European RIB facilities - status and future

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Abstract

The European landscape of Radioactive Ion Beam facilities is currently in a transformation phase. Several existing installations are undergoing extensive upgrade programmes while construction of next-generation facilities are underway. This encompasses facilities based on both the in-flight and the ISOL techniques, though such traditional scopes are being modified by developments concerning beam handling and -preparation. The facility developments are a consequence of the strong scientific potential demonstrated by experiments with radioactive ion beams in the last decades. This potential was recently highlighted in the European roadmap for Nuclear Physics, coordinated by the Nuclear Physics European Collaboration Committee (NuPECC).

A brief account of the main current facilities is made, including key instrumentation and future plans. The two major RIB facilities that are under construction in Europe, namely the NUSTAR part of FAIR (Facility for Antiproton and Ion Research) and SPIRAL-2 at GANIL, are described. An outlook and roadmap for European ISOL-research according to the NuPECC long range plan, ultimately leading to the future EURISOL facility, is presented.

Keywords:

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1. Introduction

Modern nuclear research relies heavily on the availability of radioactive isotopes, as ion beams as well as samples, as a vehicle for both fundamental studies as for many applications in various fields of science. The science quests using radioactive ion beams, shared by facilities worldwide, are extremely wide and a summary is beyond the scope of the current paper. A recent overview of contemporary scientific issues has been made in [1], as well containing a comprehensive overview of the world-wide landscape of RIB facilities [2].

2. The European Roadmap

NuPECC (Nuclear Physics European Collaboration Committee) is an expert committee under the European Science Foundation (ESF) that is regularly preparing a long range plan for Nuclear Physics in Europe through a bottom-up process. The latest issue was published in 2010[3] and includes a comprehensive plan for the development of radioactive beam facilities over the next decade and beyond. The main recommendations concerning RIBs are as follows:

- The European organisation ESFRI (European Strategy Forum on Research Infrastructures) has made a list of major large scientific facilities recommended to be built in Europe where the RIB installations FAIR and SPIRAL2 are included [4]. NUPECC recommends to complete, in a timely fashion, the construction of the two Nuclear Physics facilities on this list: FAIR at the GSI site in Darmstadt, including the NUSTAR radioactive beam facility to produce nuclei far from stability and investigate their structure, and SPIRAL2 at GANIL in Caen, including high intensity stable beams at the S3 spectrometer, and ISOL radioactive beams of very neutron-rich fission products and studied, for example, at the DESIR facility.
- Strongly support the construction of HIE-ISOLDE at CERN and SPES at LNL-INFN Legnaro which combined with SPIRAL2 will be the stepping stones towards EURISOL.
- In order to prepare the long term future strong support should be given to the inclusion of the high intensity ISOL facility EURISOL in future editions of the ESFRI list based on the successful EURISOL Design Study and also to the technical design study for intense radioactive ion beams at ISOL@MYRRHA.

The time-line of this roadmap (status as of 2010, updated time scales are given in the following) is summarised in fig. 1 and the future facilities mentioned above will be outlined below. A traditional subdivision in in-flight and ISOL-facilities will be made, although recent developments in beam handling and -preparation done in devices like coolers, gas cells, storage rings etc. tends to bridge this classification scheme.

3. In-flight infrastructures

3.1. NUSTAR at FAIR/in-flight RIBs at GSI

FAIR (Facility for Antiproton and Ion Research), located at the existing GSI facility in Darmstadt, Germany is the worldwide largest project within Nuclear Physics of the decade [5]. The envisaged programme of FAIR is subdivided into four scientific pillars and includes studies of hadrons and quarks in

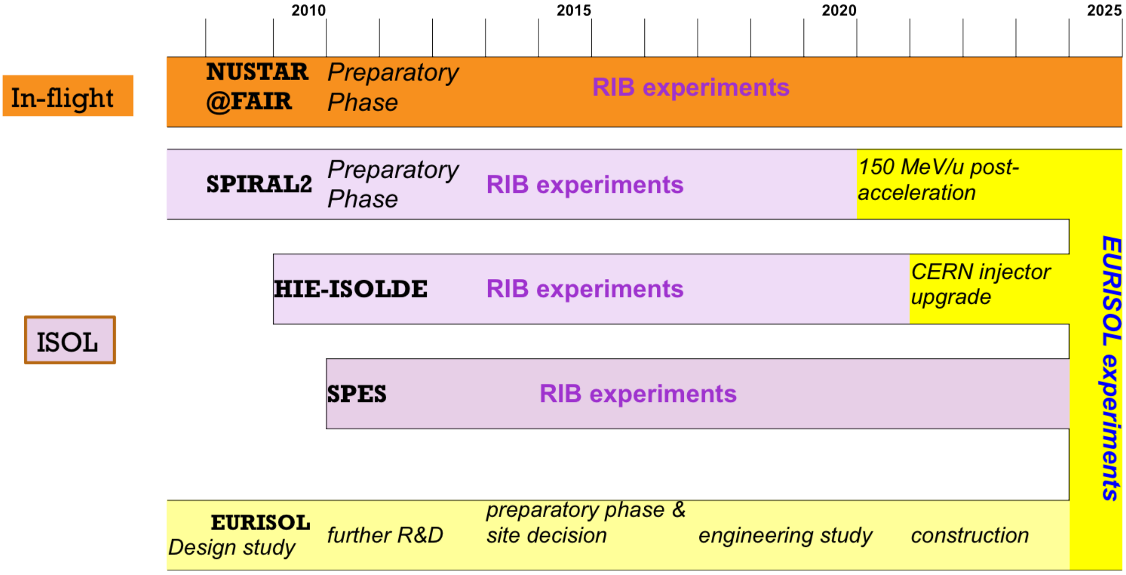

Figure 1: The NuPECC roadmap for RIB facilities [3]. Time scale refers to status as of 2010.

compressed nuclear matter (CBM); atomic and plasma physics, and 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 of most interest here the structure of nuclei, physics of nuclear reactions, and nuclear astrophysics with RIBs (NUSTAR).

The planned installations for production and utilisation of energetic RIBs by in-flight separation builds upon more than two decades of experience from the programme performed at SIS18+FRS. The SIS synchrotron at GSI can provide energies of up to 2 GeV/u, albeit with intensities much lower than at cyclotron-based facilities. This drawback is partially compensated during the production stage by the stronger forward focusing of the reaction products and the high efficiency of the FRS fragment separator. Furthermore, the high energies permits using thick secondary reaction targets in the experiments and the kinematical focussing aids in reaching detection coverage approaching 4π in the centre-of-mass system. In addition, the possibility of fast extraction of the primary beams can be combined with storage rings in a straightforward manner.

All scientific pillars at FAIR rely on the new synchrotron SIS100 which will deliver primary beams of 10^{12} $^{238}U^{28+}$ at 1.5-2 GeV/u, corresponding to an increase in intensity of 2 to 3 orders of magnitude with respect to the current GSI synchrotron SIS18. The heart of NUSTAR will be the Super-FRS fragment separator, [6, 7], with vastly improved acceptance through the use of large-aperture superconducting magnets. The device will deliver a broad range of radioactive beams with up to a factor 10^4 improvement in intensity over current values, in particular for the “hot” fragments produced in projectile fission. The beams are then directed to three branches, each with its characteristic range of beam energy and properties. The branch connected to the high-energy cave will take the beams directly from the separator, whereas the ions are degraded to intermediate energies or stopped in the low-energy cave following the corresponding branch. The ring branch permits injection, through fast extraction of the primary beam from the SIS100 synchrotron, and subsequent cooling in the CR (Collector Ring) Following the CR, the full FAIR-NUSTAR facility concept envisages the NESR storage ring for experiments with stored and cooled radioactive beams where light-ion reactions in inverse kinematics using an internal gas-jet target can be done in the EXL set-up and electron-ion scattering in the ELISe set-up[8]. The latter will be a unique installation in order to measure e.g. charge distributions for exotic nuclei. Mass measurements in storage rings is an established technique [9] and will be pursued both in the CR and the NESR within the ILIMA project.

Several experimental devices are being developed and constructed, and in some cases, precursor programmes running partial detector set-ups are already operational. In the high energy area the R^3B detector will comprise a large gap dipole along with highly efficient charged particle, neutron and gamma-ray arrays for complete kinematic coverage. The low energy branch of NUSTAR will include installations dedicated to High Resolution Spectroscopy (HISPEC) using the AGATA gamma-ray array[10], decay studies (DESPEC), and a gas-filled stopping cell [11] in order to generate ISOL-type beam, permitting mass measurements as well as radii and moment measurements through laser spectroscopy (MATS and LASPEC [12]). A schematic view of the FAIR facility and the NUSTAR area, devoted to exotic beam studies, is displayed on fig. 2.

The FAIR facility is subdivided into six modules out of which five are related to the NUSTAR program:

- 0: Heavy-Ion Synchrotron SIS100.

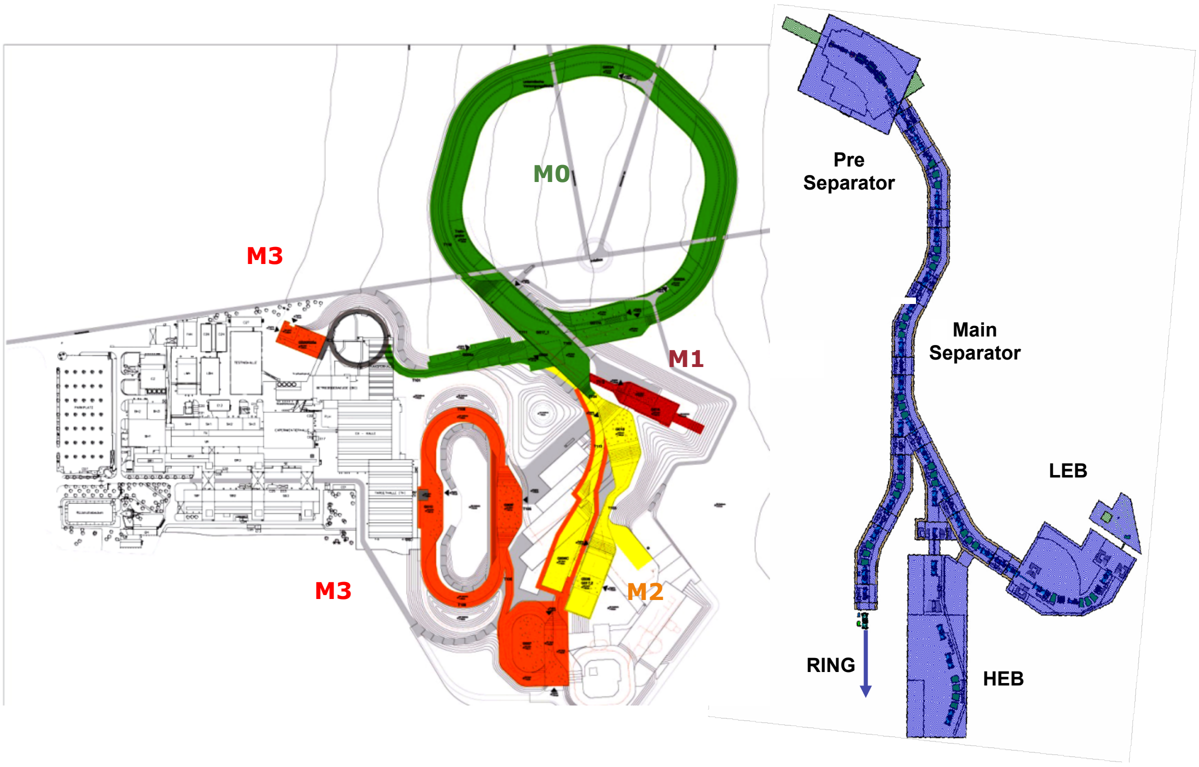

Figure 2: The FAIR facility according to the Modularized Start Version[13] with modules 0-3 indicated. Right inset depicts the Super-FRS and its three branches, constituting the NUSTAR part of the facility.

- 2: Super-FRS for NUSTAR.
- 3: Antiproton facility for PANDA, providing further options also for NUSTAR ring physics.
- 4: Second cave for NUSTAR, NESR storage ring for NUSTAR and APPA, building for antimatter programme FLAIR.
- 5: RESR storage ring for higher beam intensity for PANDA and parallel operation with NUSTAR.

Modules 0, 2 and 3 are part of the so-called modularized start version (MSV) while modules 4 and 5, which include the low energy cave of NUSTAR and the NESR storage ring would be constructed at a later stage [13]. Actions are underway to find alternative solutions permitting parts of the associated scientific programme to be pursued earlier. One example is the implementation of the low-energy storage ring CRYRING at the existing ESR storage ring that will open new possibilities for atomic and nuclear astrophysics [14]. Furthermore, in a midterm perspective there are options for feeding RIBs from the Super-FRS and antiprotons to the ESR/CRYRING and possibly modify the ESR to house further experimental installations.

3.2. *Selected further in-flight facilities*

The GANIL laboratory in Caen, France has two separated sector room temperature cyclotrons which produce heavy ions from C to Ar up to 100 MeV/u and can accelerate masses up to U at 25 MeV/u, used as driver beams for in-flight RIB production. The primary intensities can reach several μA but the secondary beam intensities are limited by the moderate forward focussing of the reaction products. A focussing superconducting solenoid named SISSI[15] was thus placed after the production target and led to an increase of the RIB intensities which could be transported to all GANIL experimental areas of up to a factor 100. Unfortunately SISSI is no longer operational since 2008 which leaves the LISE-3 separator for beam production and limits the range of experiments possible with in-flight beams.

Th JINR laboratory in Dubna operates the ACCULINA separator, a device with maximum rigidity of 3.6 Tm, connected to the U-400M cyclotron. This can be used for production of the lightest exotic nuclei at a few tens of MeV per nucleon, e.g. ^{8}He at 22 MeV/u. Currently, the ACCULINA-II separator is being constructed, with foreseen commissioning in 2014[16]. The device will have an angular acceptance of 5.8 msr and a long time-of-flight stage for high energy resolution and be operating in the low energy domain of 6-60 MeV/u and with Z_{RIB} = 1-36 [17]. Both tritium beams and secondary reaction targets are available, and the upgrade options include an RF kicker for better selectivity of proton-rich beams.

4. ISOL facilities

The long-range perspective for ISOL-research in Europe is to build the “ultimate” ISOL facility, EURISOL outlined in section 4.5. However, as can be seen in Fig. 1, the path to EURISOL goes via three existing facilities at GANIL, CERN and LNL and their corresponding upgrade programmes, namely SPIRAL-2, HIE-ISOLDE and SPES. These are briefly described in the following.

4.1. SPIRAL and SPIRAL-2 at GANIL

SPIRAL uses of the GANIL coupled cyclotrons (see 3.2) as driver, where the incident heavy-ion beam is undergoing fragmentation while being stopped in a thick graphite target, producing radioactive species. The beams are ionised in a permanent magnet ECR source. This scheme has the advantage of simplicity but limits the variety of beams available which is currently restricted to noble gases and to oxygen and fluorine. A development programme (under the name GANISOL) is underway to increase the number of elements available [18], e.g. through inclusion of FEBIAD sources for metallic beams. An ECR 1^+ to N^+ scheme is as well currently under development. The new ionisation and charge-state booster schemes are expected to be operational by the end of 2014. The CIME cyclotron is employed as post-accelerator, utilising its inherent capability as a high-resolution mass separator. The final energy, up to 25 MeV/u for light beams, is the highest of existing ISOL facilities.

The driver of the SPIRAL2 facility is a high power, CW, superconducting LINAC, delivering up to 5 mA of deuterons at 40 MeV, corresponding to 200 kW, directed on a carbon converter + uranium target. The main production method of the radioactive beams is through fission induced in the uranium by the fast neutron flux from the converter, up to 10^{14} reactions/s. The expected radioactive ion beams intensities in the mass range between A=60 and A=140 will reach up to 10^{10} particles per second for some species. These unstable beams will be available at energies ranging between a few keV/u at the DESIR facility up to 20 MeV/u (up to 9 MeV/u for fission fragments) following post-acceleration in the CIME cyclotron. The beams will be transported to the existing GANIL experimental areas where a corresponding development of the available instrumentation will take place by a large number of next generation detectors such as AGATA, PARIS and EXOGAM2 γ arrays, GASPARD, HELIOS and FAZIA charged particle detectors/arrays, NEDA neutron detector or the ACTAR active target. The DESIR low-energy RIB facility will house a large range of state-of-the-art experiments to study ground-state and decay properties.

The SPIRAL2 LINAC will as well accelerate protons up to 33 MeV and heavy ions up to 14.5 MeV/u with high intensity, up to 1 mA. This will be used to enlarge the range of exotic nuclei produced by the ISOL method towards neutron-deficient nuclei or very heavy nuclei produced by fusion evaporation, or towards light neutron-rich nuclei via transfer reactions. The heavy-ion beams will also be used to produce in-flight a large range of neutron deficient and very heavy exotic nuclei with the Super Separator Spectrometer (S3). A diagram of the facility is presented in fig. 3.

The construction of SPIRAL2[19, 20] is split into several phases:

i Linear accelerator with S3 experimental hall: commissioning expected in 2014.
ii Super Separator Spectrometer (S3): commissioning expected in 2015.
iii Radioactive Ion Beam production hall and DESIR low-energy RIB facility: commissioning expected in 2017.

All essential sub-systems of LINAC were already delivered and successfully tested. The civil construction of the facility began in the second half of 2010, and installation of equipment will proceed through 2013.

4.2. HIE-ISOLDE at CERN

The ISOLDE facility[21, 22], located at CERN, is the oldest facility capable of delivering a large range of radioactive beams located at CERN. The Proton Synchrotron Booster delivers a pulsed proton beam of 1.4 GeV energy with an average current that can reach up to 2 μA. A large range of production targets, including actinide carbide and oxide targets, can be used to produce unstable nuclei through fission, spallation, and fragmentation reactions. Converter assemblies, yielding spallation neutrons close to the production target, can as well be used to emphasise production of fission fragments relative to contaminants produced in other reactions. The such produced nuclei diffuse and effuse through a transfer line into the ion source; here, a large range of sources is employed to maximise efficiency and suppression of isobaric contamination, most notably through the Resonant Ionisation Laser Ion Source (RILIS) [23] where step-wise resonant excitation and subsequent ionisation of the wanted element is performed.

The REX-ISOLDE [24] post-accelerator was added to the facility more than a decade ago, meaning that the full range of nuclei available at ISOLDE can be accelerated up to 3 MeV/u, permitting low-energy reaction studies. The scientific programme has hitherto had emphasis on Coulomb excitation and transfer reaction experiments, the latter restricted to the lightest nuclei due to the limited beam energy. The REX-ISOLDE concept combines cooling and bunching in a Penning trap and subsequent charge breeding in an EBIS in order to permit a compact normal-conducting linear accelerator. The accelerator runs at 10% duty factor and can handle up to A/Q of 4.5, the final energy of 3 MeV/u can be reached for $A/Q < 3.5$ and 2.8 MeV/u for $A/Q < 4.5$.

In order to broaden the scientific opportunities far beyond the reach of the present facility, the HIE-ISOLDE (High Intensity & Energy ISOLDE) project [25, 26, 27] will provide major improvements in energy range, beam intensity and beam quality. A cornerstone of the project will be an increase of the final energy of the post-accelerated beams to 10 MeV/u throughout the periodic table. This will be achieved by gradually replacing the current REX LINAC modules by superconducting cavities in a staged fashion. The first stage, coinciding with the CERN “Long Shutdown 1”, will boost the energy to 5.5 MeV/u through additional “high-beta” cavities. Here, the Coulomb excitation cross sections are strongly increased and several transfer reaction channels will be opened. This physics programme is expected to start in early 2015. In the second stage, additional

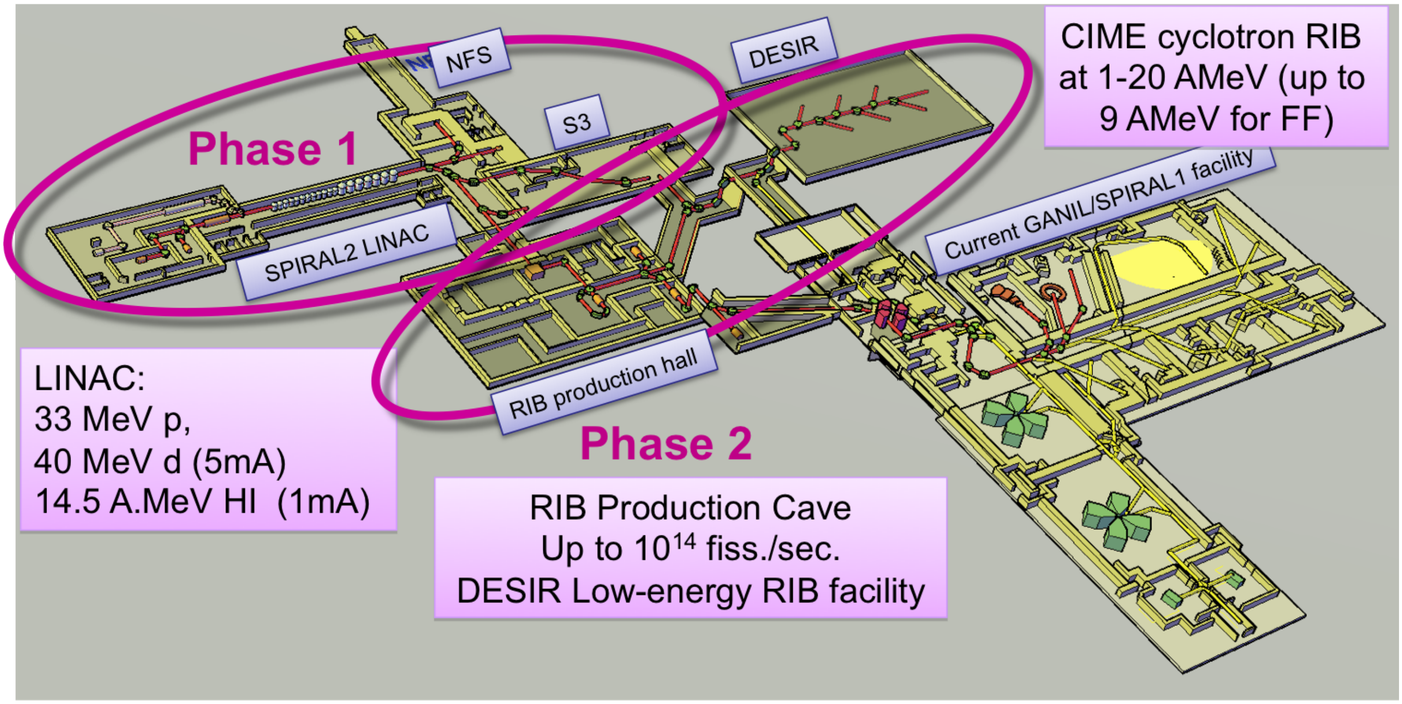

Figure 3: Schematic view of the SPIRAL2 project

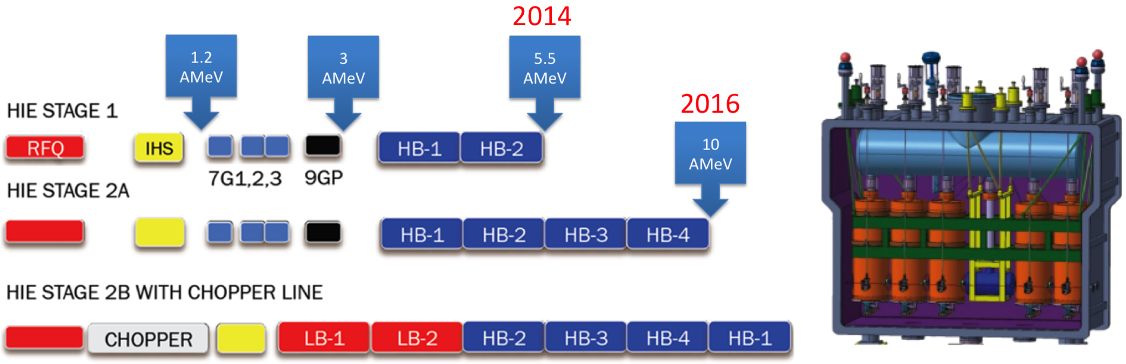

Figure 4: Staging and milestones of the HIE-ISOLDE Linac upgrades. Right inset depicts a “high-beta” cryomodule, denoted by HB in the schematic, where each module contains five superconducting cavities.

cryomodules will be added to bring the energy up to 10 MeV/u for all nuclides with A/Q = 4.5 and up to 14 MeV/u for A/Q = 3. This will offer ideal conditions for transfer reactions over the whole periodic table, particularly the heavy elements uniquely produced at ISOLDE. In the final stage, adding low-beta superconducting cavities, replacing all normal-conducting cavities, allows for CW operation and the delivery of beams with energies down to 0.5 MeV/u for astrophysics oriented measurements. Figure 4 shows the staging and the envisaged milestones of the project.

In addition, the new CERN injector LINAC 4, expected to replace the current LINAC2 in 2018, will provide a major boost of the proton intensity onto the ISOLDE target. In the framework of HIE-ISOLDE, the target areas and ion sources are also being respectively upgraded and optimised in order to make use of the more intense proton beams from LINAC4 and to improve the efficiency for ion extraction and charge breeding. This will enable up to an order of magnitude higher RIB intensity to be delivered for many nuclides. Improved beam quality will arise from several technological advances: the already implemented solid state lasers equipping the RILIS ion source and use of the recently commissioned RFQ cooler ISCOOL together with the construction of a new high resolution mass separator. The possibility of providing polarized beams is as well being investigated [28], and later it is planned to include the TSR storage ring [29].

4.3. SPES at Laboratori Nazionali di Legnaro, Italy

SPES(Selective Production of Exotic Species) is an ISOL facility under construction that is dedicated to the production of neutron-rich beams. The method chosen here is direct production through a proton driver, a commercial 70 MeV cyclotron that can deliver a total current of 750 μA. The proton beam will impinge on a ISOL target-ion source assembly, including UC_x targets, followed by a beam transport system with high resolution mass selection and the existing superconducting PIAVE-ALPI accelerator complex at LNL, which will be used as post-accelerator. The ground-breaking for the new building housing the cyclotron is planned for early 2013.

For production of fission fragments, a proton beam of 40 MeV and 200 μA will impinge on the uranium carbide target and give rise to 10^{13} fission/s. Multi-foil UC_x targets have been developed that can sustain the primary beam power of up to 10 kW [30]. The target-frontend assembly, developed in collaboration with CERN-ISOLDE, has been completed and will allow for a range of ion sources depending on the class of beams to be produced. To achieve better beam purity and adapt the beam properties to the requirements of the post-accelerator LINAC, further beam handling stages are planned. With a high-resolution mass separator that is preceded by an RFQ-cooler that reduces energy spread and transversal emittance, a mass resolution of 1/25000 is to be achieved. An ECR charge-state booster is being developed in collaboration with SPIRAL2.

The re-acceleration stage with the superconducting linac ALPI will produce high-quality beams with regard to intensity and energy spread. The final energy interval (5-15 MeV/u) is ideal for investigations of nuclear reactions between medium-heavy nuclei close to the Coulomb barrier. Figure 5 depicts the layout of the SPES project which also a part devoted to applications in conjunction with the possibility of using a second exit port at the cyclotron.

4.4. Selected further ISOL facilities

Front-line research within RIB physics is as well feasible at a smaller scale than the above mentioned installations. Several examples of national or even university-based laboratories exist, focussing on e.g. a certain production and/or beam extraction method. The ALTO installation at IPN Orsay[31, 32] concentrates on production of fission fragments in a UC_x target, using a 50 MeV electron accelerator as driver. A very productive university-based facility is JYFL in Jyväskylä, Finland where the IGISOL technique has been exploited most succesfully, using thin targets and extraction from a gas cell [33]. The facility has been receiving beams from the K130 heavy-ion cyclotron since early nineties where proton-induced fission has been complemented by heavy-ion induced reactions to explore neutron-deficient nuclei. The extracted ions are then transported to setups for measurements of ground-state properties by laser spectroscopy and a Penning trap, as well used for purification purposes in decay studies. The IGISOL facility has recently been moved and is being recommissioned [34] in order to as well take beams from the new, dedicated MCC30 proton cyclotron. This will increase the available amount of beam time considerably.

4.5. EURISOL

EURISOL is a facility concept that has evolved for more than a decade, aiming at building the ultimate ISOL installation given the technology existing or within development reach [35]. This has been concretised in a conceptual design study and subsequently in a Technical Design Study [36] that was undertaken within the European sixth framework programme. The EURISOL DS, which brought together 20 laboratories representing 14 European countries, provided a credible design for the facility. Prototypes of some essential components of EURISOL such as superconducting LINAC cavities and the mercury loop, to be used as a converter target, were constructed and tested.

The EURISOL is planned to use a large superconducting linear accelerator to accelerate H^- ions to energies of 1 GeV as the driver. Whereas CW operation is optimal for RIB production in order to reduce the thermal stress on the target, the option of using a pulsed beam at 50 Hz with a minimum pulse length of 1 ms has been kept open for possible sharing of the driver with other scientific communities. An intensity corresponding to beam power of up to 4 megawatts will be delivered to one target station, and through a newly developed magnetic beam splitting system some 100 kilowatts to three smaller target stations in parallel. The high-power target station is to be used for indirect production of radioisotopes, through a neutron spallation source where the neutrons are generated by high-energy protons impacting on a high Z material. The radioisotopes are

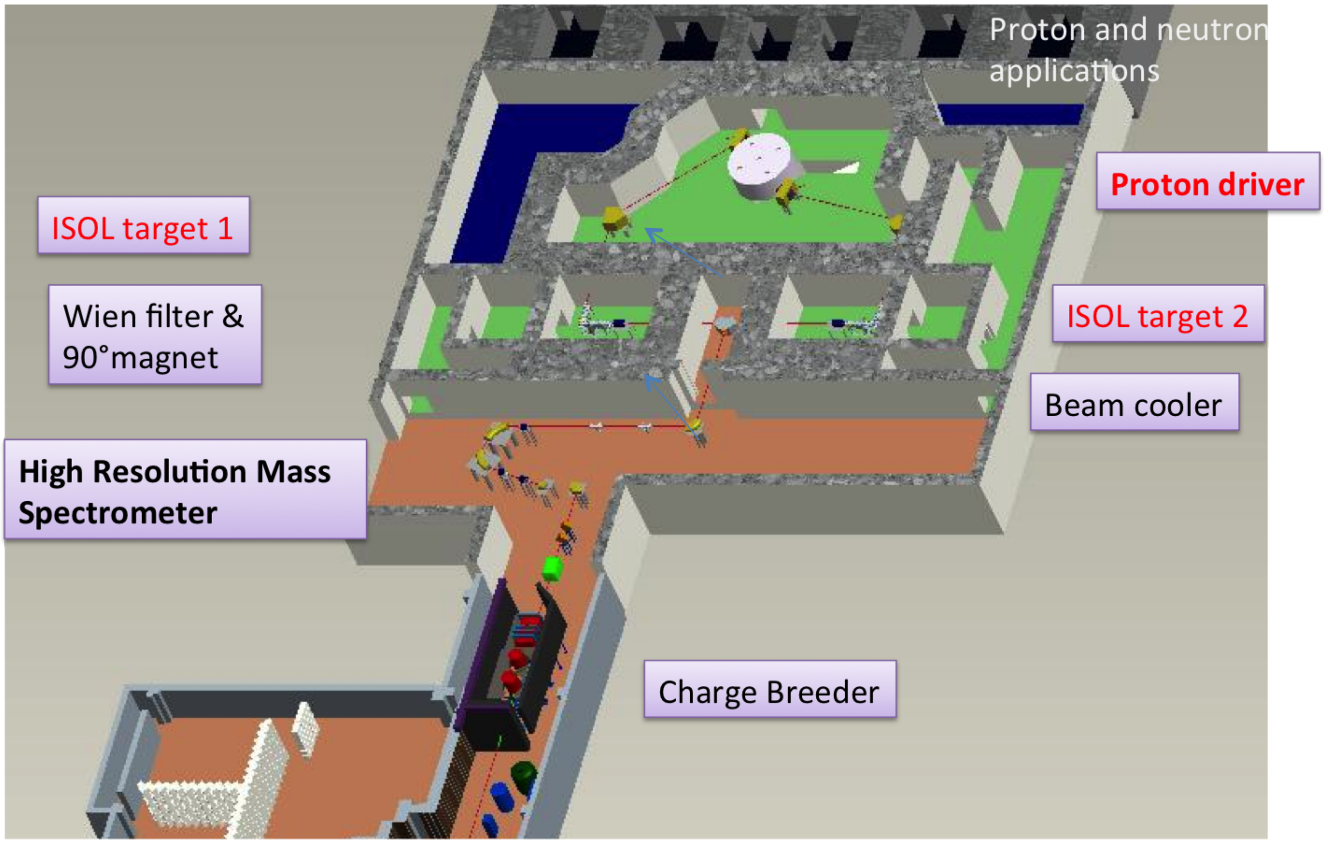

Figure 5: Layout of the low-energy part of the SPES project (adapted from [30])

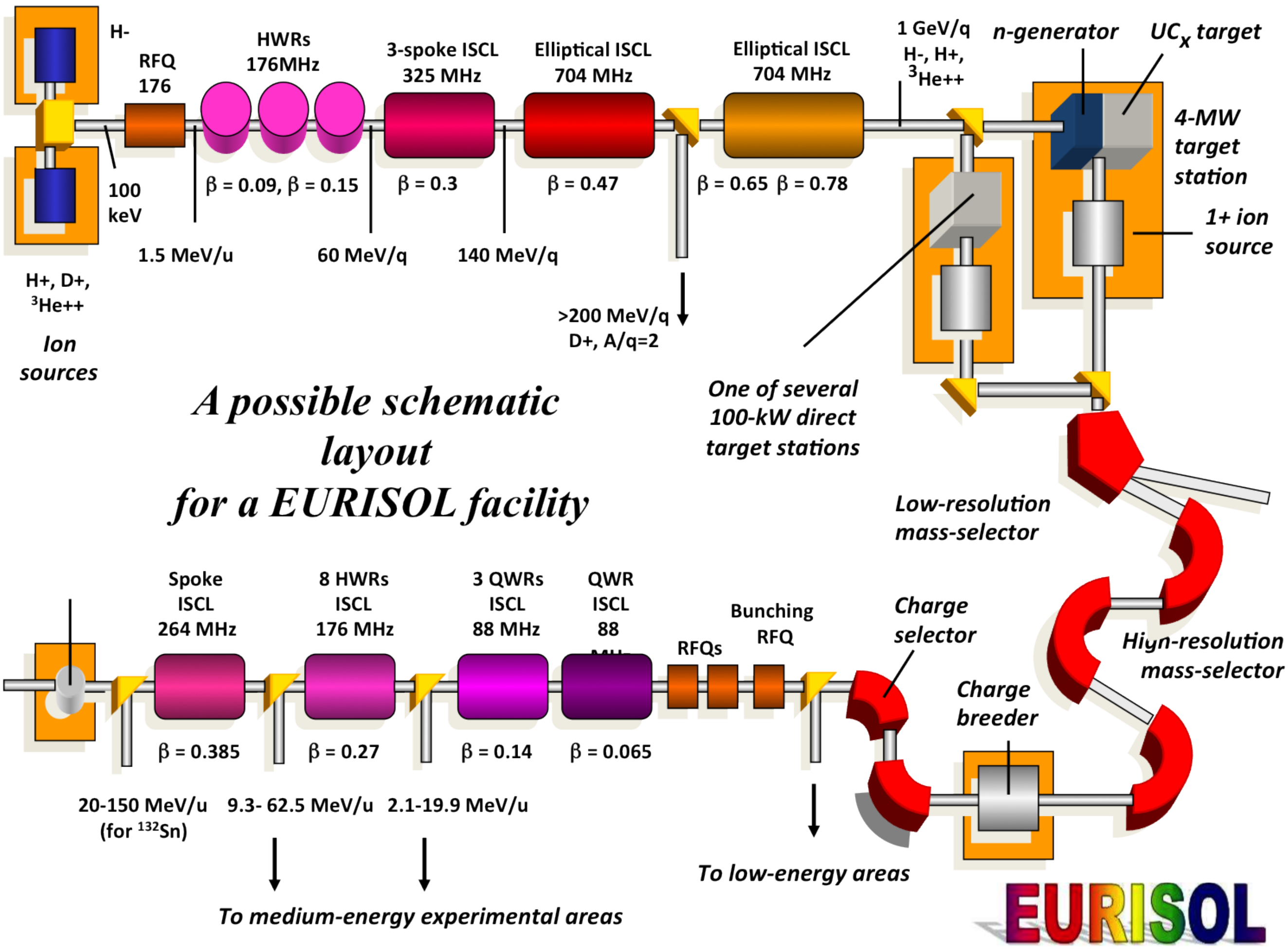

Figure 6: Schematic view of the EURISOL concept

then fission products of fissile target material positioned close to the neutron source. In order to cope with the 2.3 MW power deposited in the spallation target, out of the 4 MW EURISOL proton beam, the converter has to be made of liquid metal. Up to six targets can be positioned simultaneously, linked to 1^+ ion sources. Furthermore, up to three direct targets, in which the target material is directly exposed to the proton beam will also be available simultaneously.

In order to reach the highest intensities from the multi-MW fission targets, the beams from the six units have to be merged and subsequently cooled and mass separated before being delivered to low-energy experimental installation, alternatively transported to either an ECR source or a high-intensity CW EBIS source for charge-state breeding followed by post-acceleration. A superconducting linear accelerator, optimised for ions with mass-to-charge ratio (A/Q) up to eight, is envisaged where the RIBs will reach up to 150 MeV/u e.g. for the reference case of ^{132}Sn^{25+}. The energy is chosen to be sufficient for secondary fragmentation of such neutron-rich fission fragments, reaching further from stability than those produced by any facility existing or under construction today. Figure 6 displays a schematic diagram of the EURISOL concept.

4.5.1. ISOL@MYRRHA at SCK·CEN

The MYRRHA project aims at constructing an Accelerator Driven System (ADS) at the SCK·CEN site in Mol, Belgium, by coupling of a proton accelerator to a liquid Lead-Bismuth Eutectic (LBE) spallation target and a LBE cooled, sub-critical fast core [37]. A proposal for fundamental research at MYRRHA is the installation of an ISOL facility, ISOL@MYRRHA, using parts of the beam intensity (a few hundred μA out of several mA) of the 600 MeV proton accelerator as a driver beam. The focus would be on intense low-energy RIBs for experiments requiring very long beam times (up to several months). In order to withstand the high energies for extended periods, ruggedised target-ion source systems are foreseen. Experiments, requiring very high statistics, hunting for very rare events, or having inherent limited detection efficiency, have a particular interest in the use of extended beam time. This could be in the domain of e.g. fundamental-interaction measurements with extremely high precision to systematic measurements for condensed-matter physics and production of radioisotopes, and makes ISOL@MYRRHA complementary with the activities at other existing and future ISOL facilities. During the main shut-down maintenance periods of the MYRRHA reactor (3 months every 11 months), the full proton beam intensity could be used for ISOL@MYRRHA.

5. Conclusions

The European landscape of RIB infrastructures is heterogeneous but coherent, as ensured by the planning and prioritisation efforts by NuPECC, ESFRI and national bodies. Leading in-flight and ISOL infrastructures will be available to the European an global scientific community for decades, being both competitive and complementary on a global scale. The investments and development efforts in the associated instrumentation are as well matching. However, the focus should now be on timely completion of the upgraded and novel installations.

6. Acknowledgements

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