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Abstract

LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) aims at investigating the production of short, intense, and coherent pulses in the soft X-ray region. The project consists of a Free Electron Laser (FEL) line enabling the most advanced seeding configurations: High order Harmonic in Gas (HHG) seeding and Echo Enable Harmonic Generation (EEHG) with in-vacuum (potentially cryogenic) undulators of 15 and 30 mm period. Two accelerator types feed this FEL line : a 400 MeV Conventional Linear Accelerator (CLA) using superconducting cavities compatible with a future upgrade towards high repetition rate, for the investigations of the advanced FEL schemes; and a 0.4 - 1 GeV Laser Wake Field Accelerator (LWFA), to be qualified in view of FEL application, in the single spike or seeded regime. Two pilot user experiments for time-resolved studies of isolated species and solid state matter dynamics will take benefit of LUNEX5 FEL radiation and provide feedback of the performance of the different schemes under real user conditions.

INTRODUCTION

X-ray FEL sources open fantastic scientific opportunities but still with a limited access and high cost. LUNEX5 (see fig. 1) aims at proposing a short pulse compact FEL incorporating seeding schemes and new accelerating techniques and at efficiently producing and using stable, coherent, and short X-ray pulses and at extending the national community of X-ray users for the time resolved and coherent imaging studies.

Seeding enables to reduce the saturation length and the jitter, to improve the longitudinal coherence with respect to the Self Amplified Spontaneous Emission (SASE) one [1], which exhibits spiky longitudinal and temporal pulse distributions, apart from single spike operation for low charge regime [2]. FEL can be seeded either with amplified spontaneous emission from first stage undulators sent through a monochromator (so-called self-seeding) [3] or with an external laser or a short wavelength coherent light source, such as HHG [4, 5]. The EEHG [6] scheme with a double electron–laser interaction can extend the spectral range towards shorter wavelengths when operating on a high order harmonic of the seed wavelength.

Laser Wakefield Accelerators (LWFA) using the interacrion of intense laser beams with high electric field in plasmas progress rapidly. They are extremely compact (GeV/cm) and can provide high quality particle beams in extremely short bunches (a few fs) with very high peak currents (a few kA) [7]. FEL application can be viewed as an intermediate qualification [8] of GeV LWFA beams before proceeding to TeV LWFA colliders.

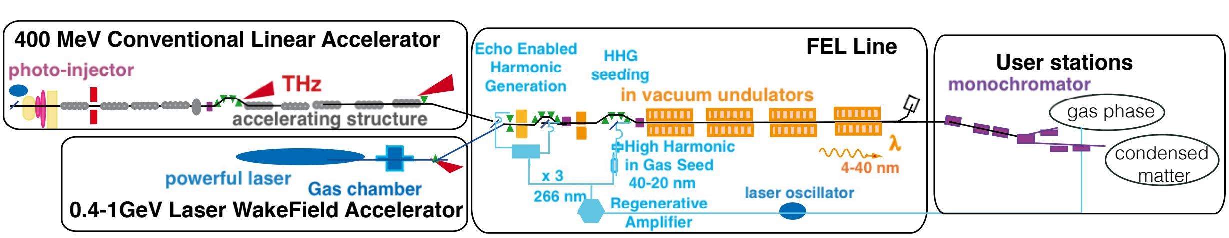

Figure 1: LUNEX5 scheme.

ISBN 978-3-95450-123-6

LUNEX5 CLA

The superconducting L-band technology [9] has been chosen for the 400 MeV LUNEX5 CLA, which allows for possible further CW upgrades, while in pulsed operation (1.4 ms with 500 µs flat-top at 50 Hz), the investment and operational costs are comparable with the normal conducting one. The gun will be a normal conducting 1.3 GHz PITZ type photo-gun [10] (1 π.mm.mrad total transverse normalized emittance, 1 nC, 60 MV/m accelerating voltage, 20 ps flat top laser profile), powered with a 10 MW multibeam klystron, pulsed by a commercial solid state modulator. The cryomodules will be operated at 24 MV/m, with a cryogenic system already anticipating a pulsed operation with 10 % duty cycle (100 bunches per macropulse), which requires 120 W at 2K. One RF transmitter and LLRF system will be used for each cavity in order to achieve a high stability in phase and amplitude. 1.3 GHz 20 kW CW solid state amplifiers will be developed at SOLEIL providing modularity and low phase noise. In the CW mode upgrade, an additional cryomodule will reduce the gradient from 24 to 16.5 MV/m, keeping the cryogenic load at a reasonable level.

ASTRA [11] simulations along the RF-gun and the first cryomodule up to about 200 MeV exhibit total transverse emittances of the order of 0.9 π.mm.mrad for 1 nC bunch and about 50 A peak current. A magnetic compressor, located just downstream of the first cryomodule, further increases the peak current. The emittance grows moderately up to 1.22 π.mm.mrad (calculation with CSRtrack [12]), mainly because of the Coherent Synchrotron Radiation) in the S-chicane compressor. A third harmonic cryomodule (16.5 MV/m) in opposite phase linearizes the longitudinal phase space profile, leading to 500 A peak current. The second cryomodule running on crest enables to reach 400 MeV is followed by a long free section for an optional third cryomodule, an achromatic dogleg dedicated to collimation and a matching section for the downstream undulalors. Beam performances are shown in fig. 2.

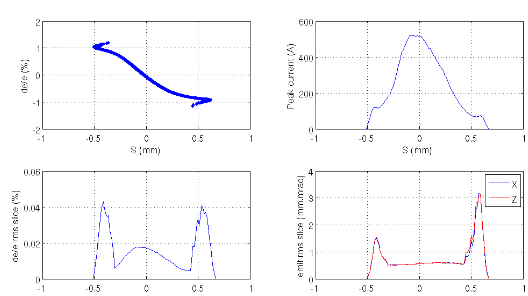

Figure 2: Longitudinal chirped phase space and slice parameters along the bunch in the undulator section at 400 MeV, (1nC).

LUNEX5 LWFA

The colliding laser pulse scheme enabling to produce very stable electrons with tuneable parameters [13] has been chosen for the baseline. Using a 1 J -30 fs laser, the electron beam can reach 350 MeV with up to 100 pC charge, 1 to 10% energy spread, 1 to 3 fs bunch duration and up to 4 kA peak current. Before using the baseline 200 TW (6 J, 30 fs, few Hz repetition rate) dedicated laser, first steps will be performed with existing lasers in the frame of CILEX (Centre Interdisciplinaire de Lumière Extrême), with APOLLON 10 PW laser and its “proximity centers” starting with the two 60 TW laser of LOA. A first implementation study in under way at Salle Jaune where an upgrade of the laser delivering two laser beams of 60 TW each will allow for exploring new regimes such as the cold injection scheme [14]. Efforts will be carried out on the reduction of the energy spread (from 1 % to 0.1 %). The transverse phase space is very strongly focused producing beam size of µm and divergence of mrad with a normalized emittance in the order of 1 π.mm.mrad. For limiting the emittance and peak current degradation during the transport to the undulator with a large energy spread and beam divergence, the matching first comports a first triplet of strong permanent magnet quadrupoles (130 T/m) [15] located at 5 cm from the source. Starting with an optimistic 0.1% energy spread, the emittance dilution induced by higher order chromatic effect is limited to 20%. The bunch lengthening induced by the large divergence is also maintained within 2 fs to 4 ps [16]. Including the 20 pC space charge effect, the emittances are further increased by 50% in both planes while the bunch length is not affected. Beam performances are shown in fig. 3. An advanced transport starting with a realistic value of the energy spread of 1 % is under study [16,17].

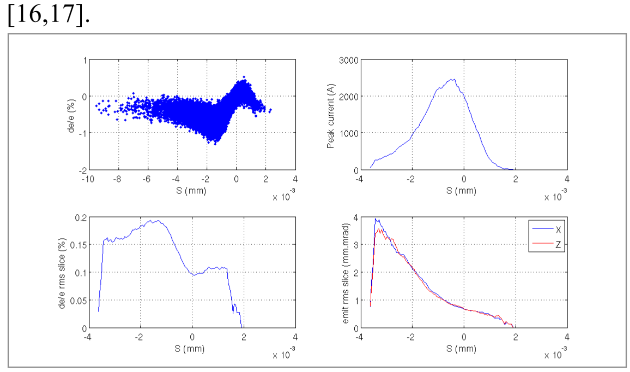

Figure 3: Longitudinal chirped phase space and slice parameters along the bunch in the undulator section at 400 MeV, (20 pC).

LUNEX5 FEL LINE

The FEL line comprises transport magnetic elements, dump dipole and cryo-ready in-vacuum undulators with periods of 30 (modulators) or 15 mm (radiators) [15]. At 3 mm gap, a peak field of 1.7 T will be produced at 77K with PrFeB magnets for a 15 mm period. R&D will start on a prototype of 3 m long cryo-ready undulators. A Ti-Sa oscillator (30 fs @ 800 nm), followed by a regenerative and a multipass amplifier (30 fs, 800nm, 10 mJ, 50 Hz, option at 1 kHz) will be used in both seeding

ISBN 978-3-95450-123-6

schemes. For the Echo, the amplifier output is tripled (266 nm) and split in*to* two parts. For HHG, the amplifier output injects directly the gas cell. The laser signal for pump-probe user experiments can be either provided by using part of the seeding laser and transporting it to the pilot experiments or by a dedicated laser (30fs, few mJ). All laser characteristics are within reach of commercially available lasers. The user laser, the electron gun, the cryomodules and the harmonic cavities will be synchronized by an optical synchronization with less than 10 fs jitter over 8 h.

The FEL light will hit a first toroidal mirror (to be interchanged with another one for the echo source point) for focusing on the exit slit; it will then pass through a double rotation monochromator operating in the Petersen mode to select and stabilize the photon energy and through two focusing mirror systems to be dispatched on the two experimental set-ups.

LUNEX5 FEL PERFORMANCES

The LUNEX5 spectrum (see fig. 4) covers the 4-40 nm range with the first, third and fifth harmonics, a fundamental peak power between 10 and 100 MW, corresponding to more than 10^{11} photons/pulse and 10^{27} peak brightness and harmonic peak power from 1 MW down to a few hundreds W. Each wavelength can be obtained with different configurations (amplifier, cascade with a HHG seed, echo with 266 nm lasers…). The FEL saturates earlier in the echo case than in the cascade one (7 vs. 11 m), with slightly lower power (65 MW vs. 0.27 GW), longer pulses (24 vs. 17 fs) at the Fourier limit [18]. Sensitivity to parameters is under way [19]. LWFA FEL performances critically depend on the electron beam quality and on the optimisation of the transport line.

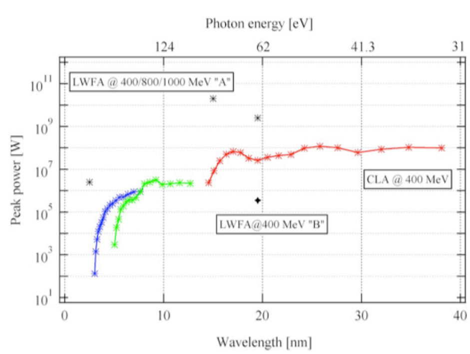

Figure 4: FEL peak power versus wavelength. Calculations with an 400 MeV electron beam, with a 1.5 π mm.mrad emittance, a peak current of 400 A, a slice energy spread of 0.02% (CLA) and case A : 0.1, case B: 0.5 % (LWFA), a bunch duration of 1 ps (CLA) and case A : 2, case B : 20) fs-RMS (LWFA).

LUNEX5 PILOT USER APPLICATIONS

The "time Resolved for isolated species" end station will consist in a high resolution velocity map imaging spectrometer allowing for spectroscopy of cold atoms/molecules, clusters or nanoparticles, issued from a multi-purpose source, combined with the full momenta characterisation of both electrons and ions using a COLTRIMS type of spectrometer based on time-of-flight and particle 2D position detection. In condensed matter, the first experiments will aim at obtaining spatially resolved information on ultrafast magnetization dynamics following a non-thermal excitation of a ferromagnetic thin film by an intense, fs short IR laser pulse. Studying non-reproducible aspects of these phenomena will be possible by single X-ray pulse based resonant magnetic small angle scattering at the transition metal's M-edges. The coherence of the radiation will allow to obtain single shot X-ray images of the magnetic domain structure, for example, to follow in real space and real time the evolution of the magnetization during the recently discovered all-optical process [20].

CONCLUSION

LUNEX5 is coupled CLA-LWFA based test facility for complementary use and test of new ideas aiming for ultra short FEL pulses quest, production and use. The CDR has been completed, R&D is starting.

ACKNOWLEDGMENT

The authors thank all the members of the LUNEX5 team, the DYNACO contract from the Agence Nationale de la Recherche, the QUAPEVA and RASYCOH contracts from Triangle de la Physique.

REFERENCES

[1] R. Bonifacio, C. Pelleigrini, L. M. Narducci, Optics Comm. 50, 373-378, 1984.
[2] Y. Din et al., Phys. Rev. Lett. 102, 254801 (2009).
[3] P. Emma, Proceed. IPAC 12, New Orleans, USA, May 2012.
[4] L.H. Yu et al., Science 289, 932, (2000).
[5] G. Lambert et al., Nature Physics 4, 296-30, (2008); T. Togashi et al., Optics Express, 1, 2011, 317-324.
[6] G. Stupakov, Phys. Rev. Lett., 102, 074801 (2009), D. Xiang et al., Phys. Rev. Lett. 105, 114801 (2010); Proceeding FEL conf, Malmö, Sweden, 15-19.
[7] T. Tajima et al., Phys. Rev. Lett. 43, 267_270 (1979) ; V. Malka et al., Nature Physics 4 447-453 (2008); E. Esarey et al., Rev. Mod. Phys. 81,1229 (2009); V. Malka et al., Phys. Plasmas 19, 055501 (2012).
[8] K. Nakajima, Nature Physics, 4 (2008) 92; H.-P. Schlenvoigt et al., Nature Physics, 4 (2008) 130-133; M. Fuchs et al., Nature Physics, 5, 826 (2009); W. Leemans, E. Esarey. , Phys. Today, 62, 3, 44 (2009); Anania et al., Proceedings IPAC10, Kyoto, Japan, 2263-2265; http://www.mpq.mpg.de/APS/gruener.php
[9] TESLA Technology Collaboration, http://tesla-new.desy.de/
[10] DESY-PITZ Collaboration, http://pitz.desy.de/collaboration

ISBN 978-3-95450-123-6

[11] K. Floettman, ASTRA code, https://www.desy.de/mpyflo
[12] M. Dohlus and T. Limberg, "CSRtrack", http://www.desy.de/xfel-beam/csrtrack/
[13] J. Faure et al., Nature 444, 737 (2006); C. Rechatin et al., Phys. Rev. Lett. 103, 194804 (2009), C. Rechatin et al., New J. Phys. 11, 013011 (2009); C. Rechatin et al., Phys. Rev. Lett. 103, 164801 (2009); O. Lundh et al., Nat. Phys. 5, 826 (2011).
[14] X. Davoine et al., Phys. Rev. Lett. 102, 065001 (2009).
[15] C. Benabderrahmane et al., these proceedings.
[16] A. Loulergue et al., these proceedings.
[17] M. Labat et al., these proceedings.
[18] C. Evain et al., these proceedings.
[19] T. Tanikawa et al., these proceedings.
[20] T. Wang et al., Phys. Rev. Lett. 108, 267403 (2012); C. D. Stanciu et al., Phys. Rev. Lett. 99, 047601 (2007).

ISBN 978-3-95450-123-6