# RECENTLY COMMISSIONED AND FUTURE RNB FACILITIES

Paul Schmor, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada, V6T 2A3

*Abstract*

There is a worldwide interest in fundamental and applied scientific research with exotic nuclear beams in order to improve our understanding of the nature of matter and of the evolution of matter in the universe. The nuclear physics working group of the OECD Megascience Forum concluded in 1999 that "A new generation of high-intensity RNB facilities of each of the two basic types, ISOL (Isotope Separator On Line) and In-Flight, should be built on a regional basis. Interested governments are encouraged to undertake the necessary decisions within the next few years, and the facilities themselves should become operational in five to ten years." [1] This interest has led to the design and development of a number of new facilities to increase both the variety and the number of exotic ions. This paper reviews and compares recently commissioned and proposed facilities.

## INTRODUCTION

There is wide range of interest, for scientific as well as for applied research, involving the use of radioactive ion beams (RIB). Several recent studies have documented the scientific case. [2,3,4,5] In nuclear physics, the motivation is centered around improving our under-standing of the origin of the elements in the cosmos, our understanding of the nature of nucleonic material and exploring the physics beyond the standard model. Much of our recent understanding of condensed matter has involved the use of microscopic magnetic probes. Radioactive nuclei can be very sensitive magnetic probes. Radioisotopes with high specific activity are of interest for biomedical R&D. Radioactive nuclei have been successfully used as diagnostics to study and improve the wear characteristics of materials. Finally programs such as the accelerator based transmutation of waste (ATW) and science based stewardship program (SBSS) require certain improved cross sections in order to enhance the accuracy of their models.

The two approaches for producing radioactive ion beams (RIBs) are complementary. The ISOL approach uses gammas, neutrons, protons or other light ions impinging on a thick target. Interactions with the target nuclei produce exotic nuclei that diffuse out of the hot target and by effusion to an ionizer where the isotopes are extracted and formed into a beam of tens of eV. The isotopic distribution and intensities depend on the target material, its chemistry, target dimensions, isotope half-lives and target temperatures. The extracted beams are of high quality but generally contain a variety of isotopes and desired isotopes can be separated by high-resolution mass-separators. The radioactive ion beams are either stopped for experimental observation or accelerated to higher energies. The diffusion and effusion processes inherently limit the exotic beams to those having half-lives greater than 10 ms.

The IF (in-flight or projectile fragmentation) approach uses an energetic heavy ion beam impinging on a thin target. The heavy ion beam fragments and the fast exotic beam that come out of the thin target are separated by an ion optical system. The energetic fragments are independent of the target chemistry, depend on the energy of the incident beam but are generally greater than 25 MeV/nucleon. A high acceptance separator is required to capture a significant fraction of the exotic beam because of the angular scattering and the momentum spread from the target. Consequently the separator has limited mass resolution. However the approach is inherently fast and half-lives of the order of microseconds can be captured.

Numerous facilities are operating, being upgraded, under construction or in the proposal stage. This activity reflects the emphasis placed on the need for such facilities by the OECD working group.[1] A list of facilities, albeit partial, is given in table 1. The status is listed as C (under construction), U (an upgrade), O (operating) and P (proposed).

Table 1: A list of RIB Facilities

| NAME | LOCATION | TYPE | STATUS |
|---|---|---|---|
| | | | |
| BRNBF | CHINA | ISOL | C |
| CRC | BELGIUM | ISOL | O |
| DUBNA | RUSSIA | IF | O |
| EURISOL | EU | ISOL | P |
| EXCYT | LNS/ITALY | ISOL | C |
| GSI | GERMANY | ISOL | O,U |
| HOLIFIELD | ORNL, USA | ISOL | O |
| IMP | CHINA | IF | O |
| ISAC I | CANADA | ISOL | O |
| ISAC II | CANADA | ISOL | C |
| ISOLDE | CERN/EU | ISOL | O |
| MAFF | GERMANY | ISOL | C |
| NSCL/MSU | USA | IF | O |
| PNPI | RUSSIA | ISOL | O |
| RCNP | JAPAN | IF | O |
| RIA | USA | ISOL/IF | P |
| RIKEN | JAPAN | IF | C |
| RMS/JAERI | JAPAN | ISOL | C |
| SPIRAL | FRANCE | ISOL | O |
| SISSE/LISE | FRANCE | IF | O |
| VECC | INDIA | ISOL | P |

These proceedings contain details of the recent status and plans of a number of the listed facilities. In what follows is a personally selected list of characteristics of ma-

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jor accomplishments at some of these facilities to give the reader an impression of where the RNB developments are heading. RIB intensities are much lower than the stable beam intensities at conventional accelerator facilities. However since the RIB flux is proportional to the intensity of the driver beam that is used to create the RIB, the driver technology is state of the art and is a key element in the facility development. As the driver current increases so do the challenges in developing the high power targets needed to create the RIBs and the remote handling to deal with the maintenance of these targets with high levels of residual activation.

## IN-FLIGHT FACILITIES

### *MSU/NSCL*

The K500 and K800 cyclotrons have been modified to operate in a coupled mode. Intense heavy ion beams are initially accelerated in the K500 cyclotron, extracted, transported to and injected into the K800 cyclotron where a foil strips off most of the remaining electrons. The nearly bare nuclei are then further accelerated in the K800, extracted and transported through a fragment production target. More recently the A1900 projectile fragment separator has been completed and commissioned.[6] The separator uses twenty-four superconducting quadrupole magnets. Compared to the previous A1200 spectrometer the acceptance has increased from 2-4% to over 90%. The design specifications for the ECR and coupled -cyclotron system predict a peak beam power of 5 kW in the A=40 region at the target, well above the ability of the present fragment target. Target development on a novel new target capable of dealing with these beam powers has begun.[7]

### *GSI*

RIB related research, using both the ISOL and IF techniques, has been an important part of the scientific program at GSI for many years. Recently there has been approval, with some restrictions, of a major facility upgrade that when completed is predicted to increase the secondary RIB intensity by a factor of $10^4$.[8] The increase is the result of a number of factors. New fast ramped superconducting synchrotron drivers will permit the heavy ion intensities to increase by a factor of $10^2$ and the energy to increase by a factor of 15. Finally a larger acceptance fragment separator (super FRS) replaces the FRS. Again a more robust target is needed to handle the increase in beam power.[9]

### *RIKEN RIBF*

Riken has been providing intense light ion beams for the production of RIBs by projectile fragmentation at energies of 100 MeV/u since 1990. Driver intensities have increased with the installation of a new 18 GHz ECR ion source, a variable frequency RFQ linac and a charge state multiplier. A major upgrade to the radioisotope facility at RIKEN is now under construction.[10] The upgraded facility requires three new cyclotrons, the fRC (fixed energy ring cyclotron), IRC (intermediate stage ring cyclotron) and SRC (superconducting ring cyclotron). It also includes the installation of a new larger acceptance fragment separator (BigRIPS). Beam experiments with this new facility are scheduled to begin in 2007.[11] When finished it will be capable of accelerating elements up to A=40 to 400 MeV/u decreasing to 350 MeV/u for uranium. Currents will be limited to about 1 pμA for the lighter elements by the radiation shielding and slightly less than 1 pμA for the heavier elements. Plans call for the facility to include an ISOL type production target as well.

## ISOL FACILITIES

### *CRC Louvain la Neuve*

The cyclotrons at Louvain la Neuve have been used to carry out a great deal of the pioneering effort in developing beams for nuclear astrophysics using a high intensity 30 MeV proton driver. Recently a K=44 cyclotron specially designed to meet the specific requirements of mass separation and high transmission for nuclear astrophysics has been brought into operation. This new accelerator has delivered a beam of $^{19}$Ne with an intensity around 5 x $10^9$ particles/sec in the energy range 7.5 to 9.5 MeV.

### *HRIBF ORNL*

The Holifield radioactive ion beam facility uses the ORIC cyclotron as a driver and the tandem as a post accelerator. This combination requires the formation of negative ions. Target development here has led to the use of $HfO_2$ fiber targets that have been shown to have excellent isotopic release and thermal properties. Recently the scientific program has expanded by creating neutron rich beams from proton-induced fission using approximately 10 μm thick uranium carbide deposited onto carbon fibers.[12] Plans have been developed to construct a second high-voltage platform that would contain a target system capable of being used at higher driver powers. Plans also include the possible replacement of the ORIC cyclotron with a higher intensity and higher energy driver in the future.

### *SPIRAL GANIL*

The GANIL RIB program began with the production of exotic beams using the in-flight projectile method with the high-intensity heavy-ion beams in the energy range 50 to 100 MeV/u from the cyclotron drivers. More recently SPIRAL (Système de Production d'Ions Radioactifs avec Accélération en Ligne) has come into operation. The exotics are created by the ISOL method, ionized in an ECR ion source and accelerated with a K=265 cyclotron (CIME) to energies between 1.7 and 25 MeV/u. The development of high power targets and a remote handling system to deal with the high level of induced radioactivity have been key elements in the success. Unlike ISOL targets at light ion facilities where spallation or proton-induced fission is major mechanism for the creation of exotic isotopes, here with heavy ions the primary production mechanism in the target is projectile fragmentation. The energy deposition profile by these heavy ions has required the development of special targets. The targets consist of a series of spatially separated carbon disks capable of handling up to 6 kW of beam power and operating at temperatures of 2300 K.[13] A detailed study has developed a conceptual design for SPIRAL2. In the initial stage the driver would be a 5 mA, 40 MV deuteron (q/A=1/2) and 1 mA (q/A=1/3) linac. This would permit the creation of exotic beams by fission either through neutrons or by direct bombardment.[14]

### *ISOLDE CERN*

ISOLDE has been producing RIBs using the ISOL technique for over 30 years, initially with 600 MeV protons from the synchrocyclotron (SC), next with 1 GeV protons from the booster synchrotron that has recently been upgraded to provide 1.4 GeV protons. With these changes has come a change in beam structure from nearly DC to pulsed with high peak currents averaging to about 2μA. The inherent thermal cycling from the pulsed operation impacts the ideal target temperature regime and hence the target performance and lifetime. Recent ion source developments using lasers and resonant laser ionization have greatly improved the mass selectivity and efficiently ionized many elements of the periodic table. The facility has been designed so that two independent target stations can be used to provide independent RIBs to two different experimental stations. Recently experiments have started with accelerated beams using the REX-ISOLDE facility. Key elements in this new facility have been the RIB post accelerators, the charge booster comprised of a cooler, Penning trap and EBIS. The optimum energy range in now 0.8 to 2.2 MeV/u but work has begun on changes to upgrade the maximum energy to 3.1 MeV/u. An additional upgrade to 4.2 MeV/u is planned. Encouraging tests have recently been carried out with two-step targets where the proton beam impacts a neutron-producing target and the neutrons are used to produce the exotic nuclei in a uranium target. The result is a significant suppression of the spallation and fragmentation products and only a slight decrease in the neutron rich fission products. The lifetime of the target should be considerably longer than with direct proton bombardment targets. CERN is examining a high-intensity superconducting linac (SPL). This linac could be configured with existing tunnels to feed the ISOLDE targets.[15]

### *MAFF MUNICH*

MAFF (Munich accelerator for fission fragments) has been designed for operation at the new high-flux Munich research reactor facility FRM-II. The reactor has recently been completed and licensed to begin operation. MAFF will provide intense beams of neutron rich isotopes at energies of 30 keV that will be further accelerated to energies from 3.7 to 5.9 MeV/u. MAFF creates the radioactive isotopes by the thermal-neutron-induced fission of uranium targets. The high neutron flux and large cross-sections for fission result in large yields of neutron rich fission products. Following the production target, MAFF includes ion sources, beam transport and a mass separator and is similar to other existing ISOL facilities. Initial RIB experiments at MAFF are anticipated in about two years. Post acceleration similar to REX-ISOLDE is foreseen.[16]

### *ISAC TRIUMF*

The ISAC facility at TRIUMF uses energetic protons from the 500 MeV cyclotron driver to produce exotic elements by the ISOL technique. The shielding, cooling and remote-handling have been designed to be compatible with 50 kW (100 μA at 500 MeV) proton beam impinging a thick uranium target. The first RIB experiment began using a radioactive potassium beam in 1998. An active scientific program with low energy beams has been formulated around a neutral atom trap, a low temperature nuclear orientation setup, a β-NMR facility capable of providing a variety of polarized exotic beams, a modified Chalk River 8π spectrometer and various general-purpose stations. Recently a precision instrument based on an EBIT (electron beam ion trap) to measure exotic masses precisely has been funded. A little more than two years after the first RIB, accelerated exotic beams became available for nuclear astrophysics experiments. The accelerators were designed to meet the basic nuclear astrophysics requirements and provide continuously variable energy beams from 0.15 to 1.5 MeV/u for masses up to A=30. They consist of a cw 8m long RFQ linac and a five-tank cw IH DTL.

An important issue continues to be the development of targets that can reliably withstand the high powers in the driver beam. Target development has resulted in target lifetimes that now exceed an integrated proton dose of $5x10^{20}$.[17] Routine proton beam power delivered to the target has gradually increased from the 1 kW in 1998 to 20 kW today. The full 50 kW was successfully tested on a prototype target. A thermal surface-ionization, ion-source has been the RIB production source up until now, but an ECR ionizer is being commissioned and a resonant laser ion source is being tested on a test bed. Video surveillance, remotely operated cranes and remote manipulators in a heavily-shielded hot-cell are needed to deal with the high levels of residual activity experienced during target changes. Radiation induced diffusion enhances the yields of short-lived activity from the target as the proton current is increased. ISAC is being upgraded to provide higher energies and a broader range of masses in the ISAC II project with an ECR charge state booster and a superconducting linac to provide energies of 6.5 MeV/u for masses up to A=150.[18] Initial operation of this new post accelerator will begin in 2005 at a maximum energy of 4.3 MeV/u. Full energy operation is scheduled to begin in 2007. High power target development has not been compatible with efficient beam delivery to experiments. Consequently a plan to build a dedicated full power target development station is being proposed. The $H^-$ cyclotron is versatile and can accommodate an additional 100 μA extracted beam.[19] The beam would be taken to an expanded target hall. Existing nuclear ventilation and remote handling equipment would be used. The technology would be similar to the presently operating target stations. It is anticipated that this facility would be complete by 2008. In the future this facility could be used to provide independent RIBs simultaneously to two experiments from a single driver. A study has proposed using a storage ring to use the exotic isotopes more efficiently or to further accelerate the RIBs. [20]

### *RIA*

RIA (rare isotope accelerator) is a new generation facility being planned in the US for basic research in nuclear physics. The facility proposes to use a unique cw driver accelerator that will lead to unprecedented yields of radioactive beams using both the ISOL and in-flight projectile fragmentation methods.[21] The proposed driver is a cw superconducting linac capable of accelerating all elements from protons to uranium through a maximum 1.4 GV potential. Beam power throughout the mass range is 400 kW. The final energy varies from 900 MeV for protons through to 400 MeV/u for uranium. In order to achieve the design beam power for the heavier elements with current technology the driver accelerator takes advantage of the large phase space acceptance of the independently phased superconducting resonators to capture and accelerate multiple charge states from the ECR and subsequent strippers. R&D on key elements of the proposed driver is being funded at a number of universities and national laboratories. This includes work on the ECR, the various types of superconducting structures required to cover the large range of $\beta$, high power stripper technology and the high power targets.[22,23] A windowless liquid lithium target is proposed for the in-flight fragmentation target.[24] A large acceptance fragment separator can be used in conjunction with energy degraders and a gas catcher to efficiently provide intense, low-emittance, radioactive ion beams suitable for stopped beam experiments or injection into a post accelerator.[25] The proposal also includes a second high-resolution, high-purity fragment separator. Traditional ISOL type targets using radiation-handling technology developed for ISAC are also proposed using direct proton irradiation as well as two-step neutron-induced fission. The proposed post-accelerator for RIB acceleration is designed for cw operation to accelerate singly-charged ions with masses up to 240 from the ion source energy to energies above the coulomb barrier.[26]

### *EURISOL*

The European ISOL community is preparing the specifications for a next generation ISOL facility. The proposed driver would provide up to 5 MW of proton beams at 1 GeV and be upgradeable to 2 GeV.. The driver should also be capable of accelerating intense beams of other light ions. The proposal also includes the possibility of a supplementary electron machine that would be used for producing fission products. The RIB post accelerators would cover the ranges from 0.2 to 1 and 5 to 10 MeV/u with the possibility of achieving 100 MeV/u for A<80 decreasing to 20 MeV/u for A=200. [5,27]

## SUMMARY

The scientific justification for exotic beams has been clearly made. There is a need to expand both the intensity and the range of exotic species. Laboratories in Asia, Europe and North America are actively pursuing technological solutions to meet the requirements. These new facilities are complex and costly. Intense stable beams from high-energy accelerators are required. Targets capable of handling the available powers are a challenge. Satisfying the legitimate safety concerns of the general public and licensing agencies is a challenge in these facilities that are designed to create and release activity easily. As the facility cost becomes significant, it has become important to find cost effective ways of providing the exotic beams to users. It is essential to find techniques that permit multiple simultaneous users.

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