Radioactive Ion Beam facilities

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Abstract. Radioactive Ion Beam facilities are transforming nuclear science by making beams of exotic nuclei with various properties available for experiments. New infrastructures and development of existing installations enlarges the scientific scope continuously. An overview of the main production, separation and beam handling methods with focus on recent developments is done, as well as a survey of existing and forthcoming facilities world-wide.

1. Introduction

Radioactive isotopes building up the nuclear chart have, since the discovery of radioactivity, been essential for fundamental nuclear physics research and for many applications in various fields of science. Developments over the last decades for the production and study of radioactive ion beams have resulted in mature techniques that allow to explore the properties of isotopes that have a proton-to-neutron ratio very different from the stable isotopes in an unprecedented way. Moving away from the valley of beta stability the production of these so-called exotic nuclei, however, is confronted with difficulties that stem from the

- extremely low production cross sections
- overwhelming production of unwanted species in the same nuclear reaction
- very short half lives of the nuclei of interest.

Originally two complementary ways to make good quality radioactive ion beams were developed: the isotope separation on line (ISOL) technique and the in-flight separation technique (see Fig. 1). Both methods transport the nuclei of interest away from their place of production, where a large background from nuclear reactions and radioactivity is present, to a well-shielded experimental set-up, where the nuclear properties can be explored. During the transport process the beam is purified and is prepared to fulfill the requirements of the different experiments.

The final aim is the production of beams of exotic nuclei that are intense and pure and have good ion optical quality, proper timing characteristics and energies essentially from rest (meV/u) to the highest energies (GeV/u). Therefore the whole production sequence must posses the following properties:

- **High Production Rate.** In order to achieve the highest production rate of a particular nucleus, the beam-target combination as well as the beam energy have to be optimized. Accelerators or reactors should deliver the highest primary beam intensities and target systems have to cope with the power deposition of the primary beam.
- **Efficient.** Any manipulation of the reaction products - e.g. ionization, purification, acceleration, transport to the detection system - has to be efficient, preferably close to 100%.
- **Fast.** As one is dealing with short-lived exotic nuclei, the losses due to radioactive decay between the moment of production and the arrival at the experimental set-up should be kept to a minimum.
- **Selective.** In a nuclear reaction process the isotopes of interest often form a minority and the unwanted - in general more stable - isotopes are produced much more abundantly. The separation process should reduce the unwanted species as well as the primary beam in an effective way.

The figures of merits of any radioactive beam facility are high *efficiency, selectivity and sensitivity* and short *delay times*. Over the last decades these figures of merit have been improved by implementing new ideas and techniques and this resulted in a wide variety of radioactive ion beams from the lightest elements to the heaviest ones. The progress in the field of in-flight separation and ISOL techniques is regularly reported in the conference series on "Electromagnetic Isotope Separators and Techniques related to their Applications (EMIS)" [1]. A detailed overview of on-line mass separators including many technical aspects was given by H.L. Ravn and B.W. Allardyce in [2]. Lecture notes on radioactive ion beam production can be found in [3, 4].

2. The emergence of RIBs

As discussed above, two production methods are commonly used in RIB facilities, in-flight and ISOL. The ISOL method was developed in the 1950's using some of the light-ion accelerators that were available at that time. In the seventies and eighties heavy ion physics was in the limelight and several high-energy heavy ion accelerators were built. It soon became apparent that in addition to studying nuclear matter at high temperature and density these machines could deliver large amounts of radioactive nuclei produced through projectile fragmentation giving birth to in-flight produced radioactive ion beams.

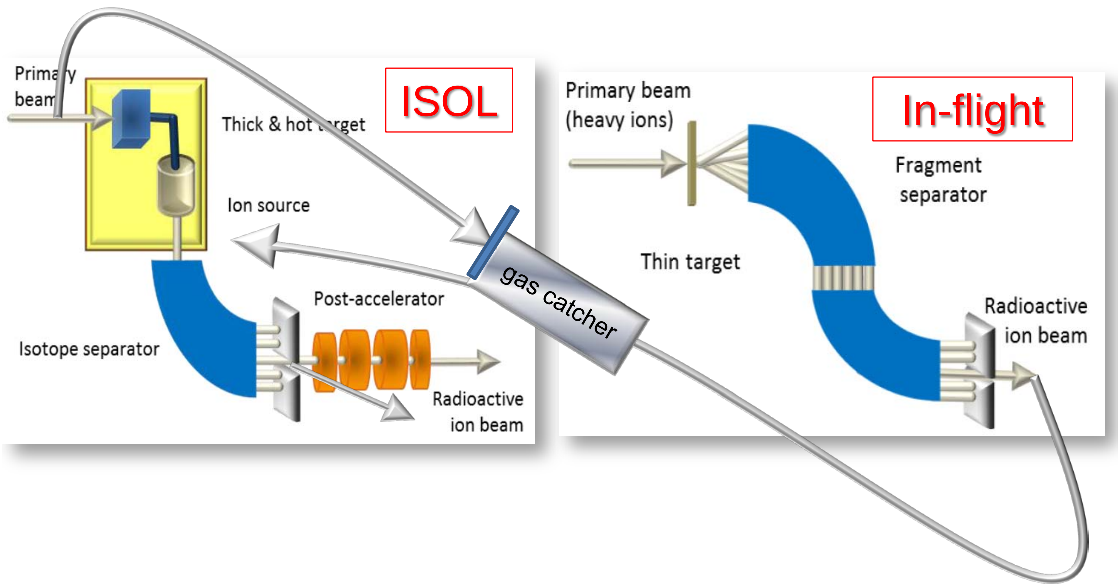


Figure 1. A schematic drawing of the ISOL and in-flight based production methods for radioactive ion beams.

ISOL The production of the first ISOL beams more then half a century ago at the Niels Bohr Institute in Copenhagen (Denmark) were reported by O. Kofoed-Hansen and K.O. Nielsen [5, 6]. They followed a two-stage approach for the production of the radioactive isotopes. Deuterons were accelerated in a cyclotron and impinged on a primary converter target to produce neutrons that induced fission in a secondary uranium target. The gaseous fission products, like neutron-rich krypton isotopes, were pumped through a 10 m long tube from the target position towards the off-line isotope separator. The krypton isotopes were ionized in a high-temperature plasma ion source, mass separated and used for beta-neutrino correlation experiments. Important technical details, like the two-stage production using a deuteron-to-neutron converter and the cooled transfer line to eliminated non-volatile elements, were already implemented right from the start. Moreover, in their paper the authors define the meaning of "on-line" by quoting "The cyclotron and the isotope separator were operated **simultaneously**,...". After these pioneering achievements, it took more then a decade for the next important step. Klapisch and Bernas coupled an on-line isotope separator to the Orsay Synchro-cyclotron in France and produced beams of the non-volatile light lithium isotopes [7]. Soon after, however, several ISOL facilities were constructed and coupled to a number of different driver machines like heavy-ion or high-energy proton accelerators, nuclear reactors or other neutron generators [2]. This period also gave in 1964 birth to what was to become the most versatile and largest ISOL facility that served as benchmark for all other projects: the ISOLDE on-line facility coupled to CERN's 600 MeV Proton Synchro-Cyclotron (Switzerland) [8]. The first experiments started there in 1967. ISOLDE underwent several upgrades until it was moved to the 1.4 GeV PS Booster in 1992, which beams it still uses today. The first successful experiments using radioactive ion beams from ISOL facilities triggered the interest in post accelerating the low-energy beams to energies up and above the Coulomb barrier for reaction studies of e.g. astrophysical interest. It took however until the late 1980's before the first post accelerated radioactive ion beam was produced by coupling the two Louvain-la-Neuve (Belgium) cyclotrons with an isotope separator [9]. The layout of the RIB facility in Louvain-la-Neuve, which displays all the features of subsequent re-accelerated beam ISOL facilities, is shown in figure 2. Since then post-acceleration of radioactive ion beams has been developed at several places using different combinations of primary driver and secondary accelerator [10].

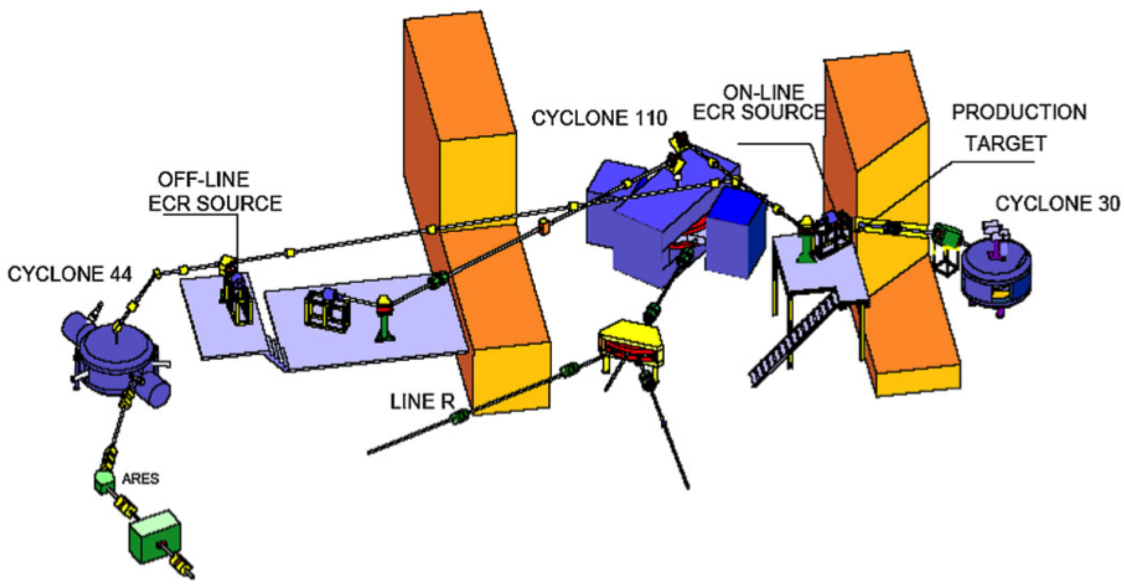


Figure 2. Schematic view of the former Louvain-la-Neuve RIB facility

In flight The pioneering work was performed at the Bevalac at Berkeley, Ca [11]. The Super-HILAC was initially a low energy heavy ion Linear accelerator set on the hillside at the Lawrence Berkeley laboratory an d the Bevatron a proton synchrotron for particle physics located over a half mile away (fig. 3). In order to produce the first relativistic heavy ion machine, both accelerators were connected by a beam line descending from the hill through the laboratory and transforming the HILAC into a heavy ion injector for the Bevalac. It was through fragmentation of the 1 GeV/A 20Ne beams from this combination that Isao Tanihata obtained the first ^{11}Be and ^{11}Li beams that led to the discovery of the neutron halo[12]. Exploitation of the Bevalac ended in 1992.

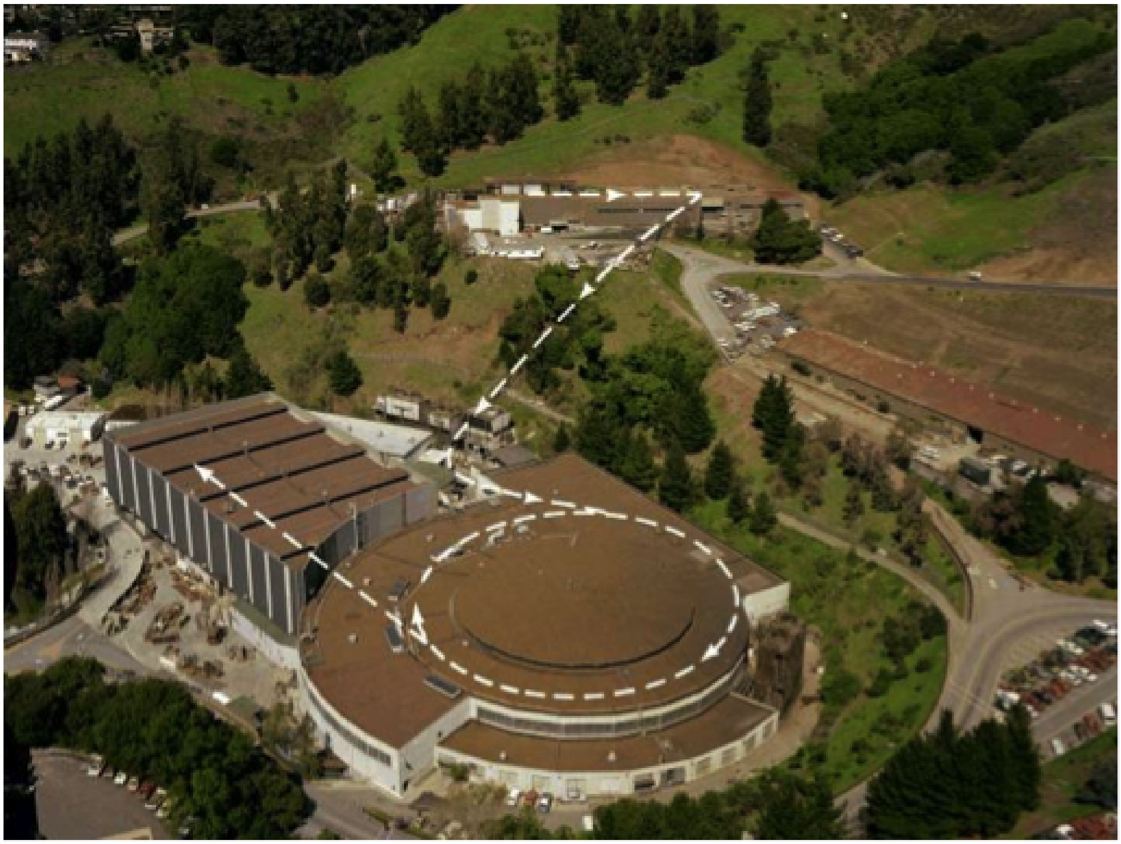


Figure 3. Photograph of the HILAC and BEVALAC in Berkeley

Extending the nuclear landscape The creation and study of unstable nuclei is a topic that has been pursued for many years using stable beams on stable or long-lived targets, where e.g. fusion-evaporation has been used to study neutron-deficient nuclei. This remains the prime method to investigate the heavy-element frontier [14], where minute cross-sections and thin targets necessitate maximum beam intensity. However, in terms of exploring the isospin frontier, in particular on the neutron-rich side, RIBs are necessary. The history of extending the nuclear chart [15] is closely connected to the technical advances of radioactive beams, at ISOL-facilities whenever an additional target material or a new ion source is employed, and at in-flight facilities when primary beam intensities are increased or the selectivity and detection efficiency is enhanced. In particular the latter have taken on the role of "isotope hunters" due to the possibility of identifying single ions of specific nuclides.

In addition, the development of laser ion source opens up the possibility to produce isomerically purified beams using the nuclear-spin dependence of the hyperfine splitting of the atomic levels [16].

3. Existing facilities

As discussed above, two production methods are commonly used in RIB facilities, in-flight and ISOL. In some of the most recent designs for future facilities this separation tends to get blurred but it remains a relevant classification to discuss historical and future facilities and we will follow it in this section.

3.1. Current Facilities

3.1.1. In flight After the pioneering work at Berkeley it was recognized that high energy heavy ion accelerator complexes offered the possibility of producing RIBs through projectile fragmentation if suitable fragment separator devices were built. Due to the broad scientific opportunities the major high energy heavy ion facilities in operation in the nineties; NSCL-MSU, GANIL, GSI and RIKEN; saw an increasing fraction of their beam time devoted to RIB production. The GANIL driver consists of 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. Large primary intensities (several μA) can be delivered but the final RIB intensities are limited by the weak forward focusing at intermediate energies (GANIL has the lowest energies of the four facilities) and the limited acceptance of the beam lines which were not optimized for RIB transmission. In order to improve the collection efficiency an ingenious superconducting solenoid named SISSI[17] was 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 in use since 2008 which imposes the use of the LISE separator for beam production and limits the range of experiments possible with in-flight beams.

Production and selection efficiencies are larger at MSU/NSCL and RIKEN where the fragment separators A1900 and RIPS were specifically built for efficient RIB selection. The NSCL/MSU facility is driven by coupled superconducting cyclotrons with K=500 MeV and K=1200 MeV, while the initial RIKEN facility, still in operation today, has a K=540 MeV room temperature cyclotron. The SIS synchrotron at GSI can provide energies of up to 2 GeV/u, albeit with intensities much lower than at the cyclotron facilities. These are partially compensated during the production stage by the stronger forward focusing and the high efficiency of the FRS fragment separator, and by the possibility offered by the high energies to use thicker targets in the experiments. The main characteristics of these first generation fragmentation facilities are summarized in table 3.1.1.

Japan has recently taken the world lead in high energy RIBs as the first "next generation" in-flight facility, the Radioactive Ion Beam Factory (RIBF) in RIKEN near Tokyo has been in operation already since 2007[18]. RIBF boasts a new high-power heavy ion accelerator system consisting of 3 ring cyclotrons with K-values of 570 MeV (fixed frequency, fRC), 980 MeV (intermediate stage, IRC) and 2500 MeV (superconducting, SRC). A final energy of 350 MeV/u is obtained up to the heaviest

Facility	Location	Driver	Primary Energy	Typical intensity	Fragment separator
GANIL	Caen, France	2 separated sector cyclotrons	Up to 100 MeV/u	^{36}S 10^{13} pps ^{48}Ca 2 10^{12} pps	SISSI + ALPHA
GSI	Darmstadt, Germany	Linac + Synchrotron	Up to 2 GeV/u	10^{10} ppspill	FRS
NSCL/MSU	East Lansing, USA	2 coupled superconducting cyclotrons	Up to 200 MeV/u	^{40}Ar 5 10^{11} pps	A1900
RARF RIKEN	Tokyo, Japan	Ring cyclotron	Up to 100 MeV/u	^{40}Ar 5 10^{11} pps	RIPS

Table 1. Characteristics of main current in-flight facilities

ions. The first phase of RIBF has started to operate in 2007, delivering in particular the world's most intense beam of ^{48}Ca at 200 particle μA and Uranium beams at an intensity of 10^9 pps which is still much lower that the design value of 1 particle μA. The radioactive beams are selected by a new superconducting fragment separator BigRIPS. Major new experimental devices are already in operation including 3 spectrometers (ZDS, SAMURAI and SHARAQ) and an electron-RIB (e-RI ring) scattering apparatus is planned to be constructed.

The ZeroDegree Spectrometer (ZDS) is a large-acceptance beam-line spectrometer for particle identification of the reaction products at the secondary target that is bombarded by the radioactive beam. SHARAQ, in connection with a long beam transport line for dispersion matching, provides a unique opportunity to carry out high resolution studies using secondary beams. SAMURAI is a versatile large acceptance spectrometer having a large gap that allows the detection of neutrons emitted forward in coincidence with other charged particles for spectroscopic studies of unbound states excited by nuclear reactions. Additional unique devices currently planned are SLOWRI and the Rare Isotope ring. SLOWRI aims to provide slow radioactive beams after stopping a fast radioactive beam by a gas catcher. The Rare Isotope ring will measure the mass of rare isotopes with a precision of 10^{-6}. As for the electron scattering facility, it will be described in paragraph 3.1.3. A schematic view of the RIBF facility is depicted in fig. 4.

3.1.2. ISOL Three major ISOL facilities proposing a large variety of beams can be counted in the world today, CERN-ISOLDE and GANIL-SPIRAL in Europe and TRIUMF in North America. The oldest, which is the precursor of ISOL installations worldwide, is ISOLDE [19] located at CERN. ISOLDE makes use of a large variety of thick targets including Uranium Carbide which are irradiated with a pulsed beam of protons at 1.4 GeV from the Proton Synchrotron Booster. At a maximum average

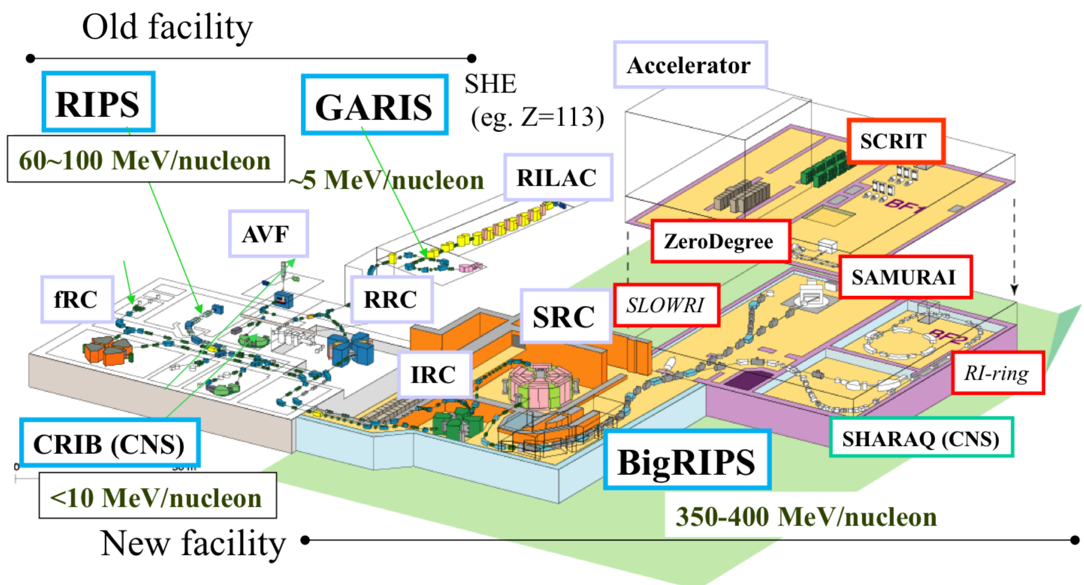


Figure 4. Schematic view of the RIKEN RIB factory

current of 2 μA the protons initiate fission, spallation, and fragmentation reactions and the produced exotic isotopes diffuse and effuse out of the heated target through a transfer line which is coupled to an ion source. Different types of ion sources are available, e.g. surface ion sources, plasma ion sources, or Resonant Ionization Laser Ion Sources (RILIS). The latter method is element selective and thus offers the possibility to obtain high purity beams. Isobaric contamination, mainly due to surface ionization, can be removed by application of mass separators after acceleration to a maximum of 60 keV. Many experiments at ISOLDE take the beam directly from the ion source, i.e., at energies of 30-60 keV. With the different setups ground state and decay properties of radionuclides are measured. Also solid state physics experiments use short-lived ions to probe lattice structures and to examine the properties of new superconducting materials [20].

Since 2001 post acceleration is available for all the nuclei produced with the REX linear accelerator up to a moderate energy of 3 MeV/u, which is sufficient to perform Coulomb excitation and transfer reactions on light nuclei. The RIBs are accelerated with a compact normal conducting linear accelerator, which makes use of a special low-energy preparatory scheme. With the buffer-gas filled Penning trap system REXTRAP the incoming ions from ISOLDE are cooled and bunched for subsequent transport to the charge breeder REXEBIS. The ion charge-state is boosted such that the mass-to-charge ratio is always $2.5 < A/Q < 4.5$. The accelerator is for a maximum A/Q of 4.5 and it delivers a final energy of 3 MeV/u for $A/Q < 3.5$ and 2.8 MeV/u for $A/Q < 4.5$. After charge breeding, the first acceleration stage is provided by a 101.28 MHz 4-rod radiofrequency quadrupole (RFQ) which takes the beam from an energy of 5 keV/u up to 300 keV/u. The beam is then re-bunched into the first 101.28 MHz interdigital drift tube (IH) structure, which increases the energy to 1.2MeV/u. Three split ring cavities are used to give further acceleration to 2.2 MeV/u and finally a 202.58 MHz 9-gap IH cavity is used to boost and to vary the energy between 2 and 3 MeV/u.

Over the past decade the ISAC facility [21] at the TRIUMF laboratory in Vancouver, Canada, using a 500 MeV proton cyclotron as a driver, has evolved into a full fledged RIB facility. There are 2 post-accelerators, ISAC1 and ISAC2, composed of an RFQ, a DTL followed by a Superconducting LINAC which can accelerate the radioactive ions up to 5 MeV/u and 11 MeV/u respectively. The recent commissioning of a UC_x target and continuous improvement of the RILIS ion source has led to the production of many new elements and a substantial increase of the intensities delivered.

SPIRAL makes use of the GANIL coupled cyclotrons as driver. A thick graphite target is used and radioactive species are produced by fragmentation of the incident heavy ion beam which is stopped in the target. The beams are ionized in a permanent magnet ECR source. This scheme has the advantage of simplicity but strongly limits the variety of beams available which is currently restricted to noble gases and to oxygen and fluorine. A 1^+ to N^+ scheme is currently under development (under the name GANISOL) which should increase the number of elements available. The post accelerator is the CIME cyclotron which also serves as a high resolution mass separator. The final energy, which can reach 25 MeV/u, is the highest of current ISOL facilities. The characteristics of the three main current ISOL facilities are summarized in table 2.

Finally the HRIBF facility at Oak Ridge National Laboratory in Tennessee deserves mention even though it is unfortunately no longer in operation. HRIBF made use of a 50 MeV proton cyclotron as driver and a large 20 MV electrostatic Tandem as post accelerator, necessitating the injection of negative ions.

Facility	Location	Driver	Post accelerator	Final energy	Main beams availabl
REX-ISOLDE	CERN, Geneva	PS Booster, 1.4 GeV protons	REX LINAC	0.3A - 3A MeV	Large variety including fission fragments
SPIRAL	Caen, France	GANIL coupled cyclotrons	CIME cyclotron	2.7A-25A	He. Ne, Ar, Kr, N,O. F
TRIUMF/ISAC	Vancouver, Canada	500 MeV proton cyclotron	ISAC I and II RFQ + SC LINAC	0.2 - 11A MeV	Large variety including fission fragments

Table 2. Characteristics of main current post-accelerated ISOL facilities

3.1.3. Niche facilities An attractive feature of the field of RIB physics is that important discoveries are not the exclusive domain of the large scale facilities but results of great interest also emanate from much smaller installations often dedicated to one type of physics problem. Several tandem accelerators, for example the TwinSol setup [22] at

Notre Dame University in South Bend, Indiana, and the so-called RIBRAS[23] facility in Sao Paolo, Brazil have been adjoined a superconducting solenoid in order to focus in-flight the products of transfer reactions. This is an efficient way to produce low energy light RIBS such as ^{6}He, ^{7}Be, ^{8}B ... One should also mention the EXCYT facility at LNS Catania, Italy [24] which uses a scheme similar to HRIBF Oak Ridge with a superconducting cyclotron as driver and a 15 MV Tandem as post-accelerator. The ALTO installation at IPN Orsay[25] uses a 50 MeV electron accelerator as driver to induce fission in a UC_x target. ALTO has recently received the authorization to run at full power (10 microA electron current) but is restricted to low energy experiments since no post acceleration is available.

An extremely productive small facility is JYFL in Jyväskylä, Finland where the best use has been made of the original IGISOL technique [26]. A 30 MeV proton beam delivered by the JYFL cyclotron impinges on a thin ^{238}U (or ^{232}Th) target immersed in 200-500 mb of He stopping gas (fig. 5). The extracted fission fragments can then be transported to various devices for the measurement of ground state properties: e.g. Penning trap and laser spectroscopy. The great advantage of the method compared to standard ISOL is that refractory elements which do not diffuse out of an ISOL target can be easily produced here. Recently a second cyclotron has been installed on-site which will be fully devoted to the IGISOL program.

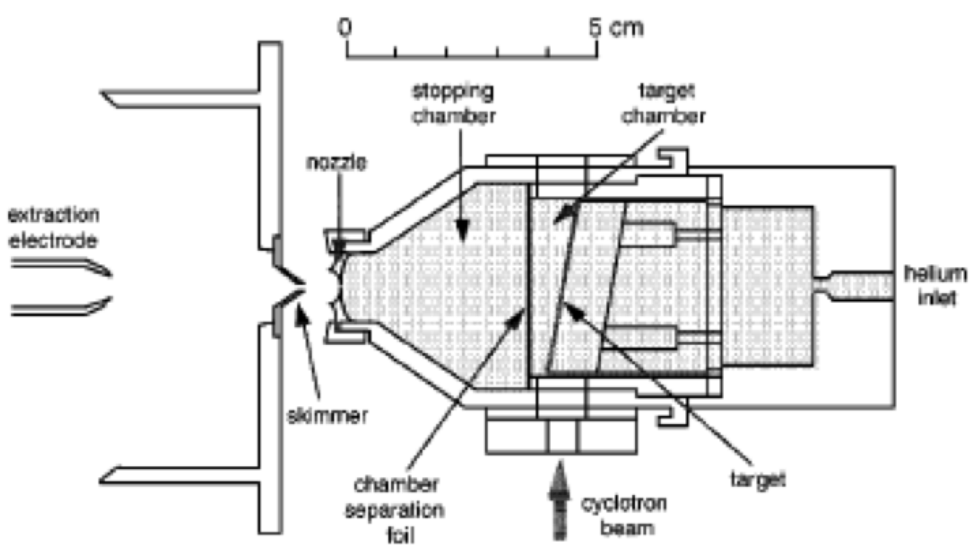


Figure 5. The IGISOL target and ion guide ay Jyväskylä

Gas catcher system that convert energetic radioactive ions into a low energy beam are under development at fragment and in-flight separators or are combined with a strong (close to a Curie activity) spontaneous ^{252}Cf fission source at the CARIBU project at Argonne National Laboratory. The low-energy ion beam of fission products from the latter facility are accelerated with the ATLAS linear accelerator. The use of laser resonant ionization in the gas cell or gas jet has been developed not only to produce isotopically pure beams of short-lived radioactive isotopes, but also for very sensitive in-source laser spectroscopy studies as developed at the LISOL facility in Belgium. These systems will be installed at different in-flight separators in RIKEN, GSI, GANIL and JYFL.

A planned small facility which will be of great value to the field is the electron scattering facility based on the Self Confining Radioactive Ion Target (SCRIT) scheme [18] to be built at RIKEN. A diagram of the set up is shown on fig. 6. This will allow measurements of charge distributions of exotic nuclei. Exotic nuclei of interest, specifically Sn isotopes including ^{132}Sn in a first stage will be produced using a 150 MeV electron beam bombarding an uranium carbide target. The ions will be externally injected and trapped by a circulating electron beam which is injected in a storage ring from the same electron microtron as that used as ISOL driver. Once the ions are trapped on the electron beam, they cannot escape. Therefore, a high collision luminosity is expected with a small number of trapped ions. Since the ions are trapped on the electron beam, electron scattering off the target nucleus takes place automatically. A non-focusing magnetic spectrometer with tracking detectors will be employed to detect the scattered electrons. This spectrometer covers a wide scattering angular range of 30-60 deg., and has a solid angle of the order of 100 msr. Tests have already been carried out with stable ^{133}Cs ions demonstrating the viability of the method. Once measurements have been completed for the fission fragments it is envisaged to couple the electron ring with the RIBF in order to extend the range of nuclei accessible.

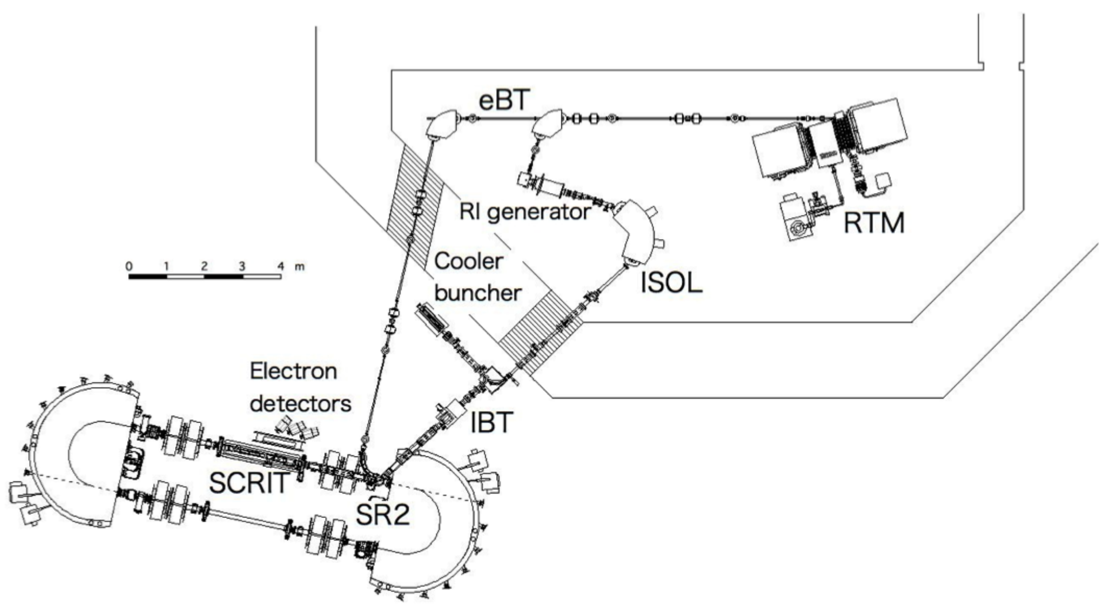


Figure 6. Schematic view of the SCRIT set up at RIKEN

4. Future Facilities

While particle physics is planned on a global scale, in the past decade nuclear physics has moved from national to regional (continental) planning. Therefore we will present the future plans for large scale RIB facilities according to the three continents involved: Europe, North America and Asia.

4.1. The European Roadmap

An expert committee called NuPECC (Nuclear Physics European Collaboration Committee) is charged with issuing a long range plan for Nuclear Physics in Europe through a bottom-up process. The latest issue was published in 2010[27] 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 Organization ESFRI (European Strategy Forum on Research Infrastructures) recommends the major large scientific facilities to be built in Europe and has included FAIR and SPIRAL2 on its list as RIB installations. The NUPECC recommendation is to complete in a timely fashion the construction of the Nuclear Physics facilities on the ESFRI list of large-scale research infrastructure projects in Europe: 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 which will allow the study of unstable nuclei 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 roadmap is summarized on fig. 7 and the future facilities listed above are described in the following.

4.1.1. NUSTAR at FAIR FAIR, located in Darmstadt, Germany is the most ambitious Nuclear Physics project of the decade [28]. The scientific reach of FAIR includes Physics of hadrons and quarks in compressed nuclear matter (CBM experiment); 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).

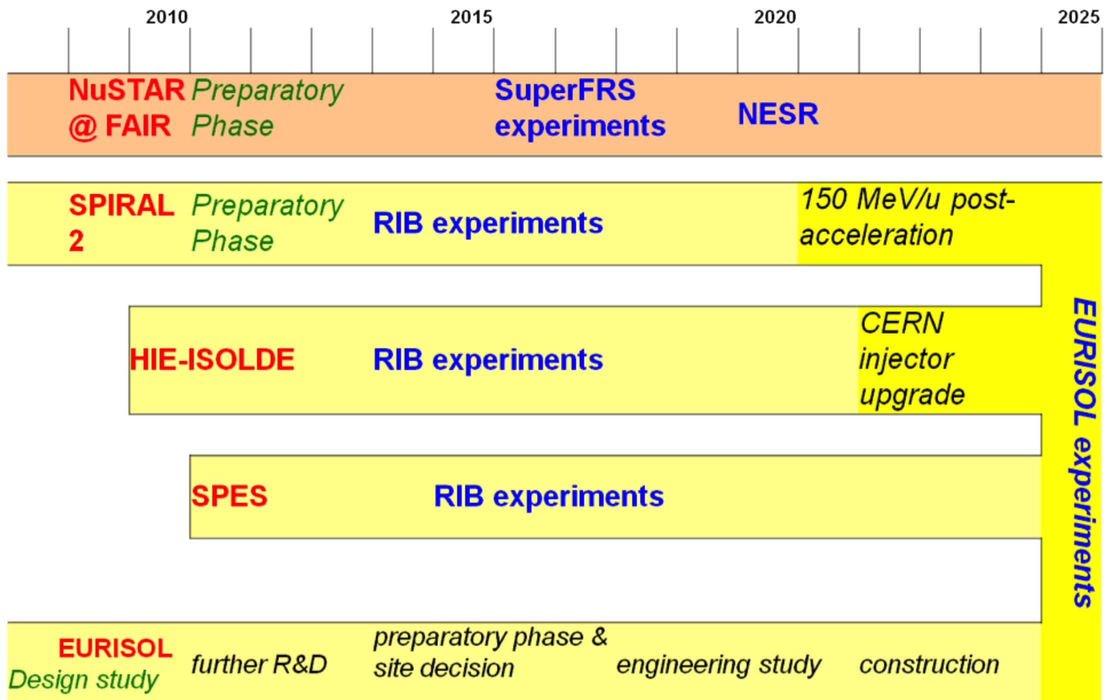


Figure 7. The NuPECC roadmap for RIB facilities

The core of FAIR is 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 a fragment separator with vastly improved efficiency, the Super-FRS, which will deliver a broad range of radioactive beams with up to a factor 10^4 improvement in intensity over current values. The beams will be used directly in the so-called high energy cave, degraded to very low energies or stopped in the low energy cave, or injected into the NESR storage ring and decelerated and cooled. Several experimental devices are being studied and constructed. 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. An internal gas-jet target installed in the NESR storage ring will allow for direct reaction studies using cooled beams with the EXL charged particle and gamma-ray detector, while electron-ion scattering with the ELISE set-up will provide unique charge distribution measurements for exotic nuclei. The low energy branch of NUSTAR will include installations dedicated to High Resolution Spectroscopy (HISPEC), decay studies (DESPEC), mass measurements (MATS and ILIMA) as well as radii and moment measurements through laser spectroscopy (LASPEC). A schematic view of the FAIR facility and the NUSTAR area, devoted to exotic beam studies, is displayed on fig. 8.

The FAIR facility is structured in six modules of which five are related to the

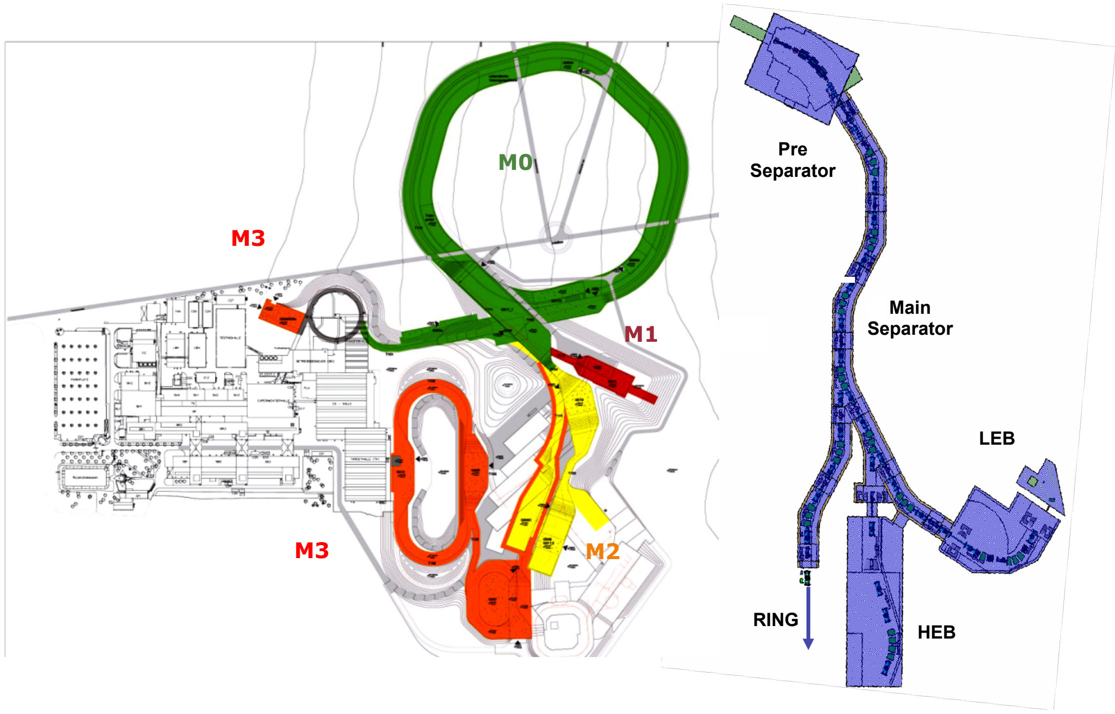


Figure 8. The FAIR facility according to the Modularized Start Version with modules 0-3 indicated. Right inset depicts the Super-FRS and its three branches, making up the NUSTAR part of the facility.

NUSTAR program:

- 0: Heavy-Ion Synchrotron SIS100 - basis and core facility of FAIR - required for all science programs.
- 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 [29]. Actions are underway to find alternative solutions permitting parts of the associated scientific programme to be pursued earlier.

4.1.2. SPIRAL2 at GANIL The driver of the SPIRAL2 facility is a high power, CW, superconducting LINAC, delivering up to 5 mA of deuterons at 40 MeV (200 kW, the highest power ever delivered by this type of accelerator) directed on a Carbon converter + Uranium target. Production of the radioactive nuclear beams is based essentially on the fast neutron induced fission of the uranium target. 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) at the existing GANIL experimental areas, which will be enriched 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 SPIRAL2 LINAC will accelerate also high intensity (up to 1 mA) heavy ions up to 14.5 MeV/u. They 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 palette of neutron deficient and very heavy exotic nuclei with the Super Separator Spectrometer (S3). A diagram of the facility is presented in fig. 9.

The construction of SPIRAL2[30] is split into two phases:

(i) Linear accelerator with S3 experimental hall : commissioning expected in 2013.

(ii) Radioactive Ion Beam production hall and DESIR low-energy RIB facility: commissioning expected in 2016.

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. A straightforward extension of the facility, namely a second heavy-ion injector for LINAC accelerating heavy ions with A/q ratio equal to 6, will allow an increase in the intensity of medium-mass and heavy beams. In the mid-term future, a secondary fragmentation of the SPIRAL2 rare isotope beams accelerated to energies greater than 150 MeV/u would be a natural progression of the facility towards EURISOL.

4.1.3. HIE-ISOLDE at CERN In order to broaden the scientific opportunities far beyond the reach of the present facility, the HIE-ISOLDE (High Intensity & Energy ISOLDE) project [31] will provide major improvements in energy range, beam intensity and beam quality. A major element 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 replacing the current REX LINAC by superconducting cavities and will be implemented in a staged fashion.z The first stage will boost the energy to 5.5 MeV/u where the Coulomb excitation cross sections are strongly increased with respect to the current 3 MeV/u and many transfer reaction channels will be opened. Physics at 5.5 MeV/u is expected to start in early 2015. In the second stage, additional cryo-modules 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. Moreover, the provision of low beta superconducting cavities allows for CW

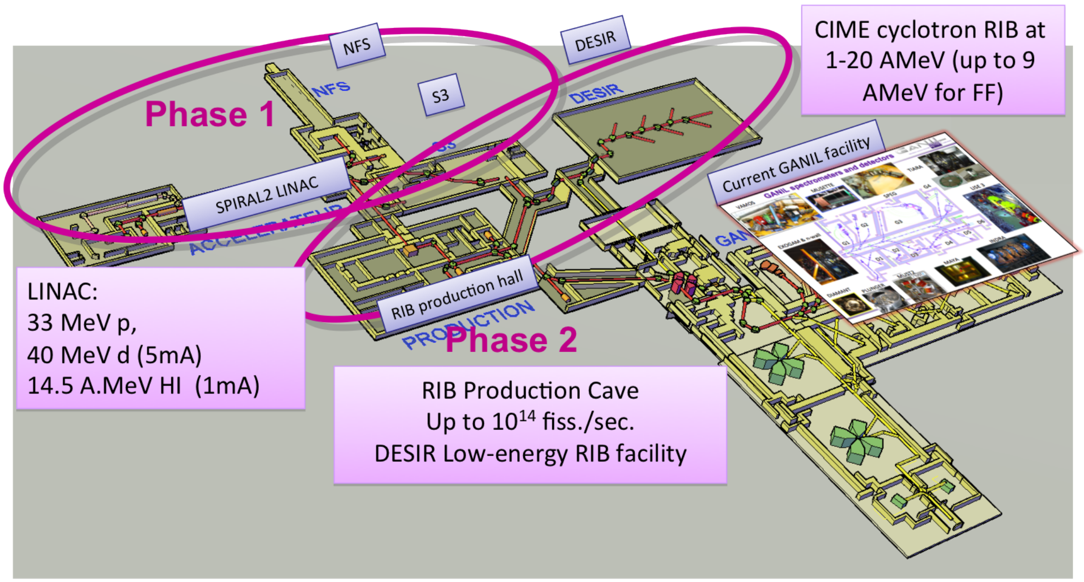


Figure 9. Schematic view of the SPIRAL2 project

operation and the delivery of beams with energies down to 0.5 MeV/u for astrophysics oriented measurements. Figure 10 shows the staging 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 optimized 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 more 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 will also be investigated.

4.1.4. SPES at Laboratori Nazionali di Legnaro, Italy SPES is a new ISOL facility dedicated to the production of neutron-rich beams. The project consists of a proton driver, a 70 MeV cyclotron with two exit ports for a total current of 750 μA, an UC_x ISOL target and ion source, a beam transport system with high resolution mass selection and the superconducting PIAVE-ALPI accelerator complex in operation at LNL, which will be used as post-accelerator. A proton beam of 40 MeV and 200 μA, delivered by the cyclotron, will impinge on a uranium carbide target and neutron rich isotopes will be produced as fission fragments with a rate of 10^{13} fission/s. The uranium carbide targets have already been developed and represent a technical innovation in terms of their capability to sustain the primary beam power. The neutron rich products will be extracted and mass separated to be reaccelerated. In particular, the radioactive ions,

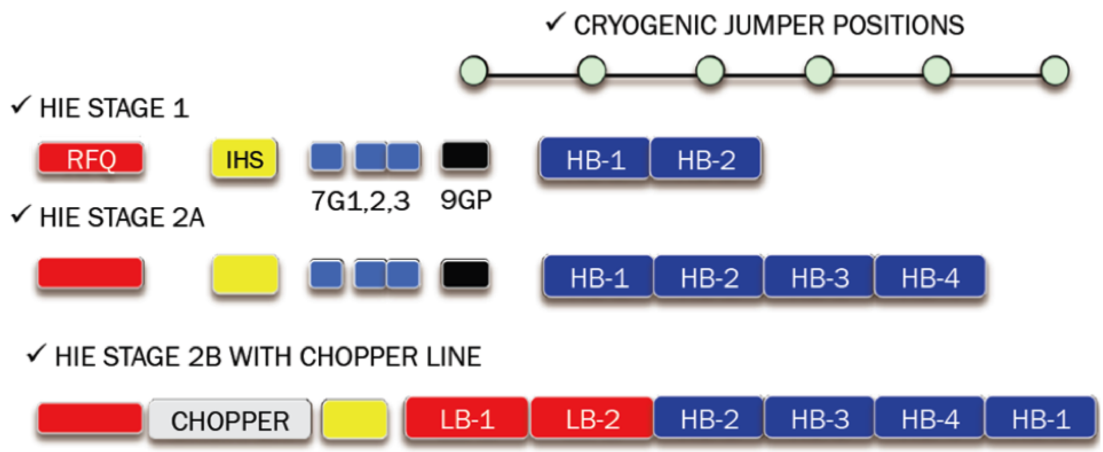


Figure 10. Staging of the HIE-ISOLDE Linac

extracted in a 1^+ state using different ion sources depending on the kind of isotope, will be transported to the linear accelerator ALPI. To fit the proper entrance parameters for beam re-acceleration with the linac, an RFQ-cooler and a charge breeder are planned to be installed. The design and construction of the charge breeder will be done 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 11 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.

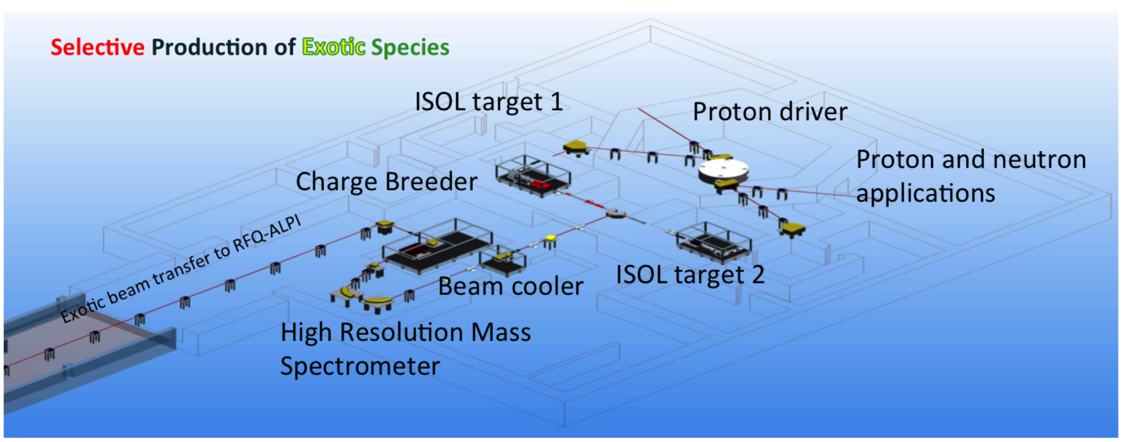


Figure 11. Schematic view of the SPES project

4.1.5. EURISOL The EURISOL concept [32] was born 10 years ago, as the "ultimate" ISOL facility for Europe. A conceptual design study was carried out as the EURISOL

Research & Technology Development project within the European fifth framework program and subsequently a technical Design Study was undertaken in the sixth framework. 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 Hg converter target loop were constructed and tested.

The planned EURISOL facility will use a large Continuous Wave (CW) superconducting linear accelerator (the "driver" accelerator) to accelerate H^- ions to energies of 1 GeV. The option of using a pulsed beam at 50 Hz with a minimum pulse length of 1 ms has been kept open to enable possible sharing of the driver with other physics users. This beam of particles will deliver a power of up to 4 megawatts to one target station, and through a newly developed magnetic beam splitting system some 100 kilowatts to three smaller target stations in parallel. To achieve these ambitious goals the low energy section of the linac will use a RFQ and Half Wave Resonator linac. The medium-low energy section is presently designed using the newly developed triple spoke cavities from IPNO in Paris while the medium energy section uses five cell elliptical cavities developed at CEA in Paris. Finally, the high-energy section will also use the five gap elliptical cavities adapted for the higher energy. The design has been optimized for beam quality and cost.

In an ISOL converter system, the neutrons are generated by high-energy protons impacting on a high Z material (so called spallation n-source). The radioisotopes are the 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. Two options based on axial or radial molten metal flow directions were investigated. Conceptually, several targets filled with ^{235}U or other actinides are inserted, through a channel created in the shielding, close to the neutron source at the position of maximum neutron flux. The neutron flux is thermalized in order to optimize ^{235}U fission while for other fissionable target materials, like ^{238}U or ^{232}Th, a hard neutron spectrum is required. Up to six targets can be positioned simultaneously, linked to single ionization ion sources (laser, plasma, ECR).

Up to three direct targets, in which the target material is directly exposed to the proton beam will also be available simultaneously. The main challenge set by the EURISOL beam power, is that the evacuation of the energy deposited by the 1 GeV protons through ionization in the target material, while the target materials (some of which are low density and open structure materials or are in the form of oxides with thermal insulating properties) are kept at the highest possible temperature to minimize the diffusion time of the radioisotopes.

The beam from the target stations has to be prepared for experiments with the merging, cooling, mass-separation and charge state multiplication of the six beams from the multi MW fission targets representing the biggest challenge. Preliminary studies have been performed of merging using a so-called arc ECRIS source which has geometry suitable for injection of several beams into an ECR plasma from which a single beam later can be extracted. The transverse cooling will be done in a newly developed high intensity RFQ cooler which also permits pulsing of the beam for experiments needing a specific time structure. The mass separation will be done with a classical dipole systems consisting of up-to four independents dipoles which should be capable of isobaric mass separation providing that the radioactive beam can be transversely cooled to a sufficiently small beam emittance. The exotic ion species from this area will then be directed towards low-energy experimental areas, where they can be captured in magnetic "traps" so that their properties can be studied, or led into the post-accelerators. Prior to post acceleration, the necessary charge breeding will be done in either an ECR source or in a new high intensity CW EBIS source.

There will be at least one superconducting linear accelerator, up to 200 meters long, in which exotic ions will reach energies up to 150 MeV (million electron-volts) per nucleon. The high-energy linac has been optimized for ions with mass-to-charge ratio (A/Q) up to eight with a final top-energy of 150 MeV/u for $^{132}Sn^{25+}$ which has been selected as the reference beam. The linac consists of only three different cavity types: independently phased quarter wave resonators, half-wave Resonators, and spoke cavities. The post-accelerated beams will have sufficient energy to undergo secondary fragmentation, leading to neutron-rich nuclei further from stability than those produced by any facility existing or under construction today. Figure 12 displays a schematic diagram of the EURISOL concept.

4.1.6. ISOL@MYRRHA The Belgian atomic energy center SCK·CEN has been studying the coupling of a proton accelerator, a liquid Lead-Bismuth Eutectic (LBE) spallation target and a LBE cooled, sub-critical fast core. The project, called MYRRHA, aims at constructing an Accelerator Driven System (ADS) at the SCK·CEN site in Mol. A proposal for fundamental research using the 600 MeV proton accelerator is the installation of an Isotope Separator On-Line facility (called ISOL@MYRRHA) with a ruggedized target-ion source system which is able to provide intense low-energy Radioactive Ion Beams (RIBs) for experiments requiring very long beam times (up to several months). This will open up unique opportunities for RIB research in various scientific fields, ranging from fundamental-interaction measurements with extremely high precision to systematic measurements for condensed-matter physics and production of radioisotopes. 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 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. A schematic view of MYRRHA and ISOL@MYRRHA is shown on fig. 13.

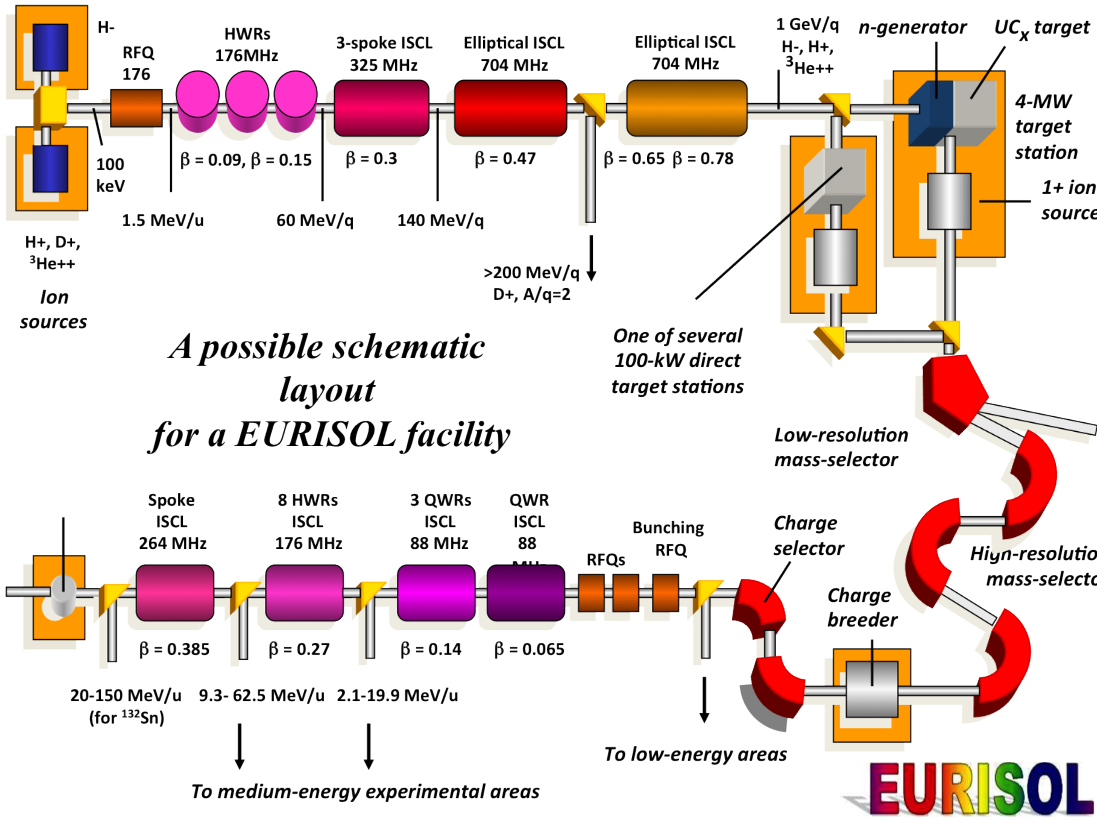


Figure 12. Schematic view of the EURISOL concept

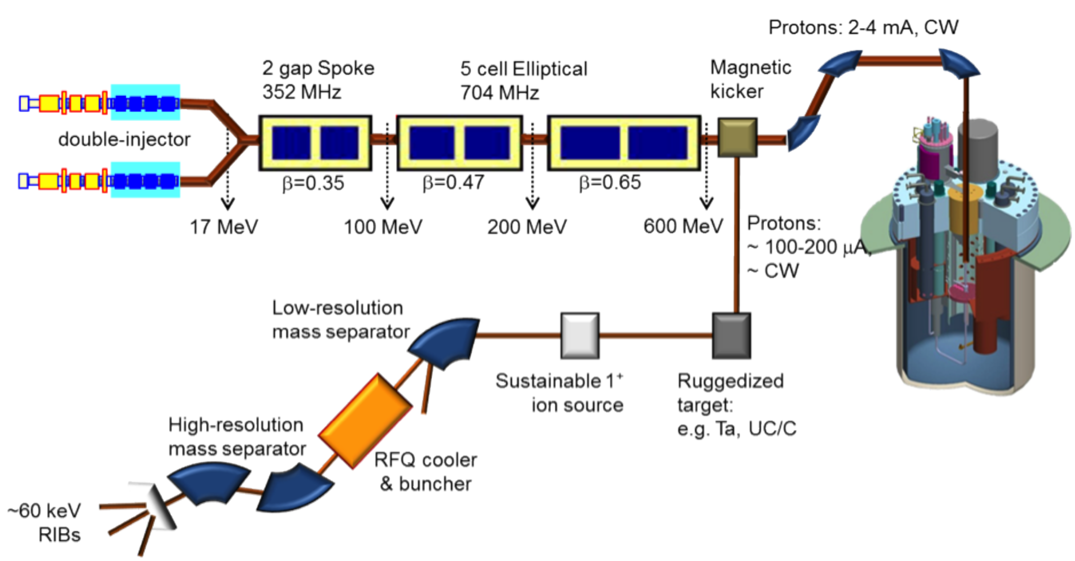


Figure 13. Schematic view of the MYRRHA and ISOL@MYRRHA project.

4.2. North America

As discussed in section 3, the two main RIB facilities in North America are the in-flight facility NSCL at MSU and the ISOL facility TRIUMF in Vancouver, Canada. Both have ambitious plans for the future which are described below.

4.2.1. FRIB at MSU The FRIB [33] driver will be a superconducting-RF linear accelerator that provides 400 kW for all beams with uranium accelerated to 200 MeV per nucleon and lighter ions with increasing energy. Provision will be made for space in the linac tunnel and shielding in the production area to allow upgrading the driver linac energy to 400 MeV per nucleon for uranium without significant interruption of the future science program. A future possibility would be to add a light ion injector in order to accelerate ^{3}He for ISOL production. Two ECR sources will be available to feed ions into the linac. The in-flight production target will be a rotating multi-slice graphite target. There will be a high momentum and angular acceptance three-stage fragment separator which will provide high beam purity and can be operated in several modes to optimize acceptance close or far from stability. The beam dump capable of stopping over 300 kW will be a rotating water-filled drum. Fast, stopped and reaccelerated beams will be provided, making FRIB the most comprehensive RIB facility in terms of energy range available. Three types of stoppers should be available: a linear gas stopper for heavier and medium mass beams, an original cyclotron gas stopper for light beams and a solid stopper for certain element at the highest intensities. These beams can be post-accelerated using the ReA3 superconducting linac which provides energy of 3 MeV/u and can be upgraded to 12 MeV/u. FRIB will make use of the current NSCL experimental areas with the possibility of expansion to double the available area. A schematic view of the FRIB facility is provided on fig. 14.

4.2.2. ARIEL at TRIUMF TRIUMF has recently embarked on the construction of ARIEL, the Advanced Rare Isotope Laboratory, with the goal to significantly expand the Rare Isotope Beam (RIB) program for Nuclear Physics and Astrophysics, Nuclear Medicine and Materials Science. The main idea is to turn TRIUMF into a multi-user RIB facility in order to increase the output of the various experimental devices and better satisfy the needs of the community. ARIEL will add electron-driven photo-fission of ISOL targets to the current proton induced spallation for the production of the rare isotopes that will be delivered to experiments at the existing ISAC facility. The goal of the ARIEL electron linac (e-linac) is to deliver 50-75 MeV, 10 mA cw electron beam as a driver for photo-fission of actinide targets to produce the RIB for nuclear physics, and materials science research. The e-linac parameters were chosen to reach rates up to 10^{14} fissions per second. The beam will be continuous to avoid thermal cycling on the target.

Combined with ISAC, ARIEL will support delivery of three simultaneous RIBs, up to two accelerated, new beam species and increased beam development capabilities. In

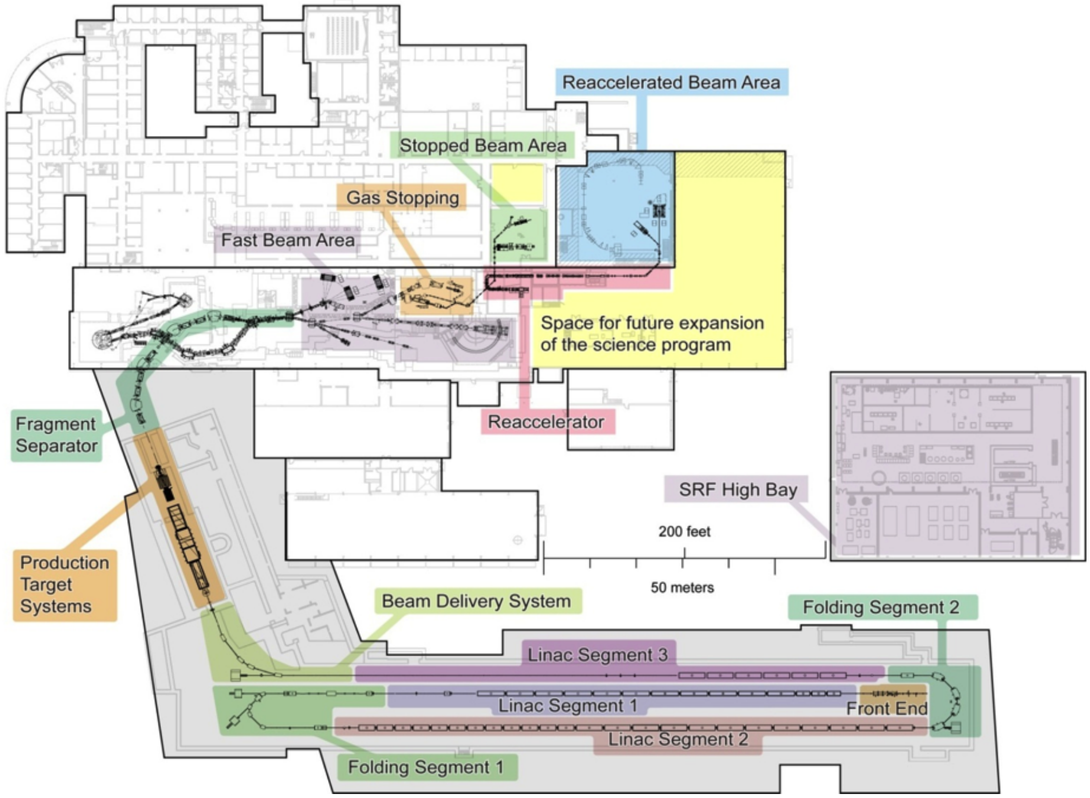


Figure 14. Schematic view of the planned FRIB project.

addition to the new Superconducting RF electron linac ARIEL will include a beamline to the targets for the electron beams; one new proton beamline from the 500 MeV cyclotron to the targets; two new high power target stations; mass separators and ion transport to the ISAC-I and ISAC-II accelerator complexes; a new building and a tunnel for the proton and electron beamlines. A schematic view of the planned facility is displayed on fig. 15.

4.3. Asia

The scientific opportunities afforded by radioactive beam facilities have motivated countries which up to now were not strongly involved in basic nuclear physics research to explore the possibilities of building ambitious and innovative RIB facilities. Therefore, in addition to the RIBF in Riken, Japan, which is already running since 2008 (see 3.1.1), Asia may soon boast additional large scale facilities. Plans are already well advanced in particularly in South Korea and also in China.

4.3.1. The KORIA project KoRIA [34] is planned as a multi-purpose accelerator facility for providing beams of exotic rare isotopes of various energies. The facility is driven by two accelerators: One is a high current proton cyclotron, the other being a high power superconducting linac for accelerating heavy ions up to Uranium. For

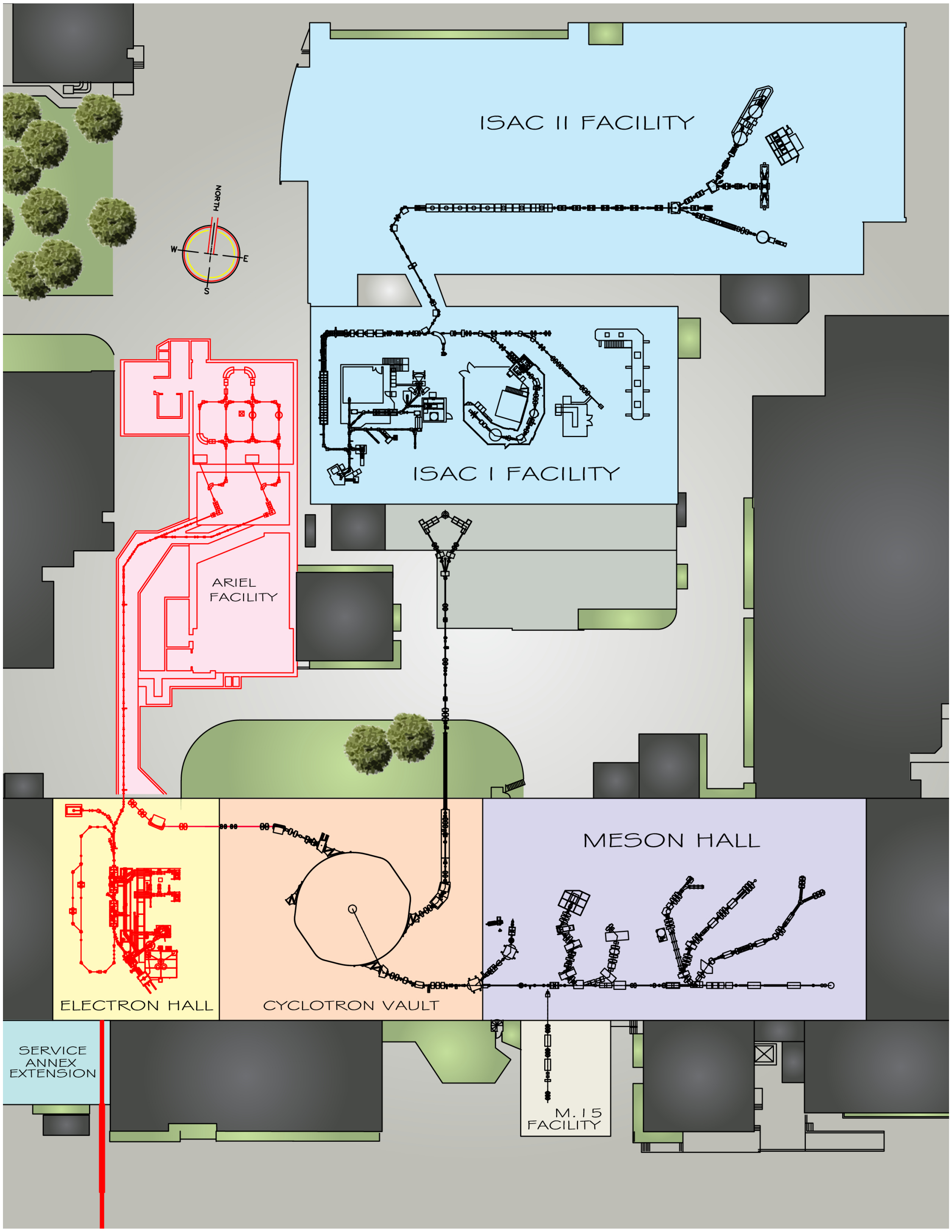


Figure 15. Schematic view of the ARIEL project

producing rare isotopes, both the ISOL method and the in-flight fragmentation method are used. The ISOL facility includes a 70 MeV, 1 mA cyclotron, a production target coupled to an ion source, a high resolution mass separator, a charge breeder and an 18 MeV/u superconducting ISOL linac. The in-flight facility includes a front end, a charge stripper, a 200 MeV/u superconducting linac, and a fragment separator. The ISOL facility can also be driven by the high energy linac, which can accelerate protons up to about 600 MeV. One of the most unique and innovative ideas in KoRIA is the combined scheme of ISOL + in-flight methods. This combination has a potential to generate more exotic rare isotopes that cannot be reached by using only ISOL or IFF. This new production method of rare isotope beams will significantly broaden the map of rare isotopes, which can open new opportunities for basic sciences. KoRIA has another unique feature of accelerating rare isotope beams at about 200 MeV/u by using the high energy linac as a post-accelerator, which cannot be obtained in any other facility.

4.3.2. The CARIF project, Beijing, China CARIF plans to use the research reactor at the Chinese atomic energy commission (CARR) as a driver to produce neutrons in order to induce fission in a UC_x target. Such a fission source would be as intense as that of EURISOL delivering 2 10^5 fission fragments per second. The beam manipulation and post acceleration stages of the facility are very similar to those of EURISOL including a post accelerating SC linac followed by a fragment separator to produce very neutron rich nuclei through secondary fragmentation of fission fragment beams such as ^{132}Sn.

5. Production reactions

The production of radioactive species can happen through a multitude of reaction classes. Tailored transfer- or fusion evaporation reactions can be used to reach specific isotopes and is to be employed at SPIRAL2 using heavy beams, as outlined in 4.1.2. However, the reaction types of more generic use, in order to cover sizeable parts of the Segré chart are fragmentation, spallation and fission. The underlying production cross section is of course a physical entity that is a function of the combined target and beam particles and the relative kinetic energy only, independent of whether a light driver beam impinges upon a thick target of heavy nuclei as for the ISOL-case or whether a heavy-ion beam is directed towards a thin, light production target as in the in-flight method. However, the latter gives rise to a much more direct relation between cross section and the observed ion rates than the ISOL method, where the beam energy varies within the thick target and the range of efficiencies listed in 6.4 can be hard to determine. A clear synergy thus exists between measuring production cross sections in-flight in order to optimise ISOL-facilities, as done in e.g. [35].

The facilities under construction and planning do focus considerably on optimising the conditions for fission fragments, both through fission reactions with low-energy spallation neutrons and the high-energy in-flight fission. The mass distributions, being dependant on the typical excitation energy of the fissioning nuclei, differ however drastically. E.g. the bench-mark nucleus ^{132}Sn is well produced in low-energy fission with the "classical" double-hump mass distribution whereas production of ^{140}Sn benefits from the flatter mass distribution in high-energy fission [36]. Fragmentation reactions on the other hand can be depicted as removal of nucleons in a statistical manner through quasi-free nucleon-nucleon collisions. These are, however, the prime tool for reaching towards the drip-lines in the light mass region as well as in secondary fragmentation of fission fragments.

6. ISOL method

Detailed descriptions of the ISOL method are given in [2, 4]. Here we briefly recall the basic ingredients needed for RIB production and concentrate on recent developments.

The different steps involved in an ISOL system include production of the radioactive isotopes, thermalization in a gas, liquid or solid catcher, ionization, extraction from the target-ion source system and acceleration, mass separation, cooling, charge-state breeding and post-acceleration. In this process the physical (e.g. production cross section, decay half life, ionization potential) and chemical (e.g. volatility, molecular formation probability) properties of the isotope and element of interest are essential and, are used to tailor the set-up in order to optimize the figures of merit given above. We will briefly describe the crucial elements and recent developments of this technique.

6.1. Target Ion Source Systems

The target ion source system (TISS) is the heart of an ISOL system and consist of target and catcher material, transfer line and ion sources.

- **Production Target and Catcher**
  Different production reactions are used depending on the isotope of interest (see section "Production reactions"). Intense primary beams impinge on different target materials and configurations. Thin targets (e.g. a few mg/cm^2 ^{58}Ni) are mainly used for light and heavy-ion fusion evaporation reactions while proton or neutron induced spallation, fragmentation and fission reactions mainly used thick targets (e.g. 500 gr/cm^2 uranium carbide). For completeness we mentioned that in some cases liquid target materials are used (e.g. liquid mercury targets) [8]. Parallel to the continuous efforts to increase the primary beam intensity of the driver accelerators developments of high-power target systems are pursuit. Both direct primary beam irradiation [37, 28, 30] as indirect production of intense neutron fluxes using a multi-MW liquid spallation targets [35] are investigated.
  In the thin-target approach the reaction products recoil from the target and are thermalized in a gas or solid catcher. In case of gas-catcher systems [38, 39, 40, 41] a pre-separator can be used to separate the primary beam from the secondary beam and the wanted from the unwanted isotopes to reduce the beam load in the gas cell (see further). In the thick-target approach the target serves at the same time as

catcher. Once the reaction products are stopped in the solid catcher, part of them diffuse from the target matrix and effuse towards the ion source through a transfer section. Part of the products are lost in the catcher matrix or diffuse in the walls of the target container. To speed up the diffusion and effusion process the TISS is heated to high temperatures (the target container can be heated up to 2300° C). Diffusion is governed by the diffusion properties of the atoms of interest in the target/catcher matrix. Effusion is controlled by a combination of factors: pumping through the pores of the target/cather material and through the connecting tube, sticking times when the atom hits a wall and diffusion properties of the atoms with respect to the wall material. In case the sticking time is long compared to the diffusion time of the atom inside the wall material, it will diffuse and eventually disappear in the walls. New developments to decrease the delay time using target materials based on e.g. carbon fibers [42] or nano particles [43, 44, 45] are currently being pursuit. Both approaches should result in more porous target material which is of interest to those element that suffer from long lingering times to the surface of the target material. In case of gas catcher systems, the reaction products can be thermalized as neutral atom or as ion. Two path are subsequently followed: the neutral atoms are transported with the gas flow to an ionization zone [46, 47] or the ions are, possibly with the help of electrical fields, transported towards the exit hole and extracted [38, 39, 40, 41].

- **Transfer from Catcher towards Ion Source**
  While thin targets are integrated in the ion source, this is not feasible with thick targets and a transfer tube between the target container and the ion source is needed (see Fig. 16). This tube is in general kept at a high temperature to avoid lingering of the atoms to the walls. The tube can also be used for purification. By cooling the tube only atoms from volatile elements will be transferred. The non-volatile elements will stick to the walls of the transfer tube where they will undergo radioactive decay and are lost [8]. Or a quartz tube can be inserted in the transfer tube which absorbs alkaline elements such as Rb [48].

- **Ion Source**
  Different ionization mechanisms are used to produce singly-charged positive or negative ions or multiply charged ions. Figure 17 shows the table of Mendelejev with a superimposed color code to indicate the different ion source types used nowadays at the ISOL-based radioactive ion beam facilities.
  Electron impact ionization whereby the atoms are bombarded with energetic electrons (10's of eV to keV) in a plasma environment is used in high-temperature plasma sources [49, 50] and Electron Cyclotron Resonance (ECR) [51] ion sources. Electron impact ionization is not element selective and can be used for literally every element potentially at the cost of strong isobaric contamination. That is why it is often used in combination with a cooled transfer tube to reduce the non-volatile elements (see Fig. 17). Most other ion sources used produce $Q=1^+$ charge states except ECR sources that can produce multiple charge states as well. This is

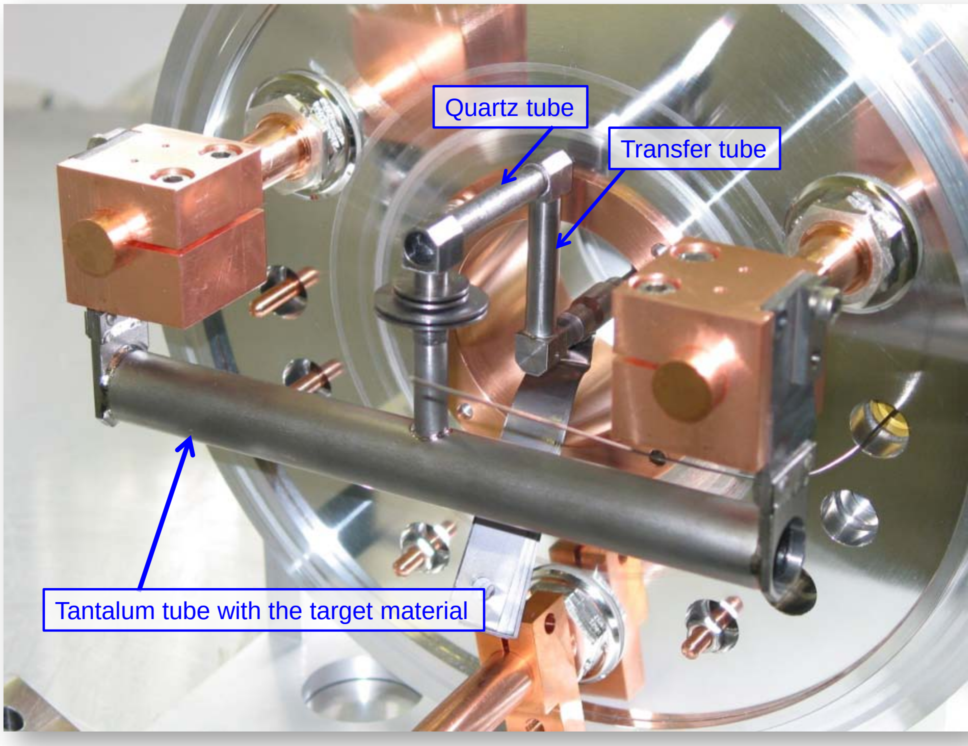


Figure 16. A photo of the ISOLDE target unit. The tantalum target container is ohmically heated. The radioactive atoms are transported to the ion source via the transfer tube. Part of the tube contains a quartz container that absorbs the rubidium atoms. This configuration was used to produce zinc beams using laser resonant ionization.

interesting for efficient and cost-effective post-acceleration and has been used on-line at the Louvain-la-Neuve (Belgium) and GANIL (France) radioactive ion beam facilities.

Surface ionization is a mechanism whereby an atom interacts with a heated surface. It can loose or gain an electron before leaving the surface as a positive or negative singly charged ion. This technique can be used efficiently for elements with $W_i < 7\,eV$ for the creation of positive ions (positive surface ionization) and with electron affinity $E_A > 1.5\,eV$ for the creation of negative ions (negative surface ionization). The probability to loose or gain an electron in this process depends exponentially on the temperature and the difference between the ionization potential respectively electron affinity and the workfunction of the surface. This makes surface ionization a very element selective method [8]. Surface ionization is mainly being implemented in a hot cavity, e.g. a tungsten tube heated to temperatures well above 2300 K [49].

A third ionization method implemented in ISOL systems is resonant photo ionization using tunable lasers [46]. During this process the atoms are stepwise

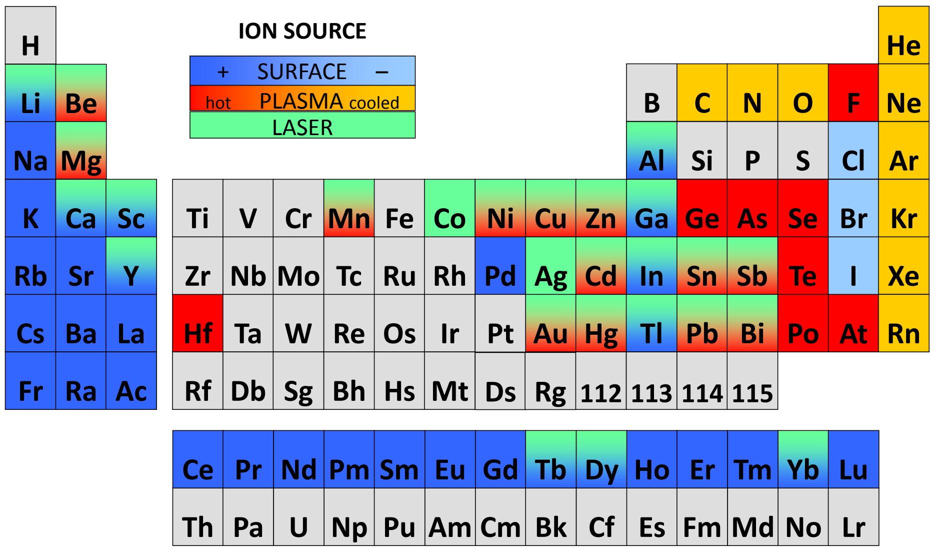


Figure 17. The table of Mendelejev showing with a color code the different type of ion sources used nowadays to produce radioactive ion beams. Surface ionization is used for the alkaline and alkaline-earth elements. The "plus" and "minus" sign indicate the creation of a positive respectively negative ion. Electron impact ionization (plasma sources with a "hot" or "cooled" transfer tube)can in principle be used for all elements but focusses on the volatile elements. Laser ionization can in principle also be used for all elements but efficient schemes are difficult to realize for the noble gases and some light elements with a high ionization potential.

excited by laser photons, leading finally to the continuum, to auto-ionizing states or to highly excited states close to the continuum. In the latter case the ionization step is achieved through infra-red irradiation, an electrical field or atomic collisions. The ionization process consists of typically two or three steps and, because of the resonant nature of most of these steps, is efficient and chemically selective, resulting in isobarically and, if the total spectral bandwidth is narrow enough, isomerically purified radioactive ion beams. Laser resonance ionization has been implemented in hot cavities (the so-called "resonant ionization laser ion source (RILIS)" approach) as well as gas cells ("in-gas cell laser ionization and spectrosocopy (IGLIS)") [61, 47, 59, 62]. The hot cavity approach is similar to the one used for surface ion sources and potentially suffers from isobaric contamination of alkaline or alkaline earth elements that are swiftly ionized through surface ionization. In the IGLIS approach the reaction products are thermalized and neutralized in the buffer gas (typically 0.5 to 1 bar of helium or argon). Together with the gas flow they are transported to the ionization zone where the laser irradiation takes place. It are mainly the surviving ions that limit the selectivity of the system. In order to increase the selectivity and the total spectral bandwidth of the system gas-jet based photo ionization is developed [55, 56, 57].

Finally, gas-catcher and ion-guide approaches make use of the ion survival probability of the reaction products when they are thermalized in a helium buffer gas. These ions are subsequently guided to the exit hole of the gas cell using gas flow (ion guide isotope separator on line (IGISOL) [40]) or using radio frequency (RF) and DC electrical fields (gas catcher [38, 39, 41]) and injected into the front-end of the isotope separator (see further).

6.2. Ion manipulation and A/Q separation

After escaping from the ion source or gas cell, the ions are either directly accelerated over a DC voltage (typically 40 to 60 kV) or manipulated in an radiofrequency ion guide or trap prior to further acceleration. This low-energy singly charged ion beam is subsequently send either directly to a dipole magnet for A/Q selection or undergoes one more manipulation stage in an RF-cooler buncher system. Depending on the quality of the ion beam, the ion optical system and the magnet high mass resolving powers, defined as R=M/△M, can be obtained. Typical values range from a few hundreds to a few thousands, the latter values are often accompanied with a lower transmission efficiency.

An potentially interesting case of ion manipulation is the "laser ion source trap" approach [52, 53]. In its original idea a RF ion guide is coupled to a hot cavity but it has now been extended to the gas-cell approach [56]. In the hot-cavity approach, the atoms diffuse from the hot cavity towards the zone in between the rods of the RF structure. In the gas-cell approach a cooled and homogenous gas jet is formed in between these rods. The atoms are then irradiated with counter propagating lasers, ionized and captured in the RF electrical fields. The photo ions are subsequently transported to the acceleration section of the isotope separator. This guarantees a beam of extreme purity as the unwanted ions (ions from surface ionization from the hot cavity or surviving ions from the gas cell) can be suppressed by electrical fields. Moreover, the ion beam can be cooled using buffer gas cooling [69, 70] resulting in a reduction of the phase space of the ion beam and thus in a better mass resolving power of the A/Q analysing system.

The technique of buffer gas cooling is also implemented in cooler-buncher devices. The low-energy ion beams is decelerated and captured in an RF-cooler-buncher using a combination of DC and RF electrical fields [69, 64] or in a Penning trap with combined magnetic and RF electrical fields[70]. Continuous accumulation of the ion beam and buffer-gas cooling forms cooled bunches of ions that are prepared for injection into a charge breeder (see further) or used to increase the peak-to-background ratio in collinear laser spectroscopy experiments [53].

6.3. Charge-State Breeding and Post-Acceleration

Post acceleration of singly charged positive and negative RIB is used at TRIUMF (Canada) and at HRIBF (US) respectively. Still it is useful to produce a multiple charge state ion beam before injection into an accelerator as the simplicity, efficiency and cost of the post-accelerator are directly related to the charge-state of the ions. Multiple-charged ions can be produced directly from the ion source (using ECR ion sources, see above) or using a charge-state breeder.

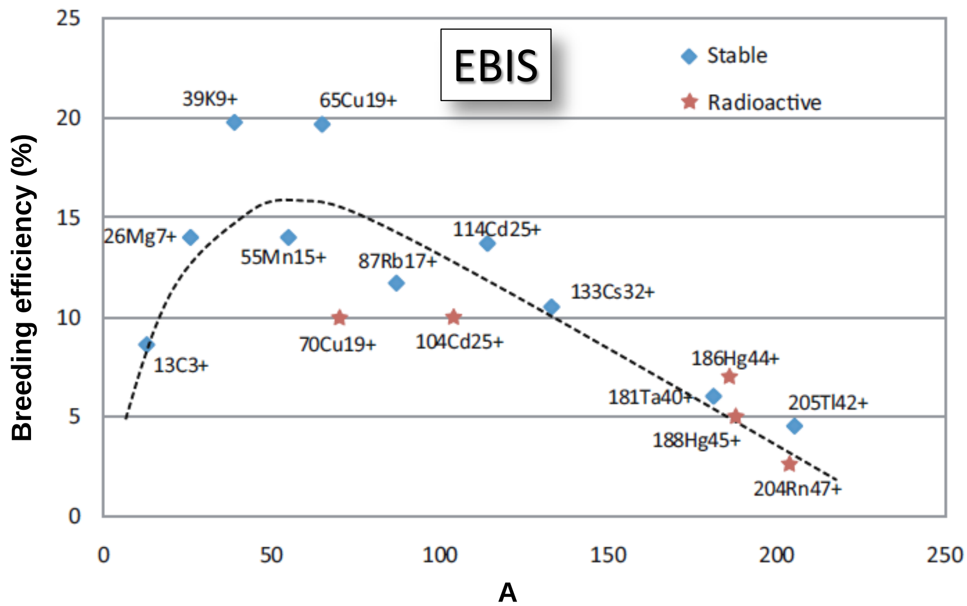
- **Charge-State Breeder**
  Charge-state breeders transform a singly charged ion beam into a multiple charged one. Two types of charge-state breeding ion sources are used: the Electron Beam Ion Source (EBIS) and the Electron Cyclotron Resonance (ECR) ion source. Both rely on the principle of intense bombardment of the ions with energetic electrons, with electron impact ionization yielding ions in higher charge states.
  Both systems have their pro's and con's as described in a recent comparative study [63]. Comparable charge-state breeding efficiencies have been reached (see Fig. 18) using similar breeding times varying between 20 and 200 ms depending on the required charge state and element of interest. While space-charge limitation have been reported for EBIS breeders for injected beam intensities in the $10^8 - 10^9\,pps$ region and above, mA beams can be extracted from ECR breeders. On the other hand the ECR approach gives a constant stable beam background from rest gas ionization on literally every A/Q value which might prevent the use of these system for weak intensity RIB. For example, the EBIS approach has produced secondary beams that were used in Coulomb excitation experiments with intensities around $1000\,pps$.
- **Post Acceleration**
  Different post accelerators are used for the production of energetic RIB. At TRIUMF (Canada) and HRIBF (US) the singly charged ions are accelerated directly and stripping is performed during the acceleration process. For all other projects, charge state breeders are required. Three type of accelerators are used for post acceleration: cyclotrons (Louvain-la-Neuve and GANIL), linear accelerators (ISOLDE and TRIUMF) and tandems (HRIBF). The combined charge-breeding and post-accelerator system have their characteristic timing and can also be used for further purification of the RIB [4]

6.4. Efficiencies

The intensity of the RIB (I) can be expressed in the following equation:

$$I \;=\; \sigma\, N_{target}\, \Phi \tag{1}$$

with σ being the reaction cross section (cm^2), N_{target} the number of target atoms per surface area (cm^{-2}) and Φ the primary beam intensity. Often to make a more general



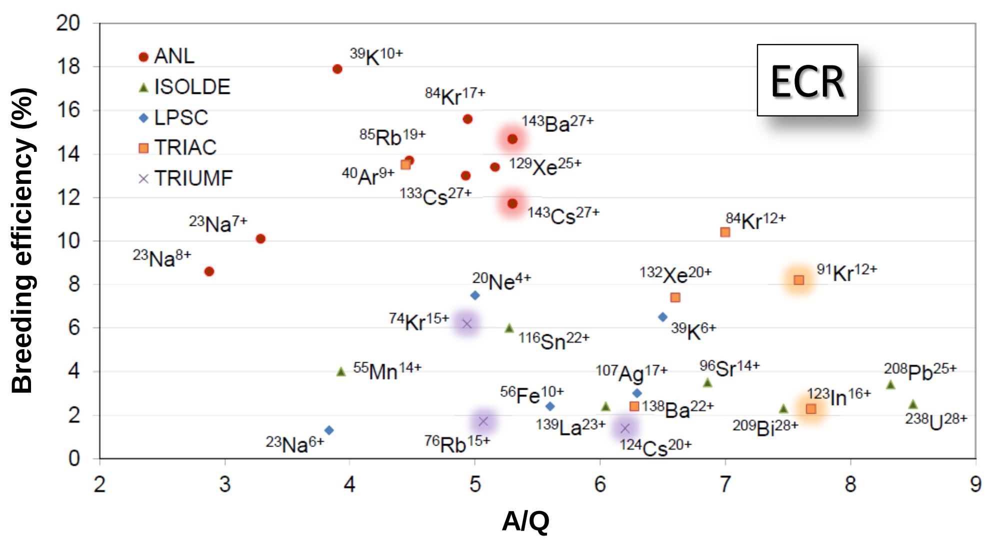


Figure 18. Charge-state breeding efficiencies for an EBIS (top) and ECR (bottom) system. Data were collected for different isotopes and charge states. Off-line and on-line data are reported. The EBIS data were collected at ISOLDE-CERN while the ECR data are a mixture from the experiments at different places. Adapted from [63].

Table 3. Partial efficiencies

ϵ_{delay}	probability of survival against radioactive decay during the time needed to extract the ion from the target-ion source system
ϵ_{ion}	ionization efficiency
ϵ_{trans}	efficiency of mass analysis and transport to the experimental set-up
$\epsilon_{cool-bunch}$	cooling and bunching efficiency
$\epsilon_{breeding}$	charge-state breeding efficiency
$\epsilon_{accelerator}$	efficiency of the post-accelerator
ϵ	total efficiency: the product of the above mentioned terms

but quantitative comparison between different beam-target combinations the luminosity (L), defined as

$$L \;=\; N_{target}\, \Phi \tag{2}$$

is used and expressed in units of $s^{-1}\, cm^{-2}$. Because of all the steps described in the previous paragraph the final intensity of the RIB will be reduced due to the different loss processes involved. One can express that final intensity of the secondary beam as

$$I \;=\; \sigma\, N_{target}\, \Phi\, \epsilon \tag{3}$$

with ϵ being the efficiency of the whole process. This efficiency is defined as the ratio of the final secondary beam intensity that arrives at the experimental set-up (I) versus the intensity of the reaction products produced in the primary reaction. It is a product of a series of partial efficiencies as given in Table 3:

$$\epsilon \;=\; \epsilon_{delay}\, \epsilon_{ion}\, \epsilon_{trans}\, \epsilon_{cool-bunch}\, \epsilon_{breeding}\, \epsilon_{accelerator} \tag{4}$$

The values for the different efficiencies depend strongly on the isotopes studied and the systems used. Typical numbers for ϵ_{trans} are over 80 %, for $\epsilon_{cool-bunch}$ between 20 and 60 %, for $\epsilon_{breeding}$ between 2 and 15 % and $\epsilon_{accelerator}$ over 90 %. It is not possible to give global numbers for ϵ_{delay} nor ϵ_{ion}. Delay efficiencies depend on the half life of the isotope and its physical and chemical properties. Delay times can be in the tens of milliseconds region in case of ion guides and gas catcher systems or tailored high-temperature target systems for swiftly diffusing and effusing elements, but can be as long as hours or more. Ionization efficiencies can reach over 50 % for noble gases using electron impact ionization, surface ion sources for elements with a low ionization potential or laser ion sources when efficient excitation and ionization steps are known. To quantify these numbers, let us take a look to the production of a $^{76}Zn(T_{1/2} = 5.7\, s)$ beam at 3 MeV/u at ISOLDE [73]. The production cross section for the $1\,GeV$ proton induced fission reaction on ^{238}U target is $0.3\,mbarn$ resulting in a primary production rate of $2\,10^8\,pps$ with a target thickness of $52\,g/cm^2$ and a proton-beam intensity of $1\,\mu A$. The $60\,keV$ beam intensity after mass separation was $\sim 10^7\,pps$ while the post-accelerated beam intensity on target was $\sim 10^5\,pps$. This results in the following efficiencies:

$$\epsilon_{delay} \times \epsilon_{ion} \times \epsilon_{trans} = 5\,\%$$
$$\epsilon_{cool-bunch} \times \epsilon_{breeding} \times \epsilon_{accelerator} = 1\,\%$$
$$\epsilon = 0.05\,\%$$

This small exercise makes it clear that the efficiency has to be optimized at every stage of the whole production process. A similar argument can be made concerning the selectivity and purity of the final RIB. Only a combination of different steps like e.g. a cooled transfer tube, laser or surface ionization, high-resolution A/Q analysis, can produce a beam with the desired degree of purity. There is room for constant improvement of the RIB intensity and quality, not only by increasing the primary beam intensity and develop high-power targets but also by tedious improvements of the efficiency and selectivity at all stages of the RIB production process.

6.5. Recent Developments

The beam intensity and thus also the figures of merit of the different steps in the ISOL process (see section 1) are constantly improved. This is done on the one hand side by increasing the primary beam intensity and developing targets that can stand this high-power deposition and on the other hand side by cross fertilization resulting from a close collaboration between the groups using the RIB for physics experiments and the RIB production teams.

The high-power thick-target development is pursuit for direct proton irradiation [37] but might reach its limit at proton beam-intensities reaching $100\,\mu$A. Multi-mega Watt liquid targets are developed to produce an intense neutron flux that irradiates a secondary target, similar to the pioneering work at the first ISOL facility (see Fig. 19 [32]. These developments are in synergy with other applications for multi-mega Watt target systems for spallation neutron sources or accelerator driven systems.

Examples of the cross fertilization are the laser ion source and production of isomeric beams that resulted from developments in the laser spectroscopy community [46] and the cooler-buncher developments resulting from mass measurement experiments using Penning traps and RF cooler-bunchers [70]. Laser ionization spectroscopy measurements are recently performed in the target-ion-source system with extreme sensitivity [60] evidencing truly cross fertilization. A continues effort is undertaken to find more optimized laser ionization schemes with respect to efficiency (more efficient excitation and ionization transitions) and to atomic level splitting through the hyperfine interaction (more effective production of isomeric beams). For the latter a reduction of the total

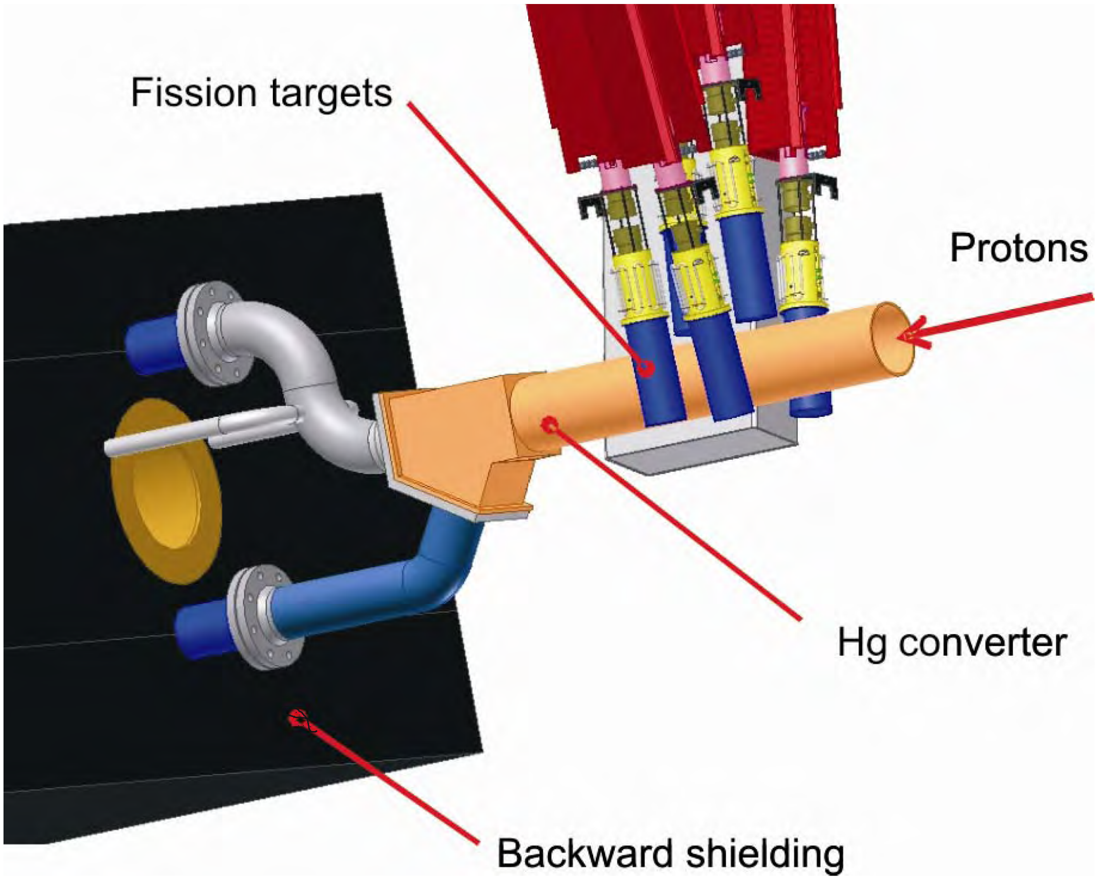


Figure 19. An artist's view of a multi-mega Watt liquid target configuration surrounded by several uranium loaded target-ion source systems.

spectral resolution of the system that is currently limited by high-temperature Doppler broadening (hot-cavity approach), laser-power broadening or pressure broadening (in-gas-cell approach) should be accomplished. Recent developments in laser ionization focusses on the LIST mode [52] as well as the in-gas jet laser ionization spectroscopy approach [56, 57].

The implementation of new target materials based on nanostructured materials and that have a higher degree of porosity, thereby reducing the delay times substantially are currently underway [43, 44]. These developments will no doubt be instrumental for the production of more intense beams of the shortest lived isotopes. Another interesting aspect here is the fact that Monte-Carlo simulations are recently being implemented to improve our understanding of the target-ion source system[35]. These simulations will guide the design of future target configurations with reduced delay times and optimized time structure.

Also chemistry will continue to play a key role in these developments. For example, finding more volatile molecules of refractory-type elements might help including new regions of the nuclear chart in the ISOL beam portfolio. Molecular formation in a high-temperature environment (hot chemistry), as used e.g. to produce pure beams of tin

[42] or selenium [65] isotopes, to produce pure RIB will continue to play a key role in these developments.

New techniques like the multi-reflection time-of-flight system, currently used at e.g. ISOLDE to obtain a pre-purification of the RIB for mass measurements in a Penning trap [53], might be implemented in the ISOL production process as an efficient extra step to increase the purity of the RIB.

7. In-flight method

In the in-flight method, the constituting elements are a heavy-ion accelerator complex, a production target followed by a separation device and optional further beam manipulation devices like range bunchers, stopping cells or storage rings. The intensity of radioactive ion beams through in-flight production and separation can, as for the ISOL method, be expressed straightforwardly in the same terms as formula 3. However, the efficiency factor ϵ differ drastically. In the terms defined in table 3, only ϵ_{trans} remains, in specific cases factorized with an ϵ_{charge} for the actual charge state of the radioactive species. This "chemical blindness", i.e. the possibility of producing radioactive ions regardless of their atomic properties constitutes a major advantage of the in-flight method. However, the ϵ_{trans} depends on many factors; in contrast to the ISOL method where the created nuclei are at rest, the kinematical conditions of the production reaction determine the emittance of the secondary beams that have to be transported through the separation device. Through the intermediate or high energy inherent from the method, the decay losses are typically negligible and thus ϵ_{delay} approaches unity.

7.1. Heavy-ion accelerator

RIB facilities using the in-flight method are or will be operating using all kind of heavy-ion accelerators, all with their own advantages and drawbacks. The primary beam properties are directly translated into the secondary beam properties and determines largely intensity and energy, as a function of production target thickness and the resulting reaction kinematic folded with the acceptance of the separation device. The first implementation at the BEVALAC was thus using a synchrotron, as well as later the FRS at GSI, whereas isotope separation devices at e.g. MSU, RIKEN and GANIL were added to cyclotron facilities at intermediate energies. Also the forthcoming and newly started second-generation facilities like RIBF, FRIB and FAIR diverge in terms of heavy-ion accelerator technology, as outlined in section 4.1.

The coupled cyclotron complex at RIBF can e.g. deliver a ^{238}U beam with 1 pμA at 345 MeV/u, the planned FRIB LINAC will deliver up to 8 pμA at 210 MeV/u whereas the capability of the forthcoming SIS100 at FAIR will be $3 \cdot 10^{11}$ ions/s, corresponds to 50 pnA. However, synchrotrons generally allow for higher energy beams, e.g. 1.5 GeV/u for ^{238}U with the SIS100, as well as flexibility in extraction schemes; slow extraction over several seconds can be employed to approach a CW beam, fast extraction in turn allows for a well-defined production time of the secondary beam for injection in a storage ring. Furthermore, larger target thicknesses can be employed and the Lorentz boost at relativistic energies increases the transmission in the separation device.

7.2. Production target

The requirements on the production targets for secondary beams differ with the beam properties. The beam power can reach several hundred kW, as in the case of FRIB, and a sizable fraction is deposited in the target through Bethe-Bloch energy loss, entailing a substantial heat deposit that needs to be cooled away. Instantaneous beam loads by e.g. 10^{12} ^{238}U ions extracted within 60 ns [28] will be encountered at the FAIR Super-FRS production target when operating in fast extraction mode, adapted to subsequent injection in the storage rings. The induced beam load can locally heat the target material to temperatures exceeding 10^{12} K [74] and requires rotating-wheel targets of e.g. graphite in order to distribute and dissipate the heat load by radiation [75].

7.3. Separation stages

An in-flight separator has typically an $B\rho$-selection (approximately corresponding to A/Q if velocities do not differ largely) in several dipole stages with an optional degrader stage in between, complemented with higher-order ion-optical devices. The degrader serves to introduce a Z-dependent energy loss, and thus lifts the degeneracy in terms of $B\rho$ e.g. when several nuclei with the same A/Q are produced, permitting a clean production of the wanted species. Detailed ion-optical considerations on in-flight separators and the importance of higher-order corrections can be found in e.g. [77]. In-flight separators adapted to higher beam intensities like the forthcoming Super-FRS [78] and the corresponding next-generation devices at RIBF and FRIB (the latter shown in Fig. 20) have further separation stages, including a pre-separator in order to safely distinguish the primary beam from the secondary species and dump it in a controlled manner in dedicated beam catchers. Furthermore, these devices are optimised for the "hot" fission fragment having a sizeable transversal momentum from the production reaction, requiring large acceptances of all involved ion-optical elements, making superconducting solutions the choice for most components. Acceptance parameters for the Super-FRS are listed in table 4

Table 4. Acceptance parameters for the Super-FRS. From [75]

$\epsilon_x = \epsilon_y$	40 π mm mrad
Φ_x	$\pm$ 40 mrad
Φ_y	$\pm$ 20 mrad
$\Delta p/p$	$\pm$ 2.5%
$B\rho_{max}$	20 Tm

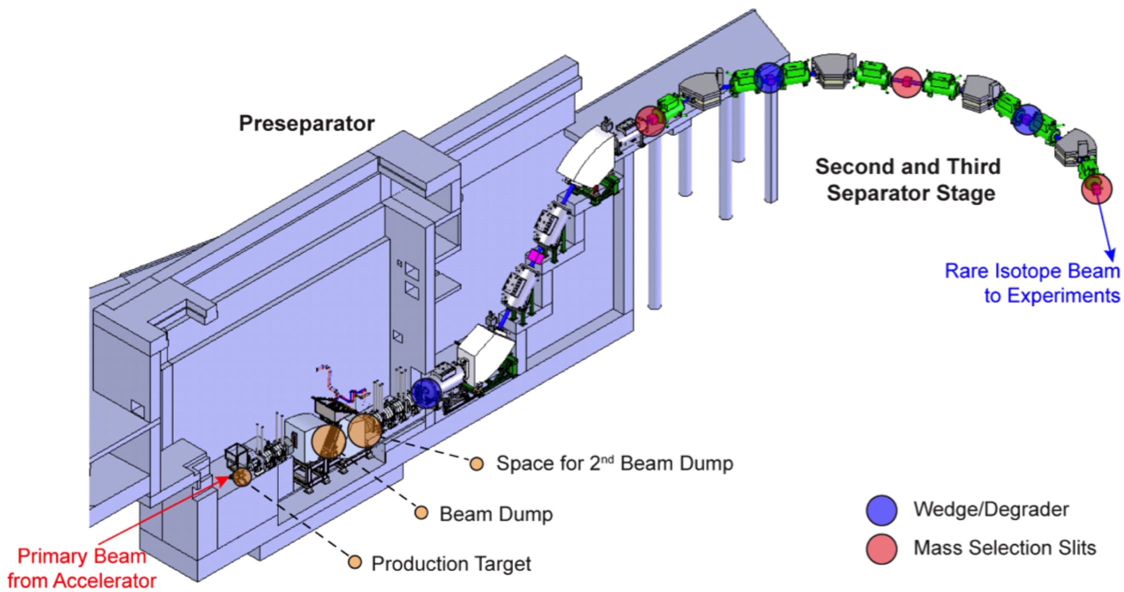


Figure 20. The foreseen separator at FRIB [76].

7.3.1. Operational modes The in-flight separation devices having several dipole and higher-order stages can be operated in different modes. The **achromatic mode** serves for separation and transport of the radioactive ions to the final focal plane, optimized for accepting the momentum spread inherent from the production process. The **energy-loss mode** utilizes the first stages of the device for separation and tagging of the radioactive species, a secondary reaction target is then inserted in the middle focal plane and the downstream part is used as a high-resolution separator for spectroscopy of the longitudinal momentum of the ions created in the reaction, where this momentum is translated in a spatial displacement. This can be employed for determination of single-nucleon spectroscopic factors through the residual momentum of the created nucleus and has been used extensively in light nuclei, see eg. [79, 80].

7.4. Ion tracking and isotope identification

The in-flight separation at high energies permits tracking of the ions at several locations in order to determine their characteristics through combining detectors that yield velocity, ΔE and spatial information. These are readily converted into Z and A/Z information by using the known rigidity $B\rho$ of the separation device and thus give a direct identification of the species and the discovery of new isotopes. Figure 21 shows an identification plot from [81] where the knowledge of half-lives in the r-process region could be extended to 18 new isotopes. Identification sensitivities of a few atoms per day have been reached, corresponding to production cross sections below the picobarn region. One example here is the production and identification of ^{44}Si at the NSCL using an ^{48}Ca beam, requiring a net pickup of two neutrons [82] or the related discoveries of ^{40}Mg and ^{42}Al [83].

The tracking detectors operate under harsh conditions concerning rates and radiation damage depending on where in the separation stages they are operated. Beam profile monitors like wire grids and intensity monitors like secondary electron transmission detectors are used as integrative measuring devices, fast scintillators to provide time and energy-loss information after the first separation. For precise determination of the position of secondary beams in an ion-by-ion manner, MWPCs and high-rate time-projection chambers (TPCs) are being employed, going towards GEM-based systems for next-generation facilities [84].

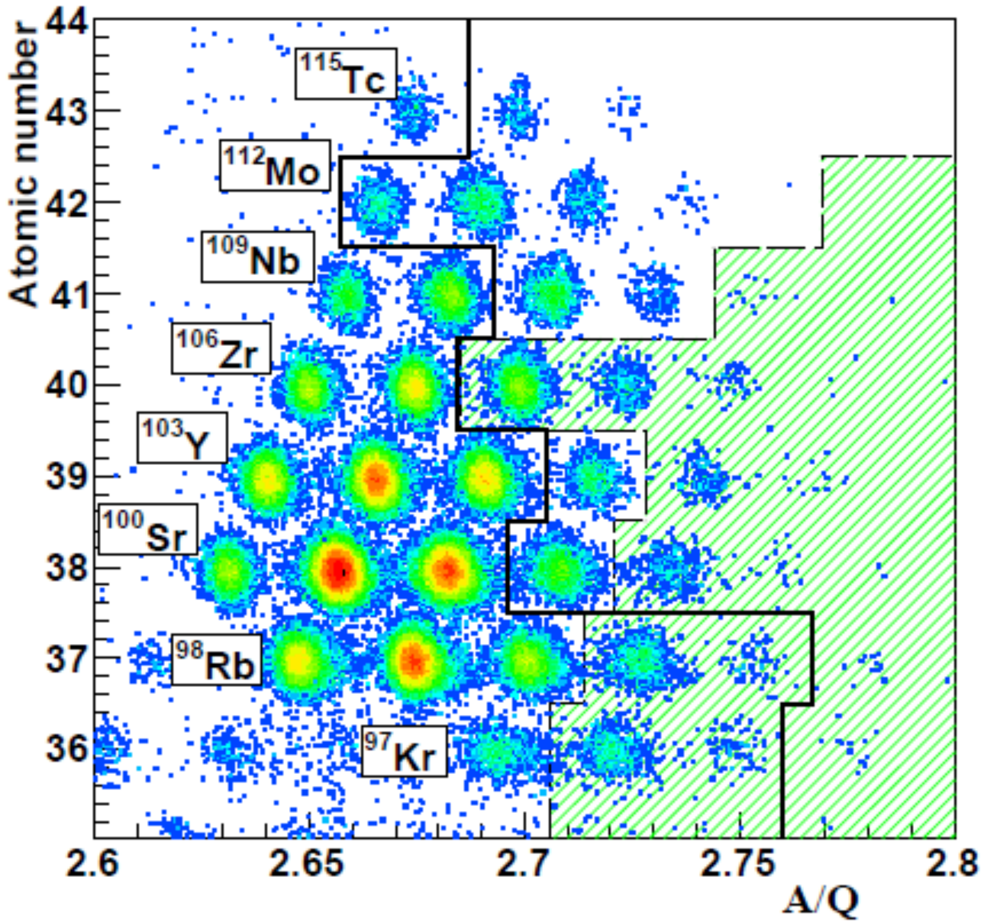


Figure 21. Identification plot depicting charge versus mass-over-charge for neutron-rich Kr to Tc isotopes, extending the known half-lives in the r-process region. From [81].

7.5. Beam manipulation

The beam properties stemming from the production reaction can be adapted to other classes of experiments than high- and intermediate reaction studies. To create low-energy beams in the straight-forward manner of using a degrader deteriorates the emittance severely, since the transverse momentum spread remains and any further focussing is complicated by the distribution of charge states after degrading. To alleviate this, range-bunching devices can be used where a dispersive stage spatially separates the different momenta, followed by a degrader stage shaped to compensate these differences [85, 86] as outlined in fig. 22. Such a range buncher can then be followed by a gas-filled stopping cell [87] as described in [72, 39, 38, 41] or inverted cyclotron [88].

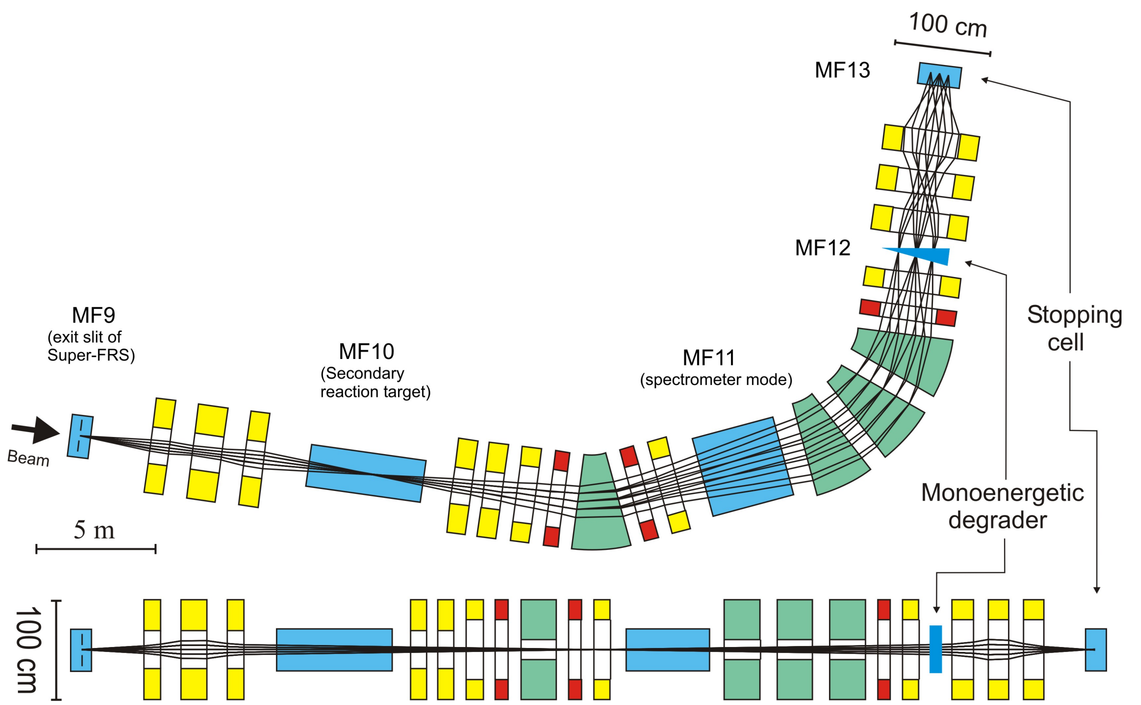


Figure 22. Layout of the energy buncher foreseen for the Super-FRS low-energy branch [89]

The reaction products can also be thermalized as neutral atoms that are subsequently transported with the gas flow to a zone where they are resonantly laser ionized and extracted from the cell, the so-called IGLIS approach (see above) [46, 47]. The extracted low-energy ions are then available for the full range of techniques already existing at ISOL-facilities. Recently resonant laser ionization in gas-cell systems has been extended to ionization in gas-jets and will allow for unprecedented laser spectrosocpy studies as well as new (isomeric) RIB production [56] (see Fig. 23).

7.6. Storage rings

In particular the pulsed secondary beams available from synchrotron-based in-flight facilities are suitable for injection, beam manipulation and experiments in storage rings, however, not limited to those. Through fast extraction of the primary ion beam, well-defined secondary ion bunches can be obtained that can be injected into a storage

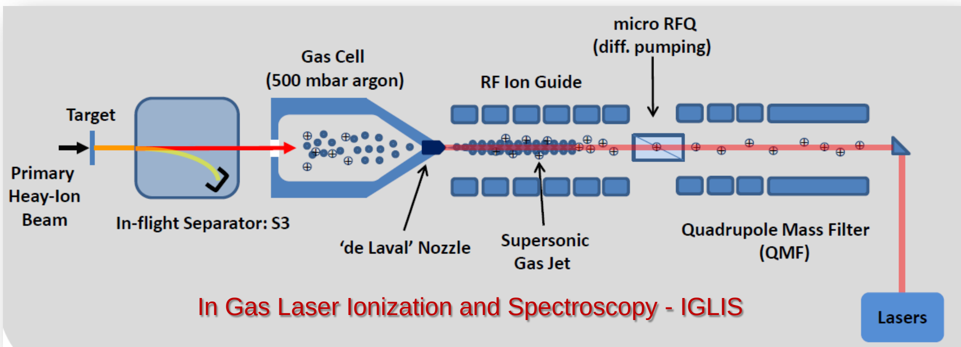


Figure 23. A buffer gas cell is coupled to the focal plane of an in-flight separator to thermalize the reaction products from a heavy-ion induced fusion evaporation reaction. This is followed by gas-jet formation and laser resonant ionization using counter propagating laser beams. The photo ions are captured in an RF Ion Guide and injected into a mass analyzing system and followed by radioactive detection of the isotopes of interest. The system will be used to perform laser spectroscopy measurements of the medium heavy and heavy isotopes as well as to produce low-energy ion beams of refractory-type elements.

ring. For precision experiments though, further cooling of the beam is necessary. A first step of stochastic cooling is then typically followed by electron cooling in order to reach $\Delta p/p \sim 10^4$ or better. Additional laser cooling can as well be employed. The method of storing high-energy RIBs has been most successful in measuring masses through Schottky mass spectrometry [90, 53] on electron-cooled beams, a further leap is underway with the advent of isochronous storage of "hot" beams where the storage ring is operated at transition energy.

The utilisation of storage rings is however not limited to synchrotron-based RIB facilities; an example is the isochronous Rare RI Ring currently under construction at RIBF where the injection is triggered on an ion-by-ion basis by upstreams identification in particle detectors. In this manner, an efficiency approaching 100% can be reached even for the CW beams. Another example is the TSR@ISOLDE project which aims at implementing the existing Test Storage Ring from MPI Heidelberg at the

CERN-ISOLDE facility. The post-accelerated ISOL beams from REX-ISOLDE, upgraded within the HIE-ISOLDE programme, can then be injected through multi-turn injection into the ring for further cooling and a multitude of experiments [91]. The scientific potential of stored, low-energy exotic beams can as well be exploited in the CRYRING@ESR project where the cooled beams from the existing ESR storage ring at GSI will be decelerated and transferred to the forthcoming CRYRING, where the high-energy production method and subsequent deceleration gives access also to highly-charged ions also at energies relevant for investigating reactions in nuclear astrophysics.

8. Conclusions and outlook

Physics using radioactive beams has in the last decades transformed nuclear science, evolving from a fringe activity to one of the main lines of development. This is an evolution purely driven by the scientific potential of RIBs, having been accompanied by a matching development of the associated instrumentation as e.g. highlighted in several contributions to these proceedings. Radioactive beams became the workhorse for nuclear structure and reaction research and are now an essential part of the experimental portfolio in nuclear astrophysics as well. The large variety of RIB allows fundamental interaction, condensed matter atomic physics and life-science studies to choose isotopes that have ideal properties for their respective experiments. Moreover, intense radioactive beam production allows the development of innovative radioisotopes for medical applications. A special feature of the field is the close connection between the production, separation etc. stages and the final conditions for experiments, necessitating a integrated view from the involved experimenters in order to fully exhaust the possibilities of the facility.

The future perspectives for RIB science are excellent, not only through the quantitative improvements concerning e.g. the intensities, beam energies and number of beam species gradually becoming available through the ambitious construction and upgrade plans worldwide. An equally important qualitative development is underway, through e.g. beam handling, cooling and purification. Together, these developments are paving the way for decades of front-line science to come.

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