed in orbit, greatly extending the physics sensitivity. Major advances and improvements in existing or future quantum technologies will be needed if topics related to the dark universe, detection of relic neutrinos or probing general foundational issues in physics are to be addressed.

Calorimetry (Task Force 6)

DRDT 6.1 - Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution.
Priority developments are geared towards the successful completion of R&D programmes for the variety of HL-LHC detector upgrades aiming at much finer spatial granularity and high accuracy timing while still delivering excellent energy resolution in high radiation environments. Further developments beyond these projects should continue towards future facilities.

DRDT 6.2 - Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods.
Developments are focused on calorimetry at future high energy e^+e^- colliders with a view to combine information from the calorimeter with other detector systems. Capitalising on the experiences at the HL-LHC, the objective is to achieve 3D-pixelated calorimetry to measure each particle individually and use of precise tracking information for charged particles. Further developments are to be pursued to exploit the different signals produced by electrons or photons and hadrons in a Dual Readout system. Eventually, combining both approaches might lead to an optimised jet energy resolution.

DRDT 6.3 - Develop calorimeters for extreme radiation, rate and pile-up environments.
Long-term R&D is to start for calorimetry systems at a future hadron collider or a muon collider to address up to two orders of magnitude more severe requirements than at the HL-LHC, related to unprecedented radiation hardness, pattern recognition in the presence of severe pile-up and the associated data handling. Appropriate models should be developed to simulate such harsh environments.

Further recommendations:
While the HL-LHC programme and several non-collider programmes are stepping stones for calorimetry towards future e^+e^- colliders, substantial R&D should be supported on additional topics, for example on novel optical materials, CMOS based sensors, the use of precision timing, test-beam validation of simulation models and improvements in liquefied noble gas detectors. The calorimetry R&D programmes must keep up with the rapid developments in industry, in particular related to the emerging of Artificial Intelligence at the level of the readout electronics. European collaboration should be promoted with a view of establishing large scale demonstrators for calorimetry. A concerted strategic approach and organisation is to be established in a timely fashion for calorimetry R&D targeting colliders further in the future, particularly for the most extreme environments.

Electronics and Data Processing (Task Force 7)

DRDT 7.1 - Advance technologies to deal with greatly increased data density.
To sustain detector performance at the expected high event rate at future experiments, data handling systems with much higher rates should be developed to cope with more channels and more bits per sample, along with new link technologies, while keeping manageable power levels.

DRDT 7.2 - Develop technologies for increased intelligence on the detector.
Radiation-tolerant processors and programmable logic elements must be made available as ASIC IP blocks on the detector and their power-performance ratio must be improved, while advanced data-reduction techniques need to be implemented and ways to exploit the Artificial Intelligence revolution need to be developed.

DRDT 7.3 - Develop technologies in support of 4D-and 5D-techniques.
High 4D (timing as well as spatial) resolution requires developing solutions to improve the noise-speed-resolution trade-offs in advanced technologies with low supply voltage and high transistor density, along with achieving an unprecedented precision for the distribution of frequency and time references. Combination with accurate measurement of the energy deposited gives the additional possibility of “5D” capabilities.

DRDT 7.4 - Develop novel technologies to cope with extreme environments and required longevity.
For many future particle physics experiments, extreme particle fluences and high magnetic fields can be anticipated, while at others operation has to be under cryogenic conditions. These often result in highly inaccessible detector systems that must be developed with vital requirements in terms of high reliability, fault tolerance, full detector control and all within a tight power and cost budget.

DRDT 7.5 - Evaluate and adapt to emerging electronics and data processing technologies.
A rolling R&D campaign should be established to keep up with commercial evolution of novel devices, materials, interconnects, communication techniques and microelectronics technologies like silicon photonics, as well as to keep pace with and adapting interfaces to new generations of commercial off-the-shelf capabilities.

Further recommendations:
The need for greater coordination in this area has been strongly emphasised in a number of preceding sections and has provided a strong motivation for several of the GSRs mentioned below. For each of the DRDTs identified above, electronics R&D in Europe should be increasingly organised around a number of dedicated RD collaborations.

Integration (Task Force 8)

DRDT 8.1 - Develop novel magnet systems.
Magnet requirements are very specific to the design of the detector. Considering the very long lead time, generic R&D programmes must be established and maintained on dedicated conductors and prototyping to achieve the variety of magnet specifications.

DRDT 8.2 - Develop improved technologies and systems for cooling.
As channel count increases in future detectors, issues of power dissipation in the detector and associated electronics naturally increase, requiring the development of ever more advanced cooling solutions whilst often needing minimal associated scattering length of the cooling system within the sensitive detector volume.

DRDT 8.3 - Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
Along with minimising multiple scattering due to material for mechanics and services in tracking detectors, developments of ultra-light structures for cryostats are mandatory for novel liquid calorimeters; for possible thin magnets in front of these and, potentially, for neutrino experiments.

DRDT 8.4 - Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects.
There is a strong need to develop standardised custom solutions for monitoring, covering a wide range of critical parameters, that can function in the extreme environments to be expected at many future facilities and to improve precision and sampling rate capabilities.

Further recommendations:
Many integration aspects require continuous R&D and synergies unfold as stepping stones through the general sequence of use cases from HL-LHC experiments towards requirements for facilities such as FCC-hh and, on the other hand, developments for Belle II, ALICE 3 and EIC are stepping stones to future e^+e^- Higgs-EW-Top factories. Advances in industry must be followed closely as, for example, aspects such as the development of 3D printing have revolutionised a number of prototyping capabilities. It is essential to develop appropriate databases of key properties including results of radiation testing and to maintain support for software packages dedicated to instrumentation.

Training (Task Force 9)

DCT 1 - Establish and maintain a European coordinated programme for training in instrumentation.
Educational opportunities and multidisciplinary training are needed at all career levels to develop an expert work force to advance instrumentation for particle physics. Under the auspices of ECFA and in consultation with organisations representing neighbouring disciplines, a coordination panel across institutions and laboratories in Europe should be created to enhance the synergies between existing training programmes and schools in contemporary and emerging instrumentation, and to stimulate the creation of complementary ones where relevant. Additional to in-person and online lectures, emphasis on hands-on tutorials in laboratories and the multidisciplinary nature of R&D in instrumentation is essential.

DCT 2 - Develop a master's degree programme in instrumentation.
The possibility to develop a joint curriculum for instrumentation that leads to an accredited master degree should be explored. The curriculum ought to be built on a portfolio of leading instrumentation courses distributed across European institutions and greatly extend the opportunities available at any single university. Virtual laboratory platforms for training in instrumentation are to be created to overcome the geographical and economic limitations.

Further recommendations
Significantly more detailed proposals are listed in Chapter 9 and many of these issues are of such importance that they are emphasised again in the GSRs. Key to this area is that early-career scientists, especially graduate students, get to participate in leading-edge instrumentation R&D, and to develop into the future HEP instrumentation experts. To achieve this coherently across Europe it is proposed that steps are taken to improve recognition and career prospects for instrumentation experts, along with provision of an adequate number of faculty/permanent positions, and to establish a high quality coordinated and structured instrumentation training programme which enjoys worldwide recognition.

General Strategic Recommendations (GSRs)

Establishing and succeeding in the DRDTs will sustain a leading role for European HEP and facilitate achieving the ambitions of upgraded and future experiments expressed in the EPPSU. In addition, it will also create expertise of considerable relevance to many other scientific disciplines and of significant benefit to a wide range of industrial partners.
For the implementation of the DRDTs identified above, Chapter 10 details a number of specific organisational and resources-related points as deserving special emphasis. Further to the more specific recommendations linked to each of the DRDTs outlined above, these lead to a number of GSRs.

GSR 1 - Supporting R&D facilities.
It is recommended that the structures to provide Europe-wide coordinated infrastructure in the areas of: test beams, large scale generic prototyping and irradiation be consolidated and enhanced to meet the needs of next generation experiments with adequate centralised investment to avoid less cost-effective, more widely distributed, solutions, and to maintain a network structure for existing distributed facilities, e.g. for irradiation.

GSR 2 - Engineering support for detector R&D.
In response to ever more integrated detector concepts, requiring holistic design approaches and large component counts, the R&D should be supported with adequate mechanical and electronics engineering resources, to bring in expertise in state-of-the-art microelectronics as well as advanced materials and manufacturing techniques, to tackle generic integration challenges, and to maintain scalability of production and quality control from the earliest stages.

GSR 3 - Specific software for instrumentation.
Across DRDTs and through adequate capital investments, the availability to the community of state-of-the-art R&D-specific software packages must be maintained and continuously updated. The expert development of these packages - for core software frameworks, but also for commonly used simulation and reconstruction tools - should continue to be highly recognised and valued and the community effort to support these needs to be organised at a European level.

GSR 4 - International coordination and organisation of R&D activities.
With a view to creating a vibrant ecosystem for R&D, connecting and involving all partners, there is a need to refresh the CERN RD programme structure and encourage new programmes for next generation detectors, where CERN and the other national laboratories can assist as major catalysers for these. It is also recommended to revisit and streamline the process of creating and reviewing these programmes, with an extended framework to help share the associated load and increase involvement, while enhancing the visibility of the detector R&D community and easing communication with neighbouring disciplines.

GSR 5 - Distributed R&D activities with centralised facilities.
Establish in the relevant R&D areas a distributed yet connected and supportive tier-ed system for R&D efforts across Europe. Keeping in mind the growing complexity, the specialisation required, the learning curve and the increased cost, consider more focused investment for those themes where leverage can be reached through centralisation at large institutions, while addressing the challenge that distributed resources remain accessible to researchers across Europe and through them also be available to help provide enhanced training opportunities.

GSR 6 - Establish long-term strategic funding programmes.
Establish, additional to short-term funding programmes for the early proof of principle phase of R&D, also long-term strategic funding programmes to sustain both research and development of the multi-decade DRDTs in order for the technology to mature and to be able to deliver the experimental requirements. Beyond capital investments of single funding agencies, international collaboration and support at the EU level should be established. In general, the cost for R&D has increased, which further strengthens the vital need to make concerted investments.

GSR 7 - "Blue-sky" R&D.
It is essential that adequate resources be provided to support more speculative R&D which can be riskier in terms of immediate benefits but can bring significant and potentially transformational returns if successful both to particle physics (as unlocking new physics may only be possible by unlocking novel technologies in instrumentation) and to society. Innovative instrumentation research is one of the defining characteristics of the field of particle physics. "Blue-sky" developments in particle physics have often been of broader application and had immense societal benefit. Examples include: the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science.

GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts.
Innovation in instrumentation is essential to make progress in particle physics, and R&D experts are essential for innovation. It is recommended that ECFA, with the involvement and support of its Detector R&D Panel, continues the study of recognition with a view to consolidate the route to an adequate number of positions with a sustained career in instrumentation R&D to realise the strategic aspirations expressed in the EPPSU. It is suggested that ECFA should explore mechanisms to develop concrete proposals in this area and to find mechanisms to follow up on these in terms of their implementation. Consideration needs to be given to creating sufficiently attractive remuneration packages to retain those with key skills which typically command much higher salaries outside academic research. It should be emphasised that, in parallel, society benefits from the training particle physics provides because the knowledge and skills acquired are in high demand by industries in high-technology economies.

GSR 9 - Industrial partnerships.
It is recommended to identify promising areas for close collaboration between academic and industrial partners, to create international frameworks for exchange on academic and industrial trends, drivers and needs, and to establish strategic and resources-loaded cooperation schemes on a European scale to intensify the collaboration with industry, in particular for developments in solid state sensors and micro-electronics.

GSR 10 – Open Science.
It is recommended that the concept of Open Science be explicitly supported in the context of instrumentation, taking account of the constraints of commercial confidentiality where these apply due to partnerships with industry. Specifically, for publicly-funded research the default, wherever possible, should be open access publication of results and it is proposed that the Sponsoring Consortium for Open Access Publishing in Particle Physics ($SCOAP^3$) should explore ensuring similar access is available to instrumentation journals (including for conference proceedings) as to other particle physics publications.

Summary

In conclusion, under the auspices of ECFA, an effort by the community developing detector systems for particle physics and closely related fields has delivered the ECFA Detector R&D Roadmap 2021. The Roadmap proposes a total of ten General Strategic Recommendations (GSRs) with a view to sustaining an adequate environment in Europe for the implementation of concrete programmes around Detector R&D Themes (DRDTs) and Detector Community Themes (DCTs) covering the entire landscape of present and emerging detector technologies.

Succeeding in the DRDTs and DCTs objectives is essential to coherently creating the technological foundation to realise the scientific ambitions expressed in the updated European Particle Physics Strategy (EPPS).

Guided by this Roadmap and engaging researchers, laboratories, research institutions and funding entities in Europe, concerted and resource-loaded R&D programmes to innovate instrumentation should emerge in a timely manner. This would transform the ability of present and future generations of researchers to explore and observe nature beyond current limits.

While each thematic programme generally spans several decades to reach the final currently identifiable R&D goal, the Roadmap includes important stepping stones along each DRDT timeline where requirements for experiments and facilities intermediate in time both exploit and help drive the programme forward.

Moving forward, synergies with adjacent research fields, knowledge institutions and industry are all vital to enhance particle physics capabilities and capitalise on investments. Progress in the implementation of the Roadmap should be monitored by ECFA and adaptations should be discussed in preparation for the next EPPS update.

Appendices

A Glossary

2PACL	Integrated 2-Phase Accumulator Controlled Loop
4D	Four Dimensional
5D	Five Dimensional
AC-LGAD	AC-coupled Low-Gain Avalanche Detector
ACF	Anisotropic Conductive Films
ACP	Anisotropic Conductive Paste
ACTAR	ACtive TARgets experiment
APOD	Advisory Panel with Other Disciplines (APOD)
APPEC	Astro-Particle Physics European Consortium
ASACUSA	Atomic Spectroscopy and Collisions Using Slow Antiprotons
ADC	Analog-to-Digital Converter
ADMX	Axion Dark Matter eXperiment
AHCAL	Analog Hadron CALorimeter
AI	Artificial Intelligence
AION	An Atom Interferometer Observatory and Network
Al	Aluminium
ALD	Atomic Layer Deposition
ALICE	A Large Ion Collider Experiment
ALP	Axion-Like Particle
AMBER	Proposed new QCD facility at the CERN SPS
AMICI	Accelerator and Magnet Infrastructure and Cooperation and Innovation
APD	Avalanche-Photo Diode
APPEC	Astro Particle Physics European Consortium
ARAPUCA	a New device for liquid argon scintillation light detection
ArgonCube	Novel design for building advanced Liquid Argon Time Projection Chambers
ARIADNE	Axion Resonant InterAction DetectioN Experiment
ARIES	Accelerator Research and Innovation for European Science and Society
ARM	Advanced RISC Machines brand: ARM Ltd.
ASIC	Application Specific Integrated Circuits
ATLAS	A Toroidal LHC ApparatuS
AT-TPC	Active Target Time Projection Chamber at NSCL, US
AX-PET experiment	A demonstrator for an axial Positron Emission Tomograph

BABAR	Experiment at Stanford Linear Accelerator
BaF_2	Barium Fluoride
BBN	Big Bang Nucleosynthesis
BEAMCAL	Electromagnetic sandwich calorimeter
Belle	Experiment at the KEK B-factory
BEOL	Back End Of Line
BES-III	Beijing Spectrometer III at the Beijing Electron–Positron Collider II, China
BGO	Bismuth Germanate
BIB	Beam Induced Background
BSM	Beyond the Standard Model
C	Čerenkov
C	Carbon
CAD	Computer-Aided Design/ Electronic Design Automation
CALICE	R&D Collaboration for highly granular calorimeters
CAS	CERN Accelerator School
CASE	Cooperative Awards in Science & Technology
CASPER	Cosmic Axion Spin Precession Experiment
CAST	CERN Axion Solar Telescope
CBM	Compressed Baryonic Matter Experiment at FAIR
CC	Charged-current
CCD	Charge-Collection-Distance
CCD	Charge-Coupled Device
CCE	Charge Collection Efficiency
CEB	Cold Electron Bolometers
CEE	External target Experiment at the Heavy Ion Research Facility at the Lanzhou—Cooling Storage Ring, China
CEPC	Circular Electron Positron Collider, proposed e^+e^- collider (sited in China)
CERN	European Organization for Nuclear Research
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymer
CFT	Crystal-field calcuation
CII	Singly-ionized Carbon
CIS	CMOS Imaging Sensors
CLIC	Compact Linear Collider (a proposed particle accelerator at CERN
CMB	Cosmic Microwave Background
CMBR	Cosmic Microwave Background Radiation
CMD-3	Detector at electron-positron collider VEPP-2000, Russia
CMOS	Complementary MetalOxide Semiconductor
CMS	Compact Muon Solenoid experiment
CNB	Cosmic Neutrino Background
CNN	Convolutional Neural Network
CO_2	Carbon Dioxide
COBRA	Cadmium Zinc Telluride 0-Neutrino Double-Beta experiment
Codex-B	Compact Detector for Exotics at LHCb
COMAP	Carbon Monoxide Mapping Array Pathfinder
COMET	COherent Muon to Electron Transition
COMPASS	COmmon Muon Proton Apparatus for Structure and Spectroscopy experiment at CERN

COMSOL	Software for Multiphysics Simulation
COTS	Commercially Of The Shelf
CP	Combination of discrete symmetries: Charge-conjugation (C) and Parity (P)
CPT	Combination of discrete symmetries: Charge-conjugation (C), Parity (P) and Time (T)
CPU	Central Processing Unit
CR	Cosmic Ray
CSC	Cathode Strip Chambers
CsI	Cesium Iodide
CsTe	Cesium Telluride
CTE	Coefficient of Thermal Expansion
CV	Capacitance-Voltage
CVD	Chemical vapor deposition
CWDM	Coarse Wavelength Division Multiplexing
D0	Experiment at Fermilab
DAC	Digital to Analog Converter
DAMA/LIBRA	DArk MAtter/Large sodium Iodide Bulk for RAre processes
DAFNE	Double Annular Φ Factory for Nice Experiments, the electron-positron collider at the INFN National Laboratory in Frascati, Italy
DAQ	Data Acquisition
DarkSide-50	Physics detector in the Darkside program
DARWIN	DARk matter WImp search with liquid xenoN
DC	Direct Current
DC-DC	Direct Current to Direct Current
DCR	Dark Count Rate
DCT	Detector Community Themes
DE	Dark Energy
DEAP-3600	Dark matter Experiment using Argon Pulseshape Discrimination
Deep RIE	Deep Reactive-Ion Etching
DESY	German Electron Synchrotron
DHCAL	Digital Hadronic Calorimeter
DIRC	Detectors for Internally Reflected Čerenkov
DLC	Diamond-Like Carbon
DM	Dark Matter
DMAPS	Depleted Monolithic Active Pixel Sensor
DR	Dark Radiation
DR	Dual Readout
DRC	Design Rule Checking
DRDC	Detector Research and Development Committee
DRDT	Detector Research and Development Themes
DREAM	Dual-REAdout Module
DRM	Detector Readiness Matrix
DS	Dark Sector
DSB:Ce	disilicate of barium (BaO_2-SiO_2) doped with Ce
dSiPM	digital SiPMs
DUNE	Deep Underground Neutrino Experiment
DUT	Device Under Test
E	Electron

E	Energy
EC	European Community
ECAL	Electromagnetic Calorimeter
ECFA	European Committee for Future Accelerators
ECR	Early Career Researchers
EDA	Electronic Design Automation
EDIT	The school of Excellence in Detectors and Instrumentation Technologies
EDM	Electric Dipole Moment
ee	electron-positron
EEE Project	Extreme Energy Events Projects
EIC	Electron Ion Collider
EJADE	Europe-Japan Accelerator Development Exchange Programme
EM	Electromagnetic
ENC	Equivalent Noise Charge
ERL	Energy Recovery Linac
ESA	European Space Agency
ESFRI	The European Strategy Forum on Research Infrastructures
ESI	The EISOForum School of Instrumentation
ESIPAP	European School of Instrumentation in Particle & Astroparticle Physics
ESPPU	European Strategy for Particle Physics Update, also sometimes EPPSU or ESU
ESR	Enhanced Specular Reflector
ESRF	European Synchrotron Radiation Facility
ET	Einstein Telescope
EU	European Union
eV	Electron Volt
EW	Electroweak
F	Flour
FAIR	Facility for Antiproton and Ion Research
FBGS	Fibre-Bragg Grating Sensors
FCC	Future Circular Collider, proposed 100-km scale collider (sited at CERN)
FCC-ee	Future Circular Collider e+e- a proposed accelerator at CERN
FCC-eh	Version of FCC with electron-hadron collisions
FCC-hh	Version of FCC with hadron collisions (proton or heavy-ion)
FCT	Portugiese Trainee Programme at CERN
FDM	Frequency Domain Multiplexing
FEC	Forward Error Correction
FEE	Front-End Electronics
FEL	Free Electron Laser
FELIX	FrontEnd LInk eXchange
FIFO	First In, First Out
FIMP	Feebly-Interacting Massive Particle
FinFET	Fin Field-Effect Transistor
FIP	Feebly Interacting Particle
FMC	FPGA Mezzanine Card
FOCAL	FOrward CALorimeter in the ALICE experiment

FOM	Figure Of Merit
FOS	Fibre-Optical Sensors
FPGA	Field-Programmable Gate Array
FR4	glass-reinforced epoxy laminate material
FTBF	Fermilab Test Beam Facility
FTEC	Portugiese Trainee Programme at CERN
FTM	FEX Test Module
FTM	Fast Timing MPGD
FWHM	Full Width at Half Maximum
GaAs	Gallium Arsenid
GAGG	co-doped garnet crystal fibres (YAG, GYAGG)
GaInP	Gallium Indium Phosphide
gamma ray	Electromagnetic radiation
GaN	Galium Nitrate
GD	Gaseous Detectors
GE1/1	First CMS GEM station from the Interaction Point (IP)
GE2/1	Second CMS GEM station from the Interaction Point (IP)
Geant4	GEometry ANd Tracking
GEM	Gammas, Electrons, and Muons
GEM	Gas Electron Multiplier
GHZ	Greenberger–Horne–Zeilinger states
GHz	GigaHertz
GlueX	A DIRC detector
GNN	Global Neutrino Network
GNN	Graph Neural Network
GPDs	Gaseous Photon Detectors
GPGPU	General-Purpose Graphics Processing Unit
GPU	Graphics Processing Unit
GRad	GigaRad
GridPix	CMOS pixel readout chip with a gas amplification grid added by photolithographic postprocessing techniques
GUT	Grand Unified Theory
GW	Gravitational Waves
GWP	Global Warming Potential
GHG	GreenHouse Gases
H1	Experiment at HERA at DESY
HAYSTAC	Haloscope At Yale Sensitive To Axion CDM
HCAL	Hadronic CALorimeter/CALorimetry
HCI	Human-Computer Interaction
HEB	Hot Electron Bolometer
HEP	High Energy Physics
Hf	Hafnium
HfF^{+}	Hafnium fluoride
HGCAL	High-Granularity CALalorimeter
hh	hadron-hadron
HL-LHC	High-Luminosity LHC
HPC	High-Performance Computing
HPDs	Hybrid Photon Detectors
HPL	High Pressure Laminate

HV	High Voltage
Hyper-K or HK	Hyper-Kamiokande
Hz	Hertz
I.FAST	Innovation fostering in accelerator science and technology
I/O	Input/Output
IAXO	International Axion Observatory
IBF	Ion Back Flow
IC	Integrated Circuits
ICARUS	Imaging Cosmic And Rare Underground Signals experiment
ID	Indirect Detection (or Identification, depending on context)
ID	Inner Detector
IDEA	International Detector for Electron-positron Accelerator proposed at FCC
IFU	Integrated Field Unit
ILC	International Linear Collider, proposed e^+e^- collider (sited in Japan)
ILD	International Large Detector
iLGAD	inverted LGAD
INFIERI	Intelligent signal processing for FrontIEr Research and Industry
INFN	National Institute for Nuclear Physics
IoT	Internet of Things
IP	Interaction Point
IR	Infrared, i.e. low energy limit
Ir	Iridium
ISAPP	International School of AstroParticle Physics
ISOTDAQ	The International School Of Trigger and Data AcQuisition
IT	Information technology
IV	current-voltage
JJPA	Josephson Junction Parametric Amplifiers
JPARC	Japan Proton Accelerator Research Complex
JUAS	Joint University Accelerator School
JUNO	Jiangmen Underground Neutrino Observatory
K	Kelvin
KEKB	B factory e^+e^- collider in Japan
kHz	kiloHertz
KID	Kinetic Inductance Detector
KLEVER	Experiment at the CERN SPS
KLOE	drift chamber
KSETA	Karlsruhe School of Particle and Astroparticle Physics
L3	Experiment at LEP
LAPD	Liquid Argon Purity Demonstrator
LAPPD	Large Area Picosecond Photo-Detector
LAr	Liquid Argon
LArTPC	Liquid Argon Time-Projection Chamber
LBNF	Long-Baseline Neutrino Facility, US
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LDMX	Light Dark Matter eXperiment
LEAPS	League of European Accelerator-based Photon Sources
LED	Light-Emitting Diodes

LENS	League of advanced European Neutron Sources
LEP	Large Electron-Positron Collider
LGAD	Low-Gain Avalanche Diodes
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty experiment
LHCb-VELO	VErtex LOcator of LHCb
LHCC	LHC Experiments Committee
LHe	Liquid Helium
LHeC	Proposed electron-hadron collider using hadrons from the LHC plus an ERL
LIDAR	Light Detection and Ranging system
LIGO	The Laser Interferometer Gravitational-Wave Observatory
LiquidO	Opaque Detector for $\beta\beta$ Decay
LISA	The Laser Interferometer Space Antenna
LN	Liquid Noble
LpGBT	Low power Giga-bit transeiver
LS	Long Shutdown
LS	Liquid Scintillator
LS2	Second Long Shutdown of the LHC
LS3	Third Long Shutdown of the LHC
LS4	Fourth Long Shutdown of the LHC
LUX	Large Underground Xenon experiment
LUXE	Experiment and European XFEL
LXe	Liquid Xenon
LZ	LUX-ZEPLIN experiment
M	Million
MAGIS	Matter wave Atomic Gradiometer Interferometric Sensor
MaPMTs	Multianode PMTs
MAPS	Monolithic Active Pixel Sensor
MARK-II	An experiment at the Stanford Linear Accelerator
MCP	Microchannel Plate
MCP-HPD	MicroChannel Plate-Hybrid Photon Detector
MCP-PMT	MicroChannel Plates PhotoMultiplier Tube
MDI	Machine Detector Interfaces
ME0	The innermost CMS Muon station from the Interaction Point (IP)
MEG II	The Mu to E Gamma II experiment
MEMS	Micro Electro Mechanical Systems
MeV	Megaelectron Volt
MGy	MegaGray
MHz	MegaHertz
MicroBooNE	Experiment at Fermilab
Micromegas	Micro-mesh gaseous structure
MIGA	Matter-wave Interferometric Gravitation Antenna
MIGDAL	Experiment close to RAL
MIMAC	MIcro-tpc MAtrix of Chambers for directional dark matter search
MINOS	MagIcal Numbers Of Shell device
MIP	Minimum Ionising Particle
MKID	Magnetic Kinetic Induction Device
MHSP	Micro Hole and Strip Plate

ML	Machine Learning
MOS	Metal-Oxide-Semiconductor
MOSFET	Metal-Oxide-Silicon Field Effect Transistor
MoTe2	Molybdenum ditelluride
MPGD	MicroPattern Gaseous Detectors
MPWs	Multi-Project Wafers
MRad	MegaRad
MRPC	Telescope Simulation for the Extreme Energy Events Experiment
MRPC	Multi-Gap RPC
MSc	Master student
μ-PIC	Micro Pixel Chamber
μ-RWELL	Micro-Resistive WELL
Mu2e	Muon-to-Electron-conversion experiment
Mu3e	Muons (Mu) to an electron and two positrons (3e) experiment
MWPC	MultiWire Proportional Chamber
N	Nucleon
NA48	Experiment at the CERN SPS
NA60+	Experiment at CERN SPS
NA62	fixed-target particle physics experiment at CERN SPS
Nb	Niobium
NbN	Niobium nitride
NbTiN	Niobium Titanium nitride
ND	Near Detector at Long baseline neutrino experiment
NDA	Non-Disclosure Agreements
NEWAGE	NEw generation WIMP search with an Advanced Gaseous tracking device Experiment
NEWS-G	New Experiments With Spheres-Gas
NEXT	Neutrino Experiment with a Xenon TPC
NIEL	Non-Ionising Energy Loss
NIR	Near InfraRed
NMR	Nuclear Magnetic Resonance
NOL	Nanostructured-Organo-silicon-Luminophores
NRZ	Non Return to Zero
NSCL	National Superconducting Cyclotron Laboratory at Michigan State University, US
NuDot	Double-Beta Decay with Direction Reconstruction in Liquid Scintillator
NuPECC	Nuclear Physics European Collaboration Committee
NV	Nitrogen Vacancy
O	Oxygen
PAM	Pulse Amplitude Modulation
PANDA	Experiment at FAIR
PandaX	Particle And Astrophysical Xenon Experiment
PandoraPFA	Pandora Particle Flow Analysis
PB	Peta-byte
PbWO4	Lead tungstate
PBC	Physics Beyond Colliders, a study
PCTFE	Polychlorotruoroethylene
pCVDD	Detector-grade polycrystalline synthetic diamond

PDE	Photon Detection Efficiency
PEN	PolyEthylene Naphthalate films
PET	Positron Emission Tomography
PF	Particle Flow
PIP-II	Proton Improvement Plan II at Fermilab, US
Phase II	Second phase of the LHC Detector Upgrade
PhD	Doctoral student
PHENIX	Pioneering High Energy Nuclear Interaction eXperiment at the Relativistic Heavy Ion Collider
PHP	micro-Pulsating Heat Pipes
PIC	Photonic Integrated Circuit
PICOSEC	Pico-second Siliconphotomultiplier-Electronics-Crystal research-Marie- Curie-Network
picoTDC	TDC in ps regime
PID	Particle IDentification
PLL	Phase-Locked Loop
PMNS	Pontecorvo-Maki-Nakagawa-Sakata
PMT	PhotoMultiplier Tube
POT	Protons On Target
pp	proton-proton
ppb	parts per billion
pQCD	Perturbative QCD
PRF	Pad Response Function
ProtoDUNE	Detector prototype at the CERN Neutrino Platform
ps	Picosecond
p_T	Transverse momentum
PTA	Pulsar Timing Array
PTOLEMY	Princeton Tritium Observatory
QUAX	QUest for AXions
QCD	Quantum Chromo Dynamics
QE	Quantum Efficiency
QED	Quantum Electrodynamics, theory of the electromagnetic interaction
QIS	Quantum Information Science
QM	Quatum Mechanics
R744	Refrigerant grade CO_2
RaF	Radium fluoride
RAL	Rutherford Appleton Laboratory
RAM	Random Access Memory
$RaOH^+$	Radium monohydroxide molecular ion
RD	Research and Development
REDTOP	Rare Eta Decays with a TPC for Optical Photons
RF	Radio Frequency
RICH	Ring Imaging CHerenkov Counter
RISC	Reduced Instruction Set Computer
RISC-V	An open standard instruction set architecture (ISA) based on established reduced instruction set computer (RISC) principles
ROC	ReadOut Chip
ROOT	Data Analysis Framework
RPC	Resistive Plate Chambers

RPWELL	Resistive-Plate WELL
RTD	Resistance Temperature Detector
S	Scintillation
SBN	Short-baseline neutrino
SC	Superconducting
ScECAL	Scintillator-strip Electromagnetic CALorimeter
SCREAM project	Scintillator Cosmic Ray Experiments into Atmospheric Muons project
S'Cool LAB	CERN's hands-on laboratory
SCTF	Super Charm-Tau Factory
SD	Shutdown
SDHCAL	Semi Digital Hadronic CALorimeter
SEE	Single Event Effects
SET	Single Event Transient
SEU	Single Event Upset
SHiP	Search for Hidden Particles
Si	Silicon
SiC	Silicon Carbide
SiO_2	Silicon Dioxide
SiPM	Silicon Photomultipliers (SiPMs; also G-APD, SSPM, MPPC)
SKA	Square Kilometer Array
SLD	Experiment at the Stanford Linear Collider
SLID	Solid Liquid Inter-face Diffusion
SM	Standard Model
sMDT	small diameter (15 vs 30 mm) Muon Drift Tubes
SMPD	Single Microwave Photon Detectors
SNOLAB	Sudbury Neutrino Observatory (SNO) Laboratory
SNR	Signal-to-Noise Ratio
SNSPD	Superconducting Nanowire Single Photon Detector
SoC	System-on-Chip
SPACAL	SPAaghetti CALorimeter
SPAD	Single-Photon Avalanche Diode
SPS	Super Proton Synchrotron
SPTRs	Single-Photon Time Resolutions
SQUID	Superconducting Quantum Interference Devices
STAR	Solenoid Tracker at RHIC
sTGC	Thin Gap Chambers
T	Temperature
T	Tesla
T	Time
Ta	Tantalum
TC	Critical Temperature
TCAD	Technology Computer-Aided Design
TDAQ	Triggered Data Acquisition
TDC	Time to Digital Converter
TDM	Time Domain Multiplexing
TEC	Thermo-Electric Coolers
TES	Transition Edge Sensor
TFM	Thermal Figure of Merit

THEIA	An advanced optical neutrino detector
THGEM	Thick GEM
ThO	Thorium Oxide
THz	TeraHertz
Ti	Titanium
TI-LGAD	Trench-Isolated LGAD
TIARA	Test Infrastructure and Accelerator Research Area Preparatory Phase
TID	Total Ionising Dose
TiN	Titanium nitride
TLPB	Transient Liquid Phase Bonding
TMDs	Transition Metal Dichalcogenides
TOF	Time-of-Flight
TORCH	Time Of internally Reflected CHerenkov light
TPB	Tetra-Phenyl Butadiene
TPC	Time Projection Chamber
TDR	Technical Design Report
TRD	Transition Radiation Detector
TREX-DM	TPC for Rare Event eXperiment for Dark Matter in the Canfranc Underground Laboratory, Spain
TSV	Through Silicon Via
TWPA	Travelling Wave Parametric Amplifiers
ULDM	Ultra-light scalar DM
USPAS	US Particle Accelerator School
UV	Ultraviolet
VCSEL	Vertical Cavity Surface Emitting Laser
VELO-3	LHCb VELO upgrade
VI	French international corporate placement programme at CERN
VIRGO	Virgo interferometer
VSiPMT	Vacuum Silicon PhotoMultiplier Tube
VTRx+	Versatile Transmitter Receiver Plus
VUV	Vacuum UltraViolet
W	Tungsten
W	Watt
WBG	Wide Band-Gap
WbLS	Water-based Liquid Scintillator
WILGA	Symposium on Photonics, Web Engineering, Electronics for Astronomy and High Energy Physics Experiments
WIMP	Weakly Interacting Massive Particle
WLS	WaveLength-Shifting
X-ray	Electromagnetic radiation
Xe	Xenon
XENON1T, XENONnT	Dark Matter Experiments
XMASS	Multipurpose physics experiment in Japan
XFEL	X-ray Free Electron Laser Facility
xTCA	Micro Telecommunication Computing Architecture
YBCO	Yttrium Barium Copper Oxide
YIG	Yttrium Iron Garnet
ZAIGA	Zhaoshan long-baseline Atom Interferometer Gravitation Antenna

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C Acknowledgements

Alongside all the inputs from members of the Process Group itself, the Roadmap could not have been completed without the huge contributions from the presenters to the Input Sessions (listed below), the speakers at the Symposia (with agenda links below), the expert contacts from adjacent fields provided by the Advisory Panel with Other Disciplines (membership listed below) and the full community contributing through lively interactions at the Symposia, questionnaires and via the ECFA appointed National Contacts.
The authors would also like to specifically thank Ana Godinho, Fabienne Landua, John Pym and Christina Skorek for all their help on the graphics, expert technical assistance, advice and assistance with the text.

Title	**Presented by**
Input Session Presentations	
Detector R&D requirements for HL-LHC	Chris Parkes
Detector R&D requirements for strong interaction experiments at future colliders	Luciano Musa
Detector R&D requirements for strong interaction experiments at future colliders	Johannes Bernhard
Detector R&D requirements for future linear high energy e^+e^- machines	Frank Simon
Detector R&D requirements for future circular high energy e^+e^- machines	Mogens Dam
Detector R&D requirements for future high-energy hadron colliders	Martin Aleksa
Detector R&D requirements for muon colliders	Nadia Pastrone
Detector R&D requirements for future short and long baseline neutrino experiments	Marzio Nessi
Detector R&D requirements for future astro-particle neutrino experiments	Maarten De Jong
Detector R&D requirements for future dark matter experiments	Laura Baudis
Detector R&D requirements for future rare decay processes experiments	Cristina Lazzeroni
Detector R&D requirements for future low energy experiments	Alexandre Obertelli

Task Force	**Date**	**Indico page**
	Overview of Symposia	
Task Force 1	29.4.2021	https://indico.cern.ch/event/999799/
Task Force 2	9.4.2021	https://indico.cern.ch/event/999815/
Task Force 3	23.4.2021	https://indico.cern.ch/event/999816/
Task Force 4	6.5.2021	https://indico.cern.ch/event/999817/
Task Force 5	12.4.2021	https://indico.cern.ch/event/999818/
Task Force 6	7.5.2021	https://indico.cern.ch/event/999820/
Task Force 7	25.3.2021	https://indico.cern.ch/event/1001692/
Task Force 8	31.3.2021	https://indico.cern.ch/event/999825/
Task Force 9	30.4.2021	https://indico.cern.ch/event/1001747/

Organisation name	**Contact name**
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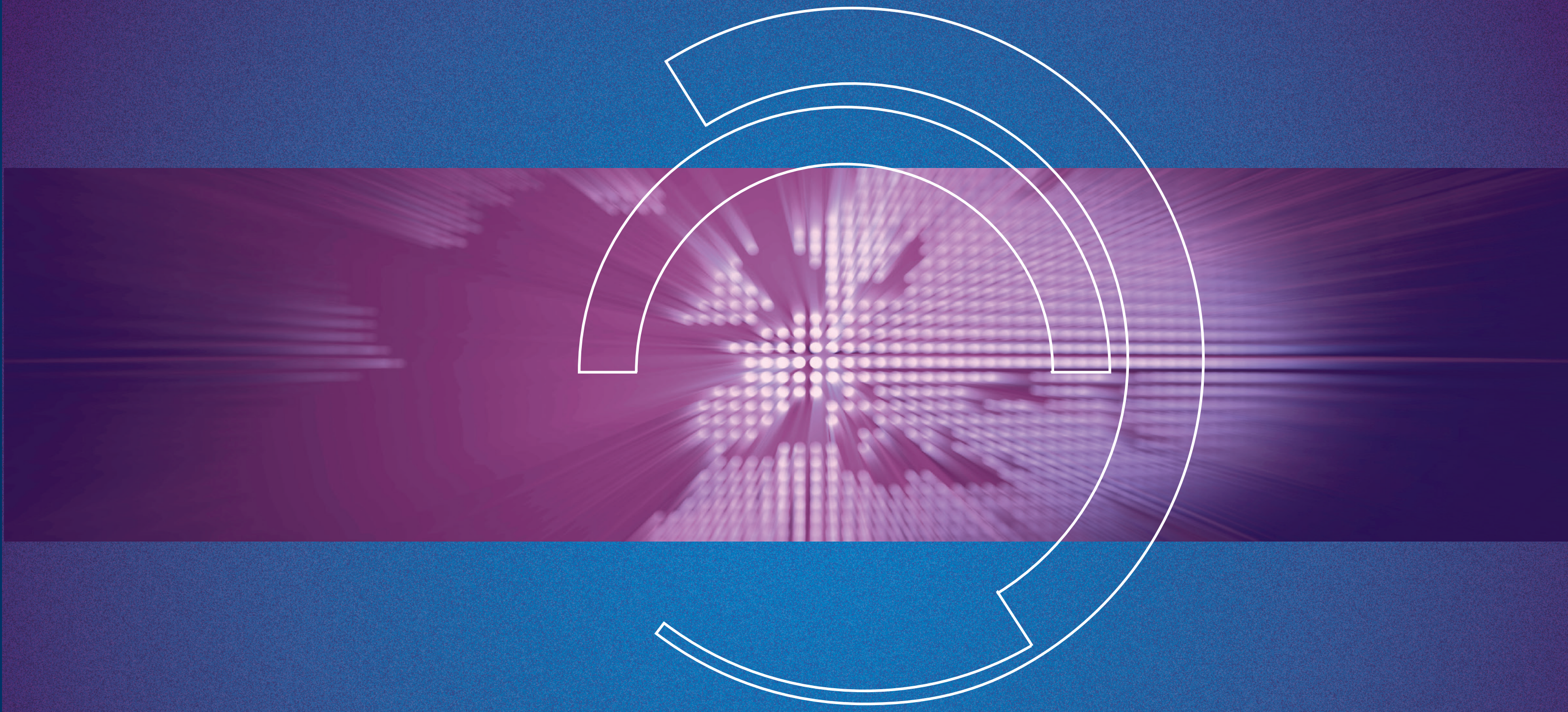
ISBN online: 978-92-9083-614-8
ISBN paperback: 978-92-9083-615-5

We ought, in every instance, to submit our reasoning to the test of experiment, and never to search for truth but by the natural road of experiment and observation.

Antoine Lavoisier

Traité élémentaire de chimie, 1789



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ISBN 978-92-9083-614-8 (online)
ISBN 978-92-9083-615-5 (paperback)

European Strategy Update

2021

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European Committee
for Future Accelerators