

FIRST GENERATION ISOL RADIOACTIVE ION BEAM FACILITIES

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Abstract

Widespread scientific interest has developed in using accelerated Radioactive Ion Beams (RIBs) for nuclear physics, astrophysics, solid-state physics, and applied studies. Two general methods can be used to produce RIBs: the recoil fragmentation method and the Isotope-Separator-On-Line (ISOL) method. The recoil-fragmentation method requires one accelerator, filters radioactive fragments produced from medium-energy heavy-ion beams incident on thin targets, and is relatively well developed. This method has been pursued vigorously at several laboratories. The ISOL method requires two accelerators, has the promise of lower energies and more intense beams, and is in an earlier state of development. The status, challenges, and plans of the first-generation ISOL accelerated RIB facilities presently operating or under construction will be discussed. These are facilities based in part on at least one existing accelerator and will produce limited RIB beam species, intensities, and energies.

I. INTRODUCTION

A remarkable level of interest has developed with accelerated radioactive ion beams (RIBs) in a short time. This interest has led to the construction, development, and proposed construction of first- and second-generation RIB facilities in Asia, Europe, and North America. This interest stems directly from the scientific opportunities RIBs provide for nuclear, solid-state, and astrophysics and applied research, and the fact that the acceleration of RIBs has become technically feasible over the last two decades.

RIBs will greatly increase the number of nuclei available for study, particularly nuclei with extreme values of neutron and proton number. Altogether, between the proton and neutron drip lines and the fission limits for heavy nuclei, there are approximately 3000 particle-stable nuclei that can be studied. Some information exists on about 40% of these nuclei. Most of our nuclear structure information is from nuclei near beta stability that were first produced with accelerated light-ion stable beams incident on stable targets and then with heavy-ion beams, particularly heavy-ion fusion reactions producing proton-rich nuclei. Much of the nuclear information on neutron-rich nuclei was obtained from reactor produced fission fragments. The development of the RIB

facilities presently underway will allow new regions of proton- and neutron-rich nuclei to be studied, providing exciting new research opportunities. Of course not all unstudied nuclei will prove to be interesting; however, much of the new information on new interesting phenomena will come from nuclei studied with RIBs.

Another extremely interesting research area for RIBs is astrophysics, and in particular nucleosynthesis. Most of the heavy nuclei in the universe have been produced in explosive stellar events with short-time scales through nuclear reactions on unstable nuclei. It is only with RIBs that these reaction processes can be studied in detail in the laboratory. The reaction network for explosive hydrogen burning, the rapid proton or RP process, is believed to have produced the proton rich stable nuclei between oxygen and the iron region. The first-generation ISOL facilities described in this paper will be uniquely positioned to produce these proton-rich unstable nuclei for inverse-proton-reaction cross section measurements.

In general, RIBs can be obtained by two very different and complimentary methods: The Projectile Fragmentation, PF, method and the Isotope Separator On Line, ISOL, method. The PR method produces RIBs in peripheral collisions between heavy-ion projectiles and light-target nuclei. [1] The incident beam is typically in the 50 to 200MeV/A range and the radioactive fragments recoil in a forward-angle cone with velocities similar to that of the incoming beam. The PF method is fast, so short half-life RIBs can be made, and does not suffer from the severe target-beam-ion-source chemistry constraints of the ISOL method. However, RIBs are produced at high energies and the RIB intensities, because of thinner targets and smaller primary beam intensities, can be several orders of magnitude lower than those from the ISOL method. The PR method requires only one accelerator system.

II. ISOL METHOD

The ISOL method requires two accelerator systems, a driver accelerator to produce radioactive atoms at rest and a post accelerator to accelerate these radioactive atoms to energies of interest. The two accelerators are coupled by a target-ion source and mass separator. This method is equivalent to selecting a low-energy RIB from an on line isotope separator and accelerating this beam to energies of

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TABLE 1. FIRST-GENERATION RIB FACILITIES USING THE ISOL METHOD

FACILITY	DRIVER ACC	POST ACC	DONE	COMMENTS
Louvain la Neuve	30MeV-p cycl	K=110 cycl	operating	4E8 pps ^{13}N , 2E9pps ^{19}Ne
ARENAS	K=110, 70MeV-p cycl	K=44 cycl	1996	0.2-0.8MeV/A
INS, Tokyo	K=65, 40MeV-p cycl	RT SCRFQ & IH Linacs	1996	RIBs<1.05MeV/A
HRIBF, ORNL	K=100, 60MeV-p cycl	25MV tandem	1995	RIBs<5MEV/A for A<80
SPIRAL, GANIL	cpl. K=400 HI cycls	K=265 cycl	1998	heavy ion RIB production
EXCYT, Catania	K=800 SC cycl	15MV tandem		heavy ion RIB production
REX ISOLDE, CERN	1000MeV PS Booster	RT RF, IH, 3-7gaps	>1997	RIBs<2.0MeV/A, trap/EBIS inj
ISAC-1, TRIUMF	500MeV-p cyclotron	RT RFQ & IH linacs		RIBs<1.5MeV/A

interest. A good example of the target-ion source and mass-separator technology required for an ISOL RIB accelerator facility is ISOLDE [2] at CERN. In fact, it was realized early by Hansen [3] in 1977 that many of the intense low-energy RIBs developed at ISOLDE, some of them reaching 1×10^{12} pps, could be accelerated to energies of interest for nuclear and astrophysics.

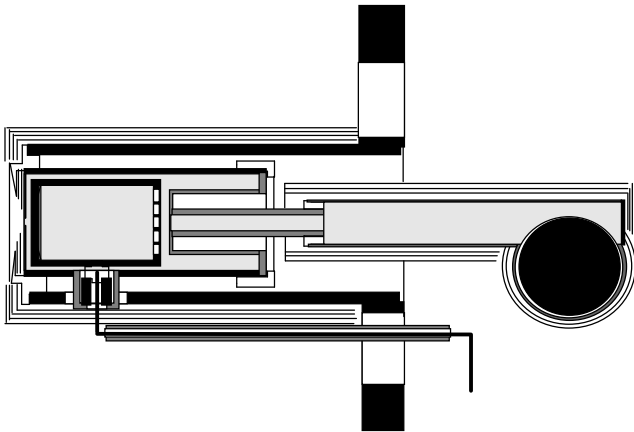


Figure 1. ISOLDE high-temperature FEBIAD target-ion source for the production of RIBs by the ISOL method.

The crucial component for the ISOL method is the target-ion source. Figure 1 shows the ISOLDE high-temperature FEBIAD target-ion source. Radioactive atoms are produced by bombarding thick targets with high-intensity beams of protons or other light ions. The resulting radioactive atoms will diffuse and desorb from the target material, which typically is a refractory ceramic in powder form which is heated to over 2000°C. The radioactive atoms will effuse through a heated transport tube into the FEBIAD ion source where they are ionized by electrons from a heated cathode and accelerated to about 50keV. Following ionization and acceleration, the desired mass can be separated with a magnetic mass separator. A very good separator, with a mass resolution greater than 1/10,000, can separate isobars from a single mass thus providing isotopically pure beams on target.

A significant disadvantage of the ISOL method, is that the diffusion and desorption of the radioactive atoms from the

target material and the effusion and surface desorption in the transport tube and ion source are sensitively dependent on the high-temperature chemistry of the target material, the beam element, and construction materials. The ISOL method is also much slower than the PF method, limiting RIBs to a half-life of at least 100ms or longer. However, for the longer lived species, the ISOL method is capable of producing more intense beams at energies needed for nuclear spectroscopy and astrophysics studies.

III. FIRST GENERATION ISOL FACILITIES

At least seven ISOL RIB facilities are either now funded or nearly funded. These facilities can all be considered first-generation facilities because they all, in some way, are limited, either by RIB species, RIB energy, or RIB intensity. These facilities are also cost effective since they each build on an existing driver accelerator. The facilities are listed in Table 1 and discussed below:

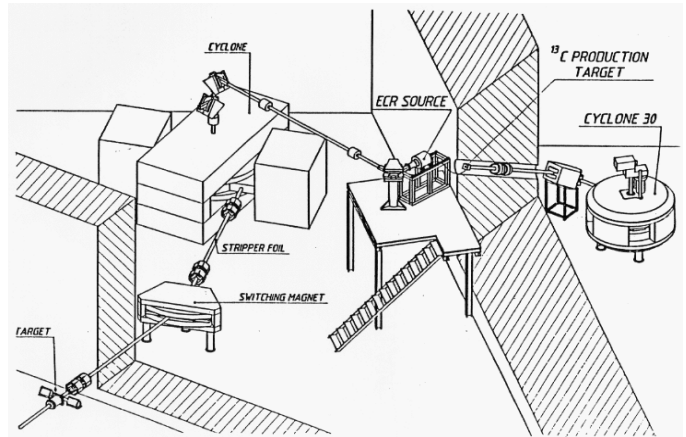


Figure 2. Sketch of the Louvain-la-Neuve facility which produced the first accelerated ISOL RIBs, ^{13}N , used for nuclear astrophysics measurements.

Louvain-la-Neuve Facility

Presently, the only operating RIB facility is at Louvain-la-Neuve where ^{13}N and ^{19}Ne beams have been accelerated for astrophysics research with intensities of 4×10^8

and 2×10^9 pps, respectively [4]. The driver, CYCLONE 30, is a compact H^- cyclotron designed to produce a 500uA, 30MeV proton beam for PET isotope production. This beam is transported, as shown in fig. 2, to a target located in a 3m-thick concrete shielding wall. For ^{13}N beams, a 50% enriched ^{13}C , thick graphite-powder target is embedded into a graphite rod in good thermal contact with a water-cooled copper cylinder. The resulting ^{13}N activity from (p,n) reactions is extracted on line as ^{13}N - ^{14}N gas molecules. The 170uA proton beam heats the target to about 2300°C. The ^{13}N - ^{14}N gas is transported to a single-stage ECR ion source that has an 8% ionization efficiency. The resulting $^{13}N^+$ ions are mass analyzed, transported to a second cyclotron, axially injected, and accelerated with a 6% efficiency.

An important problem has been the separation of evaporated ^{13}C from the ^{13}N beam. This separation has been achieved using the high intrinsic resolving power of the CYCLONE magnetic field. The ^{18}Ne beam is produced with a liquid LiF target. Beams of ^{11}C and 6He are being developed. A 110-minute half-life ^{18}F beam is being developed using (p,n) reactions on enriched ^{18}O water following a batch process very similar to that used for PET isotope production. The ^{18}F is slowly released into the ECR source as CF_4 gas.

The work at Louvain-la-Neuve will be extended with the ARENAS project which is now funded to construct a 25% efficiency, $K=44$, 0.2 to 0.8MeV/A, cyclotron post accelerator dedicated for astrophysics research. This new cyclotron is scheduled for completion in 1996 and will allow the $K=110$ CYCLONE to also be used as a driver for higher energy protons and other light ion beams for RIB production.

INS Project, Tokyo

A RIB facility has been constructed at the Institute for Nuclear Studies of the University of Tokyo, [5] originally as a part of the Japanese Hadron Project. RIBs have been made with beams from the existing $K=68$, 40MeV-proton cyclotron. The new apparatus consists of an ISOL system, a 50m low-energy transport line, and a linac complex. SI, ECR, and FEBIAD target-ion sources have been developed. A sophisticated two-stage mass separator with dipole magnets raised to different voltages to reduce background has been built. A mass resolution of 1/9000 is expected.

The post accelerator linac, shown in fig. 3, consists of a 25MHz Split Coaxial RFQ which is an extended version of a successfully tested prototype. The SCRFQ will accelerate RIBs with $Q/A > 1/30$ from 2 to 170keV/A with a duty cycle between 10 and 30%. The output beam will be stripped to $Q/A > 1/10$ and accelerated to 1.05MeV/A with a 4-cavity, 51MHz inter digital H linac. The cavities will be separated by quadruple triplets providing large horizontal and vertical acceptances. In order to use the RIBs efficiently, a pulsed RIB source has been developed to match the linac time structure. A bunching electrode operating at 300V has been added 1mm from the exit aperture of a Re surface ionization source. Tests with ^{23}Na , ^{39}K , and ^{41}K beams pulsed at 100Hz with 2ms pulses have been completed. A bunching

gain of nearly 2.5 for ^{38}K produced from 3He bombardment of a CaF powder target has been measured.

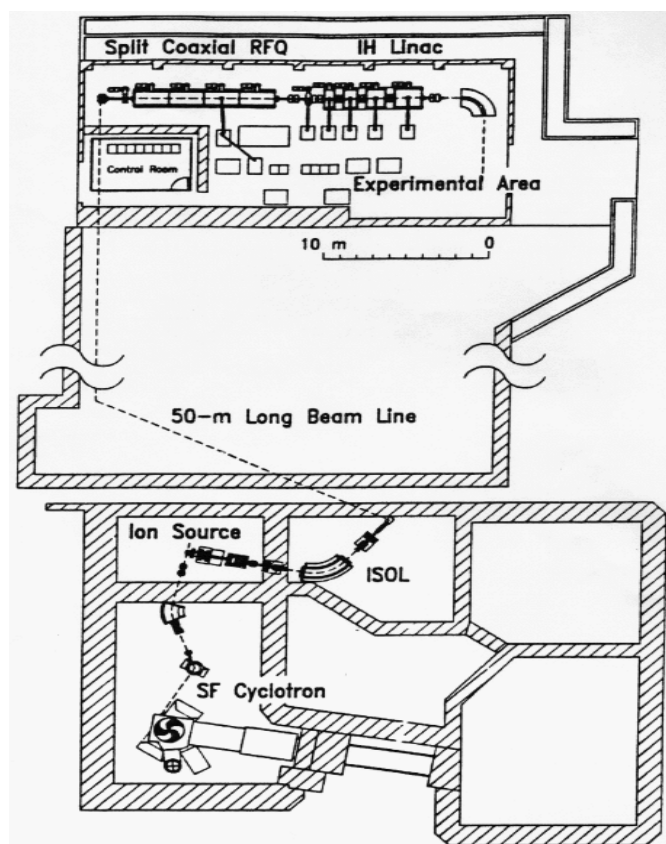


Figure 3. Layout of the RT split-coaxial RFQ and IH linac post accelerator system of the INS RIB facility.

HRIBF Project, ORNL

The Oak Ridge Isochronous Cyclotron (ORIC) and the 25MV tandem accelerator are being reconfigured to provide an economic first-generation RIB facility [6]. In the past ORIC served as an energy booster for stable heavy ion beams from the tandem. For RIBs, this process has been reversed: the tandem will be injected with RIBs produced by light-ion ORIC beams. The tandem presently operates at 25MV, the highest electrostatic accelerator voltage in the world. With single foil stripping, mass-80 beams will be accelerated above 5MeV/A for nuclear structure studies. The tandem is a DC machine, so no bunching is required. There is no low velocity problem as with linacs and its simplicity, reliability, and beam quality, are unmatched. An unusual feature of tandems is that negative ions are required for injection, not highly-charged positive ions.

The accelerators will be coupled by a RIB injector, shown in fig. 4, consisting of an ISOLDE-type target-ion source, mass separator, and charge exchange cell, all mounted on a 300kV platform constructed in an existing shielded room. The neutron fluence from the RIB target has been estimated to be up to $1 \times 10^{15} n/cm^2$ at one meter for 2kW of beam for 2000 hours. This fluence will destroy nearly all unshielded semiconductor devices. Consequently, a split

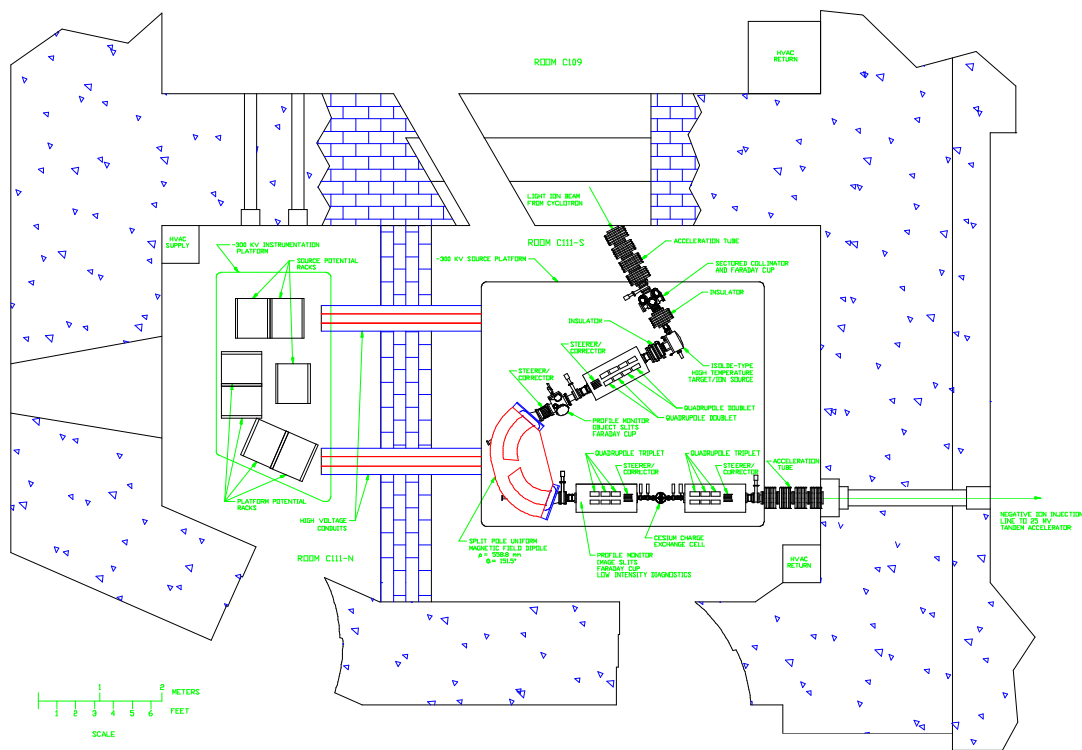


Figure 4. Recently completed HRIBF RIB injector which will mass analyse, charge exchange, and inject negative RIBs at 300KV into the 25MV tandem accelerator.

platform system separated by a shielding wall has been constructed. One platform will hold the target-ion source and mechanical equipment and the other will hold all the electronics. The first-stage mass separator will give a mass resolution of 1/1000 at 50keV and will select a mass to be refocused through a charge-exchange cell. The negative-ion injection line is configured to provide a second stage mass resolution greater than 1/10,000 at an energy of 350keV.

The RIB injector has been tested with stable beams and the remaining components have been ordered. In the summer of 1995, ORIC-produced RIBs from the new injector will be optimized. The first RIBs should be accelerated through the tandem in 1995 and scheduled experiments will start in 1996.

SPIRAL Project, GANIL

As an extension to the existing high-energy PF facility, GANIL has been funded to develop a RIB ISOL facility, SPIRAL [7]. RIBs will be produced with the 95MeV/A heavy ion beams from the existing coupled K=380 RT cyclotrons. A new 14.5GHz ECR source on a 100kV injector has increased the primary beam intensity to 3puA for ions up to Ar. A new rebuncher between the main cyclotrons should increase this intensity further allowing a maximum beam power of 6kW.

Radioactive atoms will be multiply ionized in a permanent magnet ECR source at 20kV and mass sorted with a low resolution spectrometer. There is some debate on the efficiency of light-heavy ions for RIB production. The projectile fragmentation cross sections for RIB production

with 95MeV/A light-heavy ions are significantly larger in many cases than target fragmentation, spallation, and fission cross sections for energetic protons; however, this increase in cross section may be more than compensated by a decrease in target thickness. Also, target power density is a concern at the planned intensities. These issues of RIB production are being studied at GANIL with a Caprice-type ECR source and new mass separator, SIRa. The initial measurements have been made with noble gas beams, both primary and radioactive, on a powder carbon target. Yields of 1.0×10^8 $^{76}\text{Kr}^{10+}$, 1.2×10^7 $^{34}\text{Ar}^{7+}$, and 1.5×10^7 $^{18}\text{Ne}^{5+}$ ions/s/puA have been measured. GANIL will have the special ability to vary the primary beam species, in addition to the target material, so as to maximize the intensity of a particular RIB species.

RIBs will be accelerated in a compact K=265 cyclotron, CIME, presently under construction. Beam energies will vary from 2 to 25MeV/A depending on their charge to mass ratio. Mass separation will be performed for the most part with CIME itself. RIB experiments will be done with the extensive experimental areas and equipment at GANIL. The SPIRAL project does not require any major civil construction. The new cyclotron is scheduled for delivery late in 1996 and the first RIB experiments should start in 1998.

EXCYT Project, LNS Catania

The Laboratorio Nazionale del Sud is equipped with a 15MV SMP tandem and a K=800 SC cyclotron. These accelerators will be reconfigured to provide an ISOL RIB

facility, EXCYT.[8] Radioactive atoms will be produced, in a manner similar to GANIL, using projectile fragmentation reactions with heavy ion beams from the cyclotron. In order to increase both the energy and intensity of beams from the cyclotron, a new 14.5GHz, 1.4T, SC ECR source for axial injection is being constructed. Intense heavy ion beams from the cyclotron may be limited by the electrostatic deflector. Negative radioactive ion beams will be produced with a new 150kV RIB injector, similar to the HRIBF concept, and injected into the 15MV tandem. Beams up to mass 40 will be accelerated above the Coulomb Barrier. On December 22, 1994, the first beam at LNS was extracted from the SC cyclotron., 3nA of 30MeV/A $^{58}\text{Ni}^{16+}$.

CERN ISOLDE/RAL Projects

An accelerator project REX ISOLDE has been approved to increase the ISOLDE energy from 60keV to 2MeV/A.[9] The scheme directly produces ions with $Q/A > 1/4.5$ with no stripping. ISOLDE presently uses 2uA of time-averaged beam from the 1GeV PS Booster in 3×10^{13} proton pulses at a 0.4 to 0.8Hz rate. ISOLDE $1+$ beams will be injected a Penning ion trap which will be used as an accumulator-buncher to convert the DC ISOLDE output into 50Hz pulses. These pulses will then be fed into an EBS acting as a charge state converter. About 100us wide pulses from the EBS will be injected into a 108MHz linac complex very similar to the Heidelberg TSR high-intensity injector. The linac consist of a 4-rod RFQ for 10 to 500keV/A, a 10 drift tube IH linac for 0.5 to 1.0MeV/A, and three 7-gap resonators for 1.0 to 2.0MeV/A. The system will be pulsed at 50Hz with about a 5% RF duty cycle. The accelerator would be used for experiments in nuclear astrophysics, polarization studies, and solid state applications. A building extension is under design and much of the accelerator equipment is funded. The earliest possible beam will be in 1997.

ISOLDE is also heavily involved with RAL in development of a high-power Radioactive Ion Source Test stand, RIST, as a proof of principle for a very-high-power second-generation RIB target-ion source.[10] Up to 100uA of 800MeV protons from the ISIS spallation neutron source will be used. Intense RIBs will be produced with a thick Ta target consisting of 25um disks with 25um spacing and a hot tungsten surface ionization source. A prototype target-ion source has been successfully tested at ISOLDE with a 2uA beam. High power test will be done at RAL.

TRIUMF ISAC-1 Proposal

A collaboration centered on the TRIUMF high-intensity, 500MeV H^- cyclotron has constructed and tested an on-line mass separator TISOL, installed a single-stage ECR source, and initiated an experimental physics program. Building on this experience, TRIUMF is proposing in their next five-year plan to build a facility, ISAC-1, to accelerate RIBs to 1.5MeV/A.[11] A 10uA beam from TRIUMF will produce RIBs in a new heavily-shielded building extending into the existing proton hall. This building will house all the high

activation activities of RIB production. A 60keV beam, from a variety of possible ion sources, will be delivered from this new building to either a 60keV experimental area or the new post accelerator. The first stage of this accelerator will consist of a 35MHz RT CW RFQ which will capture, bunch, and pre-accelerate RIBs, with $Q/A > 1/30$, from 2 to 150keV/A. A foil stripper will increase the Q/A ratio of the beam to at least 1/6 before further acceleration in a second-stage 70MHz RT IH linac. A switching magnet will deliver beam to three experimental areas including a recoil separator. Approval of the five-year plan containing this project is expected in 1995.

IV. CONCLUSIONS

Accelerator-based nuclear physics, which only a few decades ago moved, in part, from light-ion to heavy-ion beams, is now moving, in part, from stable-heavy-ion to radioactive-heavy-ion beams. The exciting physics opportunities presented by accelerated RIBs will lead to the construction of perhaps seven first-generation ISOL facilities. These first-generation facilities all use at least one existing accelerator and are cost effective. However, they are all limited in some way with respect to what is technically feasible, either in RIB species, RIB intensity, or RIB energy. Eventually, at least one second-generation ISOL facility, capable of producing and accelerating almost all masses to energies above the Coulomb barrier, should be developed.

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