REVIEW OF ACCELERATORS FOR RADIOACTIVE BEAMS

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Abstract

The past two decades have seen extraordinarily rapid development of radioactive beam physics throughout the world. The important scientific advances have stemmed from a large number of facilities, which incorporate diverse types of accelerators: Cyclotrons, Synchrotrons and LINACs. Previously existing stable beam machines have been adapted to produce rare isotope beams, and dedicated facilities have come on-line. This talk gives an overview of the present installations highlighting their complementary nature. Today, the Nuclear Physics community is actively proposing and starting to construct a new generation of facilities offering larger intensities and higher energies. RIBF (Japan) and FAIR (Germany) which make use of the projectile fragmentation technique are described. The path towards EURISOL, the ultimate European ISOL facility is presented in the light of the construction of “intermediate” generation facilities SPIRAL2, HIE ISOLDE, and SPES, and results from the ongoing EURISOL Design Study.

INTRODUCTION: IN-FLIGHT AND ISOL METHODS FOR RADIOACTIVE BEAM PRODUCTION

The advent of Radioactive Ion Beam (RIB) facilities has given a new impetus to nuclear structure physics during the last two decades. It has led to several major unexpected discoveries such as the existence of dilute neutron matter in halo nuclei, the modification of shell structure and magic numbers far from stability, proton and two-proton radioactivity, new regions of shape coexistence. These discoveries have been made possible by a global network of complementary facilities exploiting both the in-flight and ISOL production techniques.

The main components of in-flight facilities are a high energy (E>100A MeV) heavy ion accelerator followed by a fragment separator. The RIBs are produced by fragmentation of the projectiles on a thin target and the radioactive nuclei created are separated and selected in-flight. The secondary beam has a velocity close to the beam velocity so no post accelerator is needed; however the beam qualities are poor, rendering precision experiments often difficult to perform. In the ISOL technique an intense primary beam, generally of light hadrons, impinges on a thick target. After diffusion and effusion the radioactive nuclei are mass selected, ionized, and re-accelerated in a post accelerator. Excellent beam qualities result albeit at low energies and for a limited range of species due to chemical and transport properties of the nuclei in the targets. The two methods are schematically illustrated on fig. 1. Their evident complementary nature implies that both have been vigorously developed. In-Flight facilities will be described in the next section, followed by ISOL installations.

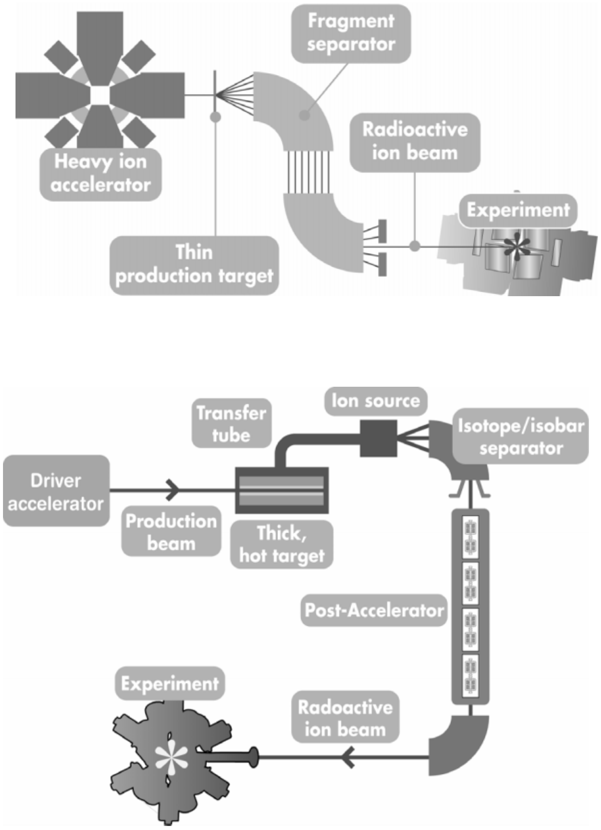

Fig. 1: Schematic view of the in-flight (top) and ISOL (bottom) production mechanisms for radioactive beams

IN-FLIGHT FACILITIES

There are currently four main fragmentation facilities in the world: GANIL and GSI in Europe, NSCL/MSU in the US and RIKEN in Japan. They are all based on Heavy Ion accelerators which preceded the RIB era and they operate in complementary energy domains. The GANIL driver consists of two separated sector room temperature cyclotrons which produce heavy ions from C to Ar up to 100A MeV and can accelerate masses up to U at 25A MeV. Large primary intensities (several μA) can be delivered but the final RIB intensities are limited by the weak forward focusing at intermediate energies and the limited acceptance of the beam lines which were not optimized for RIB transmission.

These problems are alleviated at MSU 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 2A GeV, 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 1.

Table 1: First generation in-flight facilities

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

Two second generation in-flight facilities, RIBF in RIKEN and FAIR in Darmstadt are being constructed. RIBF boasts a new high-power heavy ion booster 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 350A MeV is obtained up to the heaviest ions. The first phase of RIBF has started to operate in 2007, delivering beams of Al and U, albeit for the moment at much lower intensities that the design value of 1 particle µA. The radioactive beams will be separated by a new superconducting fragment separator BigRIPS. Major new experimental devices will be constructed including 3 spectrometers (ZDS, SAMURAI and SHARAQ) and an electron-RIB (e-RI ring) scattering apparatus.

The next generation European projectile fragmentation facility is called FAIR [1], and will be built at the current GSI location. The philosophy parallels that of the current installation, but the performances will be increased by orders of magnitude. Primary beams of 10^{12} ^{238}U^{28+} at 1.5-2 AGeV will be delivered, corresponding to an increase in intensity of 2 to 3 orders of magnitude with respect to the current facility. A vastly improved fragment separator, the super FRS, will deliver a broad range of radioactive beams with up to a factor 10^4 improvement in intensity. 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 R3B detector will comprise a spectrometer along with highly efficient charged particle, neutron and gamma-ray arrays for complete kinematic coverage. An internal gas-jet target installed in the NESR will allow for direct reaction studies 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 main characteristics of these second generation facilities are summarized in table 2 and fig.2 displays a schematic view of the FAIR facility

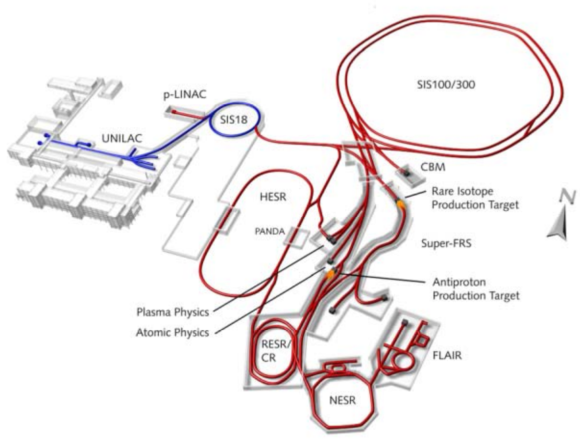

Fig. 2: schematic view of the FAIR facility

Table 2: Second generation fragmentation facilities

Facility	Location	Driver	Primary Energy	Typical intensity	Fragment separator
RIBF RIKEN	Tokyo, Japan	3 Ring Cyclotrons	350A MeV	5 10^{12} pps ^{238}U	BigRIPS
FAIR	Darmstadt, Germany	SIS 100 Synchrotron	Up to 2A GeV	10^{12} ppspill ^{238}U	Super FRS

ISOL FACILITIES AND THE ROADMAP FOR EURISOL

Four major ISOL facilities proposing a large variety of beams can be counted in the world today, CERN-ISOLDE and GANIL-SPIRAL in Europe and Oak Ridge-HRIBF and TRIUMF in North America. The oldest, which is the precursor of ISOL installations worldwide, is ISOLDE located at CERN. Using 1.4 GeV incident protons from the PS booster, an unmatched variety of beams is offered, and recently post acceleration with the REX linear accelerator up to a moderate energy of 3A MeV is available, which is sufficient to perform Coulomb excitation and some transfer reactions. SPIRAL makes use of the GANIL coupled cyclotrons as driver, while post acceleration is provided by the CIME cyclotron. The final energy which can reach 25A MeV is the highest of today's ISOL facilities. Over the past decade the ISAC facility at the TRIUMF laboratory in Vancouver, Canada, using a 500 MeV proton cyclotron as a driver, has evolved into a full fledged RIB facility. The post accelerator, composed of an RFQ, a DTL followed by a Superconducting LINAC can accelerate the radioactive ions up to 5A MeV. Ambitious future plans for the next decade include adding a 50 MeV electron LINAC as a second driver in order to enhance the multi-user capability of the installation.

Finally the HRIBF facility at Oak Ridge National Laboratory in Tennessee, uses a 50 MeV cyclotron as driver and a large 20 MV electrostatic Tandem as post accelerator, necessitating the injection of negative ions. The characteristics of the four main current ISOL facilities are summarized in table 3.

Table 3: Current ISOL facilities

Facility	Location	Driver	Post accelerator	Final energy	Main beams available
REX-ISOLDE	CERN, Geneva	PS booster; 1.4 GeV protons	REX LINAC	0.3A-3A MeV	Large variety including fission frag.
SPIRAL	Caen, France	GANIL coupled cyclotrons	CIME cyclotron	2.7A-25A MeV	He, Ne, Ar, Kr, N, O, F
TRIUMF/ISAC	Vancouver, Canada	500 MeV proton cyclotron	RFQ + SC LINAC	0.2 – 5A MeV	Large variety up to Lu
ORNL/HRIBF	Oak Ridge, Tn	ORIC 50 MeV protons	25 MV Tandem	~10A MeV	Light ions and fission frag.

The European roadmap [2] calls for the eventual construction of an "ultimate" ISOL facility called EURISOL. The concept is extremely challenging, and its implementation passes through the construction of so-called intermediate generation facilities, which will constitute a unique testing ground for many technical solutions which will be carried over to EURISOL. Three such facilities are at various stages of construction or planning. The most ambitious is SPIRAL2, located at GANIL, for which construction of the driver accelerator has already started. SPIRAL 2 will have a superconducting LINAC driver (fig. 3) capable of accelerating 5mA of deuterons up to 40 MeV or Heavy Ions with A/Q =3 up to 14.5A MeV. These high intensity stable beams can be focused directly on a reaction target for use in a dedicated experimental area or sent into a production cave equipped with a rotating Carbon converter and an UCx target for the production of up to 10^{14} fission fragments per second. After mass selection and charge breeding, post-acceleration will be performed by the current CIME cyclotron before injection into the GANIL beam lines.

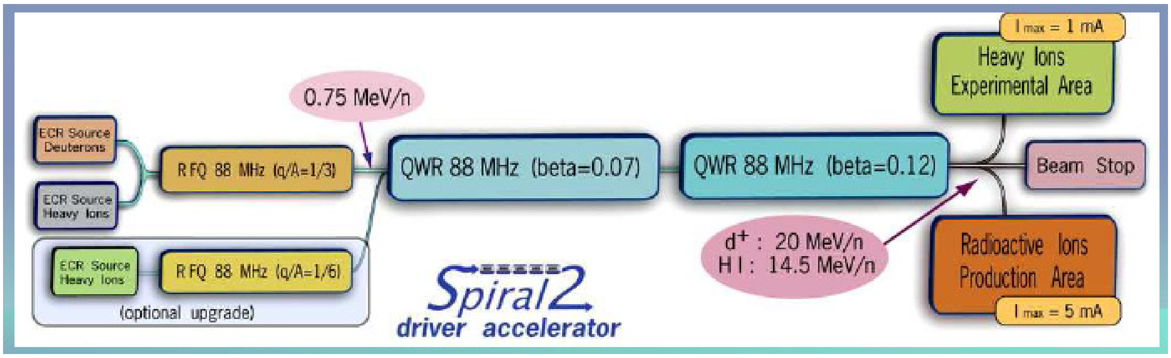

Fig 3: block diagram of the LINAG (LINear Accelerator for Ganil) accelerator of SPIRAL2

HIE ISOLDE is a major upgrade of the current ISOLDE facility at CERN with three main objectives:

- Energy upgrade of the REX post accelerator and increase of the current capacity. The energy upgrade will proceed in three stages, first to 5.5A MeV, then to 10A MeV and finally the possibility to obtain very low energies.
- Intensity upgrade of the proton driver linked to PS booster improvements. 10^{13} fissions per second will be attained.
- Increase of the beam quality, in particular smaller emittance and better mass resolution.

SPES is a project sited at LNL Legnaro driven by a 40 MeV commercial proton cyclotron. A multi-foil UCx target is envisaged, leading to the production of 10^{13} fissions per second. Post-acceleration will be performed with the current LNL equipment including an RFQ and the ALPI heavy ion LINAC. According to current plans, all three projects should come on-line around 2012, with a staging of the performances. Their characteristics are summarized in table 4.

Table 4: Main characteristics of European "Intermediate generation" ISOL Facilities and of EURISOL

Facility	Driver	Beam Power	Number of fissions	Post-accelerator	Energy
SPIRAL-II GANIL	LINAC Deuterons 40 MeV HI 15A MeV	200 kW	>5 10^{13}	Cyclotron CIME	2A-25A MeV
HIE-ISOLDE CERN	PS booster Protons 1.4 GeV	10 kW	10^{13}	Linac REX	0.8A–10A MeV
SPES Legnaro	Commercial cyclotron p 40 MeV	8kW	10^{13} +spallation	Linac ALPI	10A MeV
EURISOL	Superconducting CW LINAC p 1GeV	5 MW	>10^{15} +spallation	Superconducting LINAC	150A MeV

A baseline concept for the next generation ISOL facility was devised in the European EURISOL RTD program which ran between 2000 and 2004, and for which the detailed conclusions can be found in [3]. A schematic drawing of the concept is shown on fig. 4. The driver is a 1 GeV Continuous Wave superconducting LINAC which can accelerate a proton beam with an intensity of 5mA corresponding to 5MW power. Capability for accelerating ^{3}He, deuterons and A/Q=2 ions, will be included.

The proton beam will impinge on a liquid Hg converter to produce a copious amount of neutrons in order to induce close to 10^{16} fissions per second in a UC_X target. Thanks to an original beam splitting system based on magnetic stripping, a small fraction of the beam (100 kW) will impinge directly on spallation targets. After ionization, beams will be purified and reaccelerated by a superconducting LINAC with minimum beam losses. The design of the first stages of the LINAC is similar to that of the SPIRAL2 driver. The final energy of the RIB can be adjusted continuously from rest to 150A MeV for ^{132}Sn. EURISOL is designed to provide a large energy range for a wide selection of isotopes which will allow physicists to combine a unprecedented variety of complementary probes for the study of exotic nuclei.

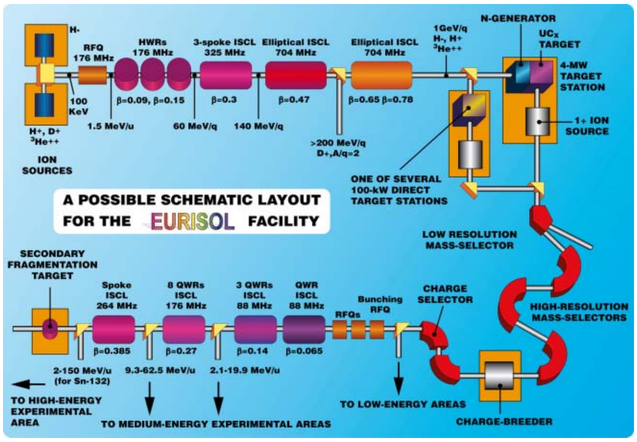

Fig. 4: Schematic view of EURISOL

The design of such an ambitious facility represents a huge endeavor which calls for combining unique expertise from many laboratories and institutions throughout Europe and beyond, which is the goal of the EURISOL Design Study. The study was initiated by a call to all European laboratories involved in RIB physics to contribute their expertise to the design of EURISOL and to build and test prototypes of the most challenging elements. Twenty institutions and laboratories from 14 European countries bid to become full participants in the project. In order to cover as efficiently as possible the studies of the various parts of the facility, the Design Study consists of 12 tasks, split into 4 topical areas: management, accelerators, targets, physics – beams – safety. In addition a conceptual design study of a beta-beam facility is an integral part of the contract. The European Union agreed to support this study with a contribution of about 9M€, out of a total cost estimated at 30 M€.

Detailed updated information can be found on the EURISOL website [4]. In parallel, different possible locations for building such a facility will be critically examined. Three types of sites have been identified:

- A national laboratory with a pre-existing radioactive beam facility such as GANIL
- An international research organization such as CERN.
- A green field site with no previous nuclear physics facility.

The charge of the DS is to provide all relevant input to allow the community and funding bodies to make an informed choice.

THE AMERICAN PROJECTS

For several years the United States community developed and supported a concept named RIA combining projectile fragmentation with reacceleration after stopping in a gas cell. This ambitious project was unfortunately not funded, but has given birth to two more modest proposals issued by the MSU and Argonne National laboratories respectively. The heart of the proposed MSU project (Isotope Science Facility – ISF) is a high power superconducting heavy-ion linear accelerator capable of delivering beams of all stable elements with variable energies up to 200A MeV and beam power up to 400 kW. The ISF will encompass a reaccelerated beam facility incorporating an advanced cyclotron stopper and for reacceleration a superconducting LINAC capable of energies up to 12A MeV. The Argonne plan (Advanced Exotic Beam Laboratory – AEBL) uses a similar driver associated with a gas stopper and the current ATLAS LINAC for reacceleration. A decision should soon be taken by the Department of Energy.

Plans exist also for a major upgrade of the TRIUMF facility in Vancouver, Canada, including an increase of the energy of the post accelerator and the construction of a 50 MeV electron driver to induce photo-fission, which will enhance the multi-user capability of the facility.

CONCLUDING REMARKS

Radioactive beam science is today at a transition point. The scientific output of first generation installations, often extrapolated from stable beam machines, has peaked, and the scientific community is eagerly awaiting the major improvements in intensity and isotopic range promised by the next generation projects. The complementary nature of the techniques used, in-flight and ISOL production, will allow the scientists to investigate the important problems with varied probes at different incident energies, hugely improving our understanding of nuclei far from stability. It is clear that due to their flexibility, modularity and ability to exhibit very small beam losses, superconducting linear accelerators for both protons and Heavy Ions will be at the heart of many of the new installations, and in many ways drive the future of the field.

ACKNOWLEDGEMENTS

In this paper I have focused on the major current and future facilities, the choice of which is subjective in many ways. I apologize not to have cited for lack of space the numerous smaller RIB facilities which have also produced many important results.

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