Challenges of Radioactive Beam Facilities - Comparing Solutions at SPIRAL2 and FAIR

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CHALLENGES OF RADIOACTIVE BEAM FACILITIES – COMPARING SOLUTIONS AT SPIRAL2 AND FAIR

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Abstract

The SPIRAL2 facility at GANIL will use a high-power p, d and heavy-ion driver to produce RIB though both ISOL and in-flight techniques. The SPIRAL2-injector beam is expected before the end of 2014. The construction of the FAIR facility has started at GSI and the outline of the accelerator complex is well defined. A clear strategy and construction schedule is defined in the framework of the international FAIR collaboration. This talk will give an overview of the accelerators at both facilities and compare the characteristics and benefits of these two approaches to meet their user needs.

INTRODUCTION

Over the last decades, the production and study of Radioactive Ion Beams (RIB) arrived at various mature techniques allowing to explore the properties of isotopes far from the valley of stability. The progress are such that the construction of a new generation of RIB facilities has been recognized by the international scientific community as a major path for the development of fundamental nuclear physics and astrophysics, as well as for applications of nuclear science. Then, beside the existing facilities, various ones are presently under construction demonstrating the increasing interest in nuclear research.

The new facilities have the objectives to provide new tools to overcome the main difficulties observed for the production of isotopes farther and farther from the stable ratio of proton to neutron; difficulties are mainly related to very low production cross sections, very short life times and the huge amount of unwanted stable or radioactive isotopes produced at the same time.

Among the facilities under construction [1] FAIR and SPIRAL2 have been recognized of prime importance by NuPECC (Nuclear Physics European Collaboration Committee) and recommended for construction by ESFRI (European Strategy Forum on Research Infrastructures). FAIR at GSI [2,3] (Darmstadt, Germany) and SPIRAL2 at the GANIL [4,5,6] (Caen, France) will both contribute in different ways to the progress in nuclear physics. The other European and international project do not demerit and should be look at in other documents.

FAIR is the largest basic research project on the ESFRI roadmap. Its scientific program includes physics of hadrons and quarks in compressed nuclear matter (CBM experiments); atomic and plasma physics; applied sciences in the bio, medical, and materials sciences (APPA); hadron structure and spectroscopy; strange and charm physics; hypernuclear physics with antiproton beams (PANDA) and the structure of nuclei; physics of nuclear reactions and nuclear astrophysics with RIBs (Nuclear Structure, Astrophysics and Reactions : NuSTAR) which is of most interest here.

SPIRAL2 is one of the major Radioactive Ion Beam (RIB) and stable-ion beam facilities for nuclear physics, astrophysics and interdisciplinary research in Europe. From the very beginning of the SPIRAL project in GANIL, the SPIRAL2 upgrade was envisaged to increase both the range and the mass of exotic nuclei produced by SPIRAL. The facility will extend the GANIL possibilities to heavier radioactive beams and/or much higher production rates [5]. The extracted exotic beams will be either used in a new low energy experimental area called DESIR or accelerated by the existing SPIRAL1 cyclotron CIME. The S^3 (Super Spectrometer Separator) exotic production will be also analyzed in the DESIR experimental hall.

CHALLENGES FOR RIB PRODUCTION

As already said, the challenges come from the low production cross section and short life time of the desired isotopes. A higher production rate is then generally associated to a higher intensity of the primary beam to increase the number of reaction products. An efficient extraction and/or separation of the desired isotope from a huge number of parasitic isotopes and the management of the high level of radioactivity produced are then the main challenges of the new RIB production facilities.

The production of radioactive ions through fragmentation, spallation and fission methods gives access to most part of the chart. The production rate depends of the target materials and geometries, the type of primary particles and kinetic energy. The production rate is independent of either accelerated light ions interacting with a thick target of heavy material (the ISOL method) or from heavy ions beam accelerated toward a light and thin target (in-flight separation of projectile fragments). Figure 1 illustrates the two methods.

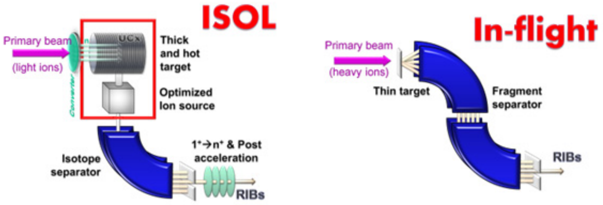

Figure 1: ISOL and In-flight RIB production methods.

In the case of ISOL, the beam energy varies within the thick target and so does the efficiency of the production, making difficult to establish a relation between the cross sections and the observed production rates. On the opposite, the in-flight case provides direct relation between the two, therefore leading to a valuable knowledge for the optimization of ISOL methods. Both solutions are complementary providing very different excitation energy of the resulting nuclei, therefore allowing the production of different fission fragments. In both cases the total number of fissions per second can be estimated and is a key parameter for the design of the new facilities. The optimization is done considering the primary beam intensities, the safety aspects and the beam power sustainable by the production target. The FAIR project uses the in-flight technique while the SPIRAL2/Phase 2 will use the ISOL technique and the fusion/evaporation in-flight technique with S^3 in SPIRAL2/Phase 1.

The second ISOL facility challenge comes with the extraction and separation of the isotopes of interest. At first the reaction products must go out of the thick target via diffusion and effusion. This step which depends on the target material properties, temperature and geometries can already be selective since the diffusion/effusion time makes difficult the extraction of extremely short lived elements. The ISOL method integrates an ion-source optimized for each RIB to produce and the secondary beams are transported through electro-magnetic separators to select the wanted isotope. A beam cooling at low energy (RFQ-cooler) can be used to improve this selection. Due to the low energies (≈60 keV), a post accelerator is needed if the rare isotope beam is used to produce secondary reactions. In GANIL SPIRAL2/Phase 2 it will be done through the existing CIME cyclotron.

In the in-flight technique, the primary beam is not stopped in the thin target. The projectile fragments are all created with almost the same vector momentum as the primary beam and are separated in sophisticated electro-magnetic separators (post acceleration is not mandatory). This is the role of the S-FRS for the FAIR project. Low energy RIBs are accessible through dedicated energy degraders and then cooled in storage rings. The high energy of the particles explains the size of the separators.

FAIR APPROACH

FAIR, officially launched on November 2007, will provide worldwide unique accelerator and experimental facilities allowing a large variety of fore-front research in physics and applied science. The existing GSI infrastructure (UNILAC, SIS18) will be used as driver injector. FAIR will deliver high intensity and high quality antiproton, stable and radioactive ion beams. Its sophisticated accelerator system will be able to deliver parallel beams to the various equipments of the different experimental collaborations (APPA, NuSTAR, CBM, PANDA).

A start configuration (figure 2) has been approved accounting for recent cost estimates and the funding commitments. For this purpose the start version is structured in relatively independent modules:

- Module 0: Double ring heavy-ion synchrotron SIS100 required for all science programs.
- Module 1: CBM/HADES cave, experimental hall for APPA and detector calibrations
- Module 2: Super-FRS for NuSTAR
- Module 3: Antiproton facility for PANDA, providing further options also for the NuSTAR ring physics

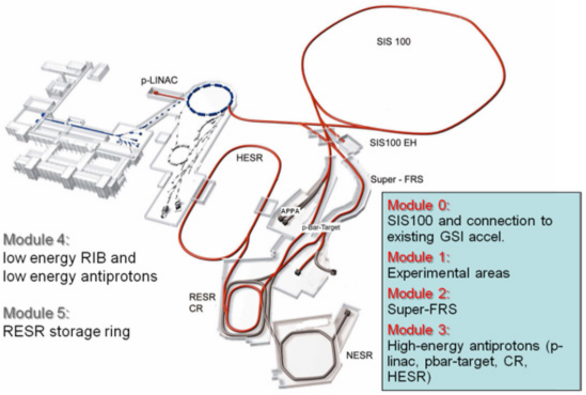

Figure 2: FAIR modules 0 to 3 (start version, in red).

Two other modules will later strengthen the long-term potential and scientific viability of FAIR (NESR ring, second target for NuSTAR, RESR storage ring). They will provide active phase space cooling in the transverse and longitudinal planes, providing high quality beams.

A major upgrade of the existing GSI facility is also required and partly completed [7].

FAIR Accelerators

The updated SIS18 will deliver its beams to the SIS100 via a fast extraction ('bunch to bucket' transfer). The core of the FAIR accelerator is the new fast ramping (4 T/s), superconducting heavy ion synchrotron SIS100 [8] (1100 m circumference), with $^{238}U^{28+}$ as reference ion and intensities of up to 5×10^{11} ions/s. The final energy will be chosen for optimal radioactive ions or antiprotons production (p up to 30 GeV, U up to 1.5 GeV/u). Eddy current heating is a real challenge for the superconducting magnets and the according vacuum chambers will have wall thicknesses of only 0.3 mm.

The ground foundation is finished and all the major SIS100 components having long production times are ordered. The SIS100 and HEBT equipments are developed as in-kind contributions by various FAIR member states: Germany, Russia, Poland, India, Slovenia. The detailed status of the FAIR project is presented in this conference [9].

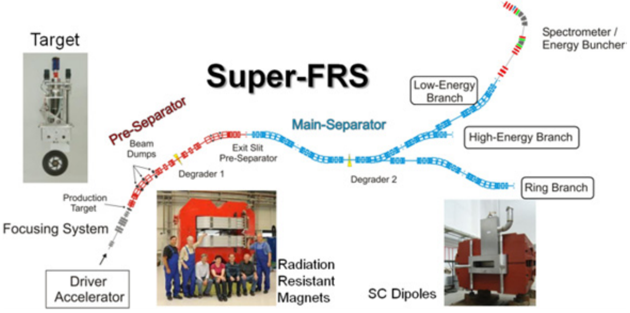

Figure 3 : FAIR Super-FRS with its three exit branches.

FAIR S-FRS

A key element of FAIR will be its main separator: the

Super FRS where isotopes of all elements up to uranium will be produced and spatially separated. A 10^4 gain is expected on intensities with respect to the radioactive beams produced so far. The operating principle of the Super-FRS is based on a combination of magnetic field ($B\rho_{max}$=20 T.m) and degraders specially shaped for each element to produce (figure 3). Only 10% of the driver beam will interact with the rotating wheel. The RIBs will be used at high energy in a dedicated hall or will be degraded to very low energies or, in the future, injected and cooled in the CR-RESR-NESR storage ring complex.

SPIRAL2 APPROACH

The intense primary stable beams (deuterons, protons, light and heavy ions) will be accelerated by a CW superconducting linac driver. They will be used at various energies for nuclear physics as well as neutron-based research and multi-disciplinary research experiments in new dedicated areas.

The project already described in many documents (eg. [6]) will be built in two phases to compromise with the available funding. The first phase (green parts of fig. 4) includes the linac building, the linac experimental halls (AEL) and the conventional facilities. The AEL include the Neutrons For Science (NFS) hall and the Super Separator Spectrometer (S^3) hall (in-flight techniques). NFS will provide efficient in-flight measurement equipments and irradiation stations for cross-section measurements and material studies using d, p and light beams [10]. S^3 is designed for fundamental research in nuclear and atomic physics at the Coulomb-barrier energy regime with rates above 10^{13} ions/s. A recent evolution of the project includes also the DESIR low energy RIB hall.

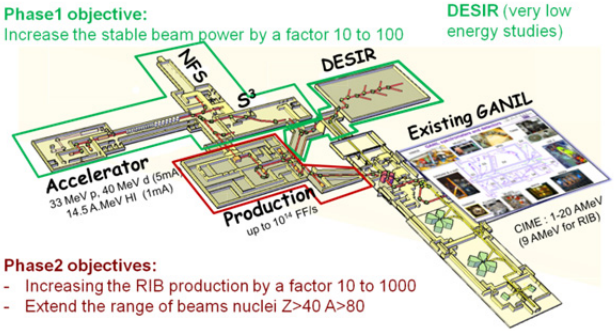

Figure 4 : Existing GANIL and SPIRAL2 extension.

Phase two (red part of figure 4) includes the ISOL RIBs production equipments and infrastructure, starting from the HEBT to the production building and the connections with the existing GANIL facility. This ISOL method requires the highest possible power of CW stable beams (200 kW) for the production of secondary beams with maximum efficiency.

SPIRAL2 DRIVER ACCELERATOR

The accelerator is presently being installed in the building with the objective to start the first beam commissioning by the end of this year.

Beams Requirements

The layout of the SPIRAL2 driver [11] takes into account the wide variety of beams to satisfy the physics demands (figure 6). It is a high power CW superconducting LINAC delivering up to 5 mA proton and deuteron beams or 1 mA ion beams with q*/A>1/3* (table 1). Our biggest challenge is to manage this large variety of beams, a quite high beam power (200 kW, CW) and the safety issues with the deuteron beam.

Table 1 : Beam Specifications

Particles	H^+	$^3He^{2+}$	D^+	ions	Ions option
Q/A	1	3/2	1/2	1/3	1/6
Max. I (mA)	5	5	5	1	1
Min. energy (MeV/A)	0.75	0.75	0.75	0.75	0.75
Max energy (MeV/A)	33	24	20	15	9
Max. beam power (kW)	165	180	200	45	54

Injector

The injector is composed of two specialized ECR ion sources, a warm RFQ connected to the superconducting LINAC. Both ECR sources and their LEBT have been successfully tested in the past years at LPSC Grenoble and IRFU Saclay. Numerous important points like source efficiencies, diagnostics, control systems, power supplies... have been developed and qualified at an early stage. Beam quality was measured up to the RFQ matching point [11].

Most of the sources and LEBT are now installed in the SPIRAL2 building at GANIL (figure 5).

Figure 5: source and LEBT @ GANIL/SPIRAL2

Developed by the CEA/IRFU team, the RFQ [12] is a 4-vanes, 5-meter long normal conducting cavity. It ensures an efficient adiabatic bunching at 88 Mhz and accelerates all the ion species up to 0.73 MeV/u ($\beta \approx 0.04$). This RFQ specially designed to provide a transmission better than 99% will be installed very soon in the tunnel.

The long transfer line between the RFQ and the linac allow the insertion of a future Q/A=1/6 injector.

Linac

The LINAC is based on superconducting independently-phased resonators. In order to satisfy the broad requirements on particle species, intensities and energies, the linac is composed of two families of short cryomodules developed by the CEA/IRFU and

Figure 6 : SPIRAL2 accelerator scheme.

IN2P3/IPNO teams [13]. The first family is composed of 12 β_0=0.07 quarter-wave resonators (A-type QWR with 1 cavity/cryomodule and the second family of 16 β_0=0.12 B-type QWR with 2 cavities/cryomodule (figure 7). The maximum reference gradient in operation is $E_{acc}=V_{acc}/\beta\lambda$=6.5MV/m. The whole set of cavities, eight A-type of cryomodules and four B-type have been validated (see table 2). The main difficulties faced during the first tests were related to pollution problems explained in detail in [13].

Figure 7: The SPIRAL2 superconducting cryomodules (left: β_0=0.07 – 1 cav, right: β_0=0.12 - 2cav).

The transverse focusing is ensured by means of warm quadrupole doublets located between each cryomodule. These warm sections also include beam diagnostic boxes and vacuum pumps. They are presently under assembly in clean room.

Table 2 : Cryomodules Performances

	Unit	Specs	CMA4	CMA6	CMA7	CMA2	CMA3	CMA5	CMA9	CMA8
Max. acc. Gradient	MV/m	>6.5	8.85	8.34	9	8.6	7.95	9.1	8.44	9
Rx activity @6.5MV/m	µSv/h		560	91	14.3	730	494	1.5	677	32
Total losses @4K, 6.5MV/m	W	<20.5	20.8	11.4	11.8	15.56	17.9	11.3	12.6	10.38
Static losses @4K	W	<8.5W	6.5	3.98	4.1	3.11	4.34	3.6	4.47	3.12
Pressure sensitivity	Hz/mbar	<5	-1.58	-1.32	-1.45	-1.31	-1.08	-1.22	-1.24	-1.66
Cavity alignment	mm	◎ 1.3	0.52	0.4	0.48	1.46	0.4			
	Unit	**Specs**	**CMB1**		**CMB2**		**CMB3**		**CMB4**	
Max. acc. Gradient	MV/m	> 6.5	>8.0	>8.0	>8.0	>8.0	>8.0	>8.0	>8.0	>8.0
Rx activity @6.5MV/m	µSv/h		22000	0	160	0	0	0	70	0
Total losses @4K, 6.5MV/m	W	< 36.0	29		29		27		31.5	
Static losses @4k	W	<12.5	17		19		19		19	
Pressure sensitivity	Hz/mbar	< 8.0	-5.3	-4.95	-5.4	-5.8	-5.2	-4.5	-4.9	-5.2
Beam vacuum	mbar	< 5.0e-7	5E-08		3E-08		4E-08		6E-08	
Cavity alignment	mm	◎ 1.2	0.16	0.34	0.62	0.42	0.24	0.38	0.14	0.36

The cryomodules will start to be installed in the linac tunnel next month and this process will last until the delivery of the final cryomodule in early 2015.

The 5, 10 and 20 kW solid-state amplifiers used to power the linac cavities [10] are being manufactured. The amplifier units will soon be delivered.

SPIRAL2 HEBT

The high energy beam transfer lines (HEBT [14]) are divided into two main parts:

- HEBT1with a straight beam line up to the beam dump needed for the commissioning, machine studies and beam tunings. The beam dump can handle the maximum beam power of 200 kW. Depending on nuclear safety licensing requirements, mainly related to material activation, the effective beam power will depend on ion species.

This line will also deliver deuteron beams to the NFS cave for neutron experiments and light or heavy ions beams to the S^3 cave.

- HEBT2 will transport light- and heavy- ion beams to the RIB production areas located in a separate building (SPIRAL2/Phase 2).

All dipoles and quadrupoles are constructed and measured. The 200 kW beam dump is expected by the end of the year. In order to limit possible activation induced by deuteron/proton, the choice was made to build the long vacuum pipes in aluminum (under construction).

The building reception is expected in August, the first source beams will be produced in September this year, the first RFQ beam in February next year and the first linac beam by September 2015 (The final safety authority authorization is expected by mid 2015, partial authorization is needed for the RFQ beam commissioning).

SPIRAL2 Super Spectrometer Separator

S^3 takes the opportunity of the unprecedented intensities from the SPIRAL2 driver accelerator for nuclear physics research in the Coulomb-barrier energy regime, with rates above 10^{13} ions/s.

With the S^3 project [15], it will be possible to produce, select and study these nuclei using complementary detection methods, like spectroscopy of their decay or by ground state property measurements. This program also has strong synergies with the Atomic Physics community, specifically in interaction studies in the unknown regime of fast ion-slow ion collisions. The project “Fast Ion Slow Ion Collisions” (FISIC) will be a tool unique in the world to investigate ion-ion collisions in the intermediate velocity regime.

The S^3 basic design is composed of a two-stage separator (figure 8). A first momentum achromat will filter the primary beam by at least 1:1000 and will be followed by a mass separator to do further beam suppressions (physical energy and mass channel selection) by a mass separator. The backbone of this device is based on superconducting multipole triplets providing large acceptance while keeping an excellent resolution through correction of higher order aberrations. It is also well optimized for direct and symmetric kinematics fusion-evaporation reactions.

The room temperature dipoles were already received and will be measured soon. The open quadrupole are under final definition and the superconducting triplets are well advanced. A first SC singlet has been cold tested and a full triplet will be tested at Argonne in the fall.

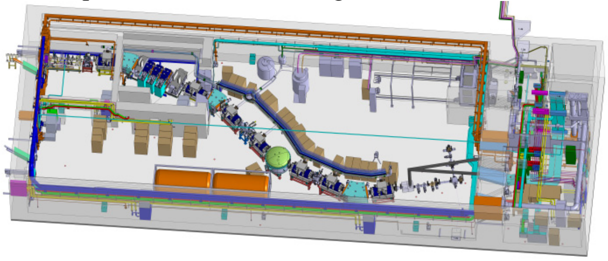

Figure 8: S^3 experimental hall.

SPIRAL2 RADIOACTIVE ION BEAM

The SPIRAL2/Phase 2 will add the isotope separator on line (ISOL) method to the S^3 low-energy in-flight techniques to produce a radioactive ion beams.

Target Ion-source (TIS) Production System

The primary beams (d, p or heavy ions) will impinge on different target assemblies to produce the RIBs. Mostly, the primary 200 kW deuteron beam will interact with a carbon wheel converter, producing the fast neutrons which will induce fissions on a uranium carbide targets. A rate of up to 10^{14} fissions/s is expected. The RIB intensities in the mass range from A=60 to A=140 will be of the order of 10^6 to 10^{11} part./s, one or two orders of magnitude above existing facilities in the world [5]. The UC_x targets are heated above 2000°C to decrease the diffusion time of the products that will then effuse toward an ion source for transformation to 1^+ ions. The detailed study of the TIS production module is completed.

The beams will be available at energies ranging from a few keV/u for the DESIR facility up to 20MeV/u (9MeV/u for fission fragments) for the existing GANIL experimental areas.

SUMMARY

FAIR and SPIRAL2 are major RIBs projects in Europe that will permit a broad range of researches in nuclear physics, atomic physics and astrophysics. They are complementary since they are using different production methods. Also, the slow production rate and the long time needed for a precise experiment are promoting the existence of several research facility to cover the physics to be done.

The FAIR RIB production is based on in-flight techniques with high-energy pulsed heavy-ion primary beams leading to high energy pulsed secondary beams. The size of the machines (synchrotrons) and spectrometers is then large and the low energy experiments require energy degraders and additional rings to cool the beams. They are an expensive part of the project. With additional capabilities such as its "antiproton factory" FAIR will be a unique research facility allowing parallel experiments. First beam is expected in 2019 for SIS100 and 2020 for Super-FRS.

SPIRAL2/Phase 2 is mainly based on the ISOL technique with a quite low energy but high-power CW deuteron primary beam used to produce an intense neutron flux sent to massive pyrophoric UCx targets. The main challenge is to manage the safety issues induced by the very high activity of these targets and the need to install them in inerted hot cells. The total size of the SPIRAL2 facility is nevertheless much smaller than the FAIR facility one and the construction and operation budgets are significantly lower (roughly one order of magnitude compensated by the fact that FAIR is "multi-users").

The SPIRAL2 accelerator is now under final installation, the beam commissioning should start during the last quarter of 2014.

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