OVERVIEW OF LINAC APPLICATIONS AT FUTURE RADIOACTIVE BEAM FACILITIES

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Abstract

There is considerable interest worldwide in the research which could be done at a next generation, advanced radioactive beam facility. To generate high quality, intense beams of accelerated radionuclides via the “isotope separator on-line” (ISOL) method requires two major accelerator components: a high power (100 kW) driver device to produce radionuclides in a production target/ion source complex, and a secondary beam accelerator to produce beams of radioactive ions up to energies on the order of 10 MeV per nucleon over a broad mass range. In reviewing the technological challenges of such a facility, several types of modern linear accelerators appear well suited. This paper reviews the properties of the linacs currently under construction and those proposed for future facilities for use either as the driver device or the radioactive beam post-accelerator. Other choices of accelerators, such as cyclotrons, for either the driver or secondary beam devices of a radioactive beam complex will also be compared. Issues to be addressed for the production accelerator include the choice of ion beam types to be used for cost-effective production of radionuclides. For the post-accelerator the choice of ion source technology is critical and dictates the charge-to-mass requirements at the injection stage.

Introduction

There are about 20 nuclear physics laboratories around the world which are either currently active in basic research with accelerated radioactive beams or are proposing new facilities for such research. Two major studies have been carried out recently to consider the research opportunities and technical options for future radioactive beam facilities, one by a North American committee [1] and the other by a European committee [2]. In the recently completed 1996 Long Range Plan for nuclear physics in the United States, the Nuclear Science Advisory Committee has recommended high priority for investment by the National Science Foundation and the Department of Energy in accelerator facilities to create advanced capabilities for research with radioactive beams.

One method of generating energetic beams of short-lived isotopes is via peripheral nuclear reactions with primary beams of stable heavy ions which are directly accelerated to energies per nucleon in the range of 50–1000 MeV. At such high energies the kinematics of these reactions are such that the secondary beams have relatively good transverse and longitudinal emittances and, after separation in the beamlines via magnetic rigidity and differential energy loss in absorbers, are appropriate for a variety of nuclear reaction studies. There are several laboratories which are currently doing research with radioactive beams generated via this fragmentation mechanism; examples are GSI near Darmstadt in Germany, GANIL in Caen, France, NSCL in East Lansing, Michigan, and RIKEN near Tokyo, Japan.

A variation on the fragmentation method is to create secondary beams of radioactive ions in the beamline at lower energies via nuclear transfer reactions utilizing inverse kinematics. The details of producing a beam of the short-lived radionuclide ^{17}F via this method for nuclear astrophysics studies at ATLAS are given in a contribution to this conference [3].

A second general method of generating radioactive beams is known as the two-accelerator or ISOL (Isotope Separator On-line) method. The ISOL technique has been used for over thirty years to produce, ionize, mass separate, and study short-lived nuclear isotopes. ISOLDE [4] at CERN is a premier example of a facility based on this technique. At ISOLDE radionuclides are produced via nuclear spallation reactions with 1 GeV proton beams from the Booster synchrotron which is part of the high energy accelerator chain at CERN. Other ISOL facilities are based at research reactors and use thermal neutron fission of ^{235}U as the radionuclide production mechanism; the OSIRIS facility at the reactor in Studsvik, Sweden is an example of this type. Using the ISOL method for the production of radioactive beams at energies high enough for nuclear reaction studies is a relatively new concept which has not been used extensively to date. Pioneering work to develop accelerated radioactive beams using this method has been carried out at Louvin-la-Neuve [5]. The present paper addresses the issues involved in selecting appropriate accelerators for both the driver and secondary beams for ISOL-type facilities.

Typical ISOL-type Radioactive Beam Facilities

An ISOL-type accelerated radioactive beam facility comprises several major components: the primary beam (driver) accelerator or reactor to create the radionuclides, the target/ion source complex, a high resolution mass separator, the secondary beam accelerator, and a variety of experimental areas and apparatus for the research program. A schematic technical layout of such a facility as envisioned by the Iso-Spin Laboratory study [1] was presented by J.M. Nitschke [6].

Of the several laboratories around the world which are either constructing or proposing new radioactive beam facilities there are a wide variety of choices of primary and secondary beam accelerators. In most cases radioactive beam facilities are evolving via upgrades or modifications to existing nuclear physics laboratories by adapting and utilizing one or more existing accelerators. In some cases the radioactive beam facilities are attached to production accelerators or reactors which exist primarily for other applications.

Table 1
Configurations of a few selected ISOL-type radioactive beam facilties, under construction and proposed

Project/Laboratory	Location	Primary beam accelerator	Secondary beam accelerator	Status
HRIBF	Oak Ridge	Cyclotron, k = 100 MeV	Tandem, 25 MV	Commission, ‘96
		Cyclotron, k = 200–250 p	Tandem + SC Booster, 50 MV	R&D
INS	Tokyo	Cyclotron, k = 67 MeV	RFQ + IH Linac, 14 MV	Test, 1996
	Tsukuba	Synchrotron, 3 GeV p	RFQ + IH Linac	JHP future
ARENAS	Louvain-la-Neuve	Cyclotron, k = 110 MeV	Cyclotron, k = 44 MeV	Constr./1998
SPIRAL/GANIL	Caen	Cyclotrons, k = 400 (HI)	Cyclotron, k = 265 MeV	Constr./1998
REX-ISOLDE	CERN	Synchrotron, 1 GeV p	RFQ + IH Linac, 16 MV	Constr./1998
ISAC/TRIUMF	Vancouver	Cyclotron, k = 500 (H^-)	RFQ + IH Linac, 13 MV	Constr./2000
PIAFE	Grenoble	Reactor, thermal n	Cyclotrons, k = 88, 160 MeV	R&D
ATLAS	Argonne	Linac, 245 MV	RFQ + SC Linac, 70 MV	R&D

To illustrate some of this variety, the configurations of a few ISOL-type radioactive facilities are listed in Table 1. A review of these new projects and others, including fragmentation-type facilities, was given by A. Mueller [7]; progress reports on several specific facilities will be included in the proceedings of the recent Fourth International Conference on Radioactive Nuclear Beams. Some of the challenges to be confronted in developing powerful, broad-based ISOL-type radioactive beam facilities are:

High intensity radioactive beams,
Cost effective solutions,
Exotic beams/ far from stable isotopes,
Excellent beam quality and energy variability,
Broad mass range of secondary beams,
High resolution isobar separation,
Diagnostics for tuning weak exotic beams,
Target/ion sources for high power primary beams,
Shielding and remote handling at production target.

Below, in separate sections, primary and secondary beam accelerators are discussed.

Driver Accelerators

A general-purpose facility for producing intense accelerated radioactive nuclear beams must incorporate a powerful driver device to generate large quantities of radionuclides. Some ISOL facilities have been located at high-flux research reactors to produce and study the neutron-rich isotopes produced via thermal neutron-induced fission of ^{235}U. The new radioactive beam project PIAFE [8], listed in Table 1, will utilize the ILL reactor at Grenoble as the production device. All other present projects are using or planning to use some type of accelerator as the driver device; either a synchrotron, cyclotron, or linac in various implementations. Essentially all existing or proposed radioactive beam facilities utilize either a pre-existing driver device or post accelerator, or both. The only proposed “green field” facility listed in Table 1 is that planned as part of the Japanese Hadron Project. Even in this case, however, the radioactive beam capability will coexist with other major research interests in an extensive accelerator complex.

Radionuclide-Production Mechanisms

The choice of driver device for a radioactive beam facility is intimately related to the overall goals of the laboratory and the capabilities of the secondary beam accelerator. In many instances, as mentioned above, the driver device is pre-existing and the other components must be adapted to its capabilities. For example, a reactor is a prolific source of medium-mass, neutron-rich radionuclides which result from thermal neutron fission. Hence, Phase II of the new PIAFE facility will be dedicated to the acceleration and study of nuclear reactions with this class of radionuclides. On the other hand, high energy proton synchrotrons can prolifically produce both proton-rich and neutron-rich isotopes over a broad mass range via the spallation reaction mechanism. The REX-ISOLDE collaboration [9] is constructing a secondary beam accelerator at ISOLDE to utilize the existing synchrotron and ion source infrastructure at that facility.

However, the costs of reactors and GeV energy proton synchrotrons probably exclude them from consideration as dedicated drivers for future radioactive beam facilities. For the production of radionuclides there are a variety of nuclear reaction mechanisms at the disposal of designers. With primary beams of protons and heavy ions in the energy range of 10’s to 100’s of MeV per nucleon several reaction mechanisms can be utilized: compound nucleus/fusion-evaporation reactions, primarily for proton-rich products; light-ion induced fission, primarily for medium mass, neutron-rich products; spallation reactions with intermediate energy (~100 MeV per nucleon) heavy ions; and fragmentation of heavy ions such as ^{18}O. A desirable driver accelerator for an advanced radioactive beam facility is one capable of delivering a variety of beam types over a range of beam energies. Such flexibility permits selecting a beam/target combination and an associated reaction mechanism to selectively populate radionuclides in a specific mass region.

A Proposed Heavy-Ion Linac Driver

A driver accelerator with a beam power of up to 100 kW would be desirable for radioactive beam production. Most experience to date is with up to a few kilowatts of beam power and improvements in target/ion source technology are expected to lead to higher beam powers being feasible. A linear accelerator capable of delivering a variety of ion species with beam power up to 100 kW at energies per nucleon of 100 MeV is shown schematically in Fig. 1. This is the type of driver accelerator suggested by the Argonne group in a working paper [10]. To accelerate light ions, such as ^{1}H, ^{2}H, and ^{4}He, a multicusp or microwave ion source and a light-ion RFQ would be used in the injector. Whereas, for heavy ions, such as ^{18}O, would require an ECR ion source operating with an m/q of 6, pre-acceleration in an RFQ and ion linac to an energy per nucleon of 5 MeV for stripping a higher charge state for further acceleration to 100 MeV per nucleon.

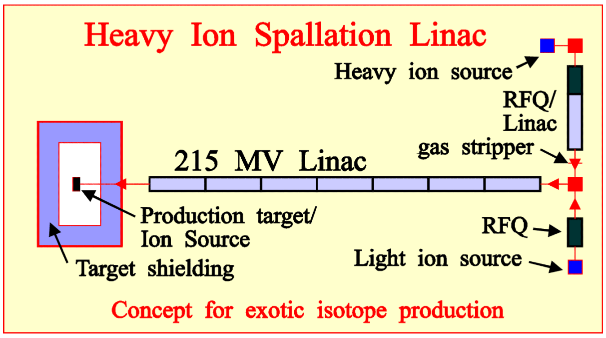

Fig. 1. Schematic view of a high-beam-power linac to deliver a variety of ion beams for radionuclide production.

Conventional Linac Option. The driver shown schematically in Fig. 1 could be implemented as a conventional linac with the parameters indicated in Table 2. The linac main stage could be a conventional DTL or possibly a CCDTL structure [11]. A preliminary physics design study of the DTL configuration for the heavy ions has been carried out by AccSys Technology, Inc. [12]. As indicated in Table 2 the beam currents for the heavy ions would be limited by the ion sources rather than by the linac beam power capability, due to the high peak current requirement.

Superconducting Linac Option. An alternative to the conventional DTL or CCDTL linac discussed above is a superconducting linear accelerator. This would involve the extension of the well-established technology now used for low energy heavy ion linacs to higher beam currents and to a somewhat higher velocity regime. Two technical advantages of a superconducting linac with CW beams are: (a) the continuous beam would eliminate a potential problem with voltage ripple at the production target/ion source, and (b) the heavy ion beam intensities available from a DC ion source would permit the achievement of much higher beam powers than with the low duty cycle conventional linac (as indicated in Table 2). Furthermore, the superconducting option is likely to be significantly less expensive to operate, by an estimated $2M/year, due to a much lower electrical power requirement and the elimination of the maintenance of the set of high-peak-power klystrons required for the conventional linac.

By using independently phased two- or three-gap superconducting resonators the velocity range possible with such structures would permit the nominally 200 MV linac to deliver beams of 200 MeV protons as well as the 100 MeV per nucleon heavy ions with m/q~2 as discussed above; this is a very useful additional beam for radionuclide production purposes. There are several well established superconducting structures for ion velocities up to about 0.15c [13], but this application would require the extension of this technology up to v = 0.55c. Prototypes of structures which could possibly be modified for operation in this velocity regime have been developed and tested by Delayen, *et al*. [14], one of which is illustrated in Fig. 2. Alternate geometries, including a "spoke" structure, have been proposed by Delayen, *et al.* [15].

Table 2
Parameters of a Conventional Drift Tube Production Linac

Max Output Beam Energy:	100 MeV per nucleon
Max Output Beam Power:	100 kW
Typical Light Ions: (microwave ion source)	^{1}H, ^{2}H, ^{4}He
Typical Heavy Ions: (pulsed ECR ion source)	$^{12}C^{2+,6+}$; $^{16,18}O^{3+,8+}$; $^{20,22}Ne^{4+,10+}$; $^{36}Ar^{6+,16+}$
Typical Max. Currents: (Light Ions @100 kW)	^{1}H, 1 mA; ^{2}H, 0.5 mA; ^{4}He, 0.25 pmA
Typical Max. Currents: (Heavy Ions @100 kW)	$^{18}O^{8+}$, 55 pμA; $^{36}Ar^{16+}$, 28 pμA
Typical Ion Currents: (Source/Stripping Limits)	$^{18}O^{8+}$, 20 pμA; $^{36}Ar^{16+}$, 3 pμA

Linac Specifications:

Injector RFQ/Linac:	5 MeV/u output @q/m = 1/6, (30 MV)
Main Linac:	100 MeV/u out @q/m = 8/18, (215 MV)
Duty Cycle:	2.5% @ 120 Hz
Input Power:	1.75 MW
Output Energy Variation:	15% increments
Controls:	Pulse-pulse ion source and energy variation possible

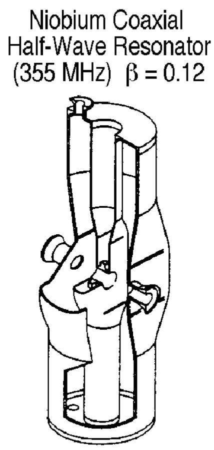

Fig. 2. A two-gap superconducting niobium resonator which was constructed and tested at ANL by Delayen, *et al.* [14].

Papers presented at this conference by K.C. Chan and G. Geschonke discuss possible uses of superconducting linear accelerators for very high power applications, such as for neutron spallation sources, transmutation of waste, and production of tritium. To date these applications are considering superconducting structures for velocities above 0.5c, to be operated at higher frequencies and lower temperatures. For the radioactive beam driver accelerator application it seems desirable to keep the frequency below about 400 MHz so that operation at 4.5 K is economically feasible. To keep the capital cost of a superconducting driver competitive with that of a conventional linac, efficient fabrication methods for structures in this low-velocity regime will have to be developed [16].

Other Driver Accelerator Options.

As indicated in Table 1 above several radioactive beam projects are using synchrotrons or cyclotrons as the driver accelerators. Synchrotrons are generally used in projects which share the accelerator with other applications, typically for high energy physics research, as in the case of ISOLDE and the Japanese Hadron Project. There is also the possibility that there will be a proposal to use the rapid cycling synchrotron of the ISIS facility at the Rutherford Appleton Laboratory in Great Britain as the driver for a future radioactive beam facility [17]. These synchrotrons use high energy protons to produce radionuclides via spallation reactions.

The cyclotrons at GANIL will be used with beam power up to 6 kW and a variety of species from deuterons to heavy ions at energies up to 100 MeV per nucleon to produce radionuclides for the new SPIRAL facility [18] via various production mechanisms including fragmentation and light ion induced fission. The cyclotrons at GANIL have been in operation for several years for basic research in nuclear physics including the production of radioactive beams via the fragmentation mechanism. The SPIRAL project is an upgrade which gives the laboratory the option to produce radioactive beams via both fragmentation and the ISOL-method.

Similarly, the existing 500-MeV H^- cyclotron at TRIUMF will be used as the driver for the new ISAC radioactive beam project [19]. The initial plans are to use beam currents up to 10 μA, and to increase to higher currents as the target/ion source technology permits.

The HRIBF project [20], currently in commissioning stages at ORNL, is using the existing ORIC cyclotron as the driver, but there are plans to possibly upgrade to an advanced radioactive beam facility in the future, which would involve the addition of a more powerful driver accelerator. Various types of cyclotron are currently under consideration, including compact superconducting and conventional separated sector styles [21], either of which could deliver 250 MeV proton beams at currents of 100–200 μA. A review of cyclotrons which could be constructed for use as drivers was given recently by Y. Jongen [22].

Post-Accelerators

The requirements of the post-accelerator of an advanced radioactive beam facility are to a large extent dictated by the choice of ion source for the secondary beams. Two common classes of ion source are the standard ISOL-type 1+ sources as used at ISOLDE [4], GSI [23], and other on-line isotope separator facilities, and higher charge-state sources as are planned for use, for example, at SPIRAL [18]. The ISOL-type 1+ ion sources have been developed to have high efficiencies and excellent emittances for a broad range of elements, but place great demands on the post-accelerator due to the very low q/m values for heavy masses. ECR ion sources generally have worse emittances, but have been demonstrated to have good efficiencies for noble gases, and are under development for other elements [24]. Other developments are in progress to use ISOL-type ion sources in combination with an ion trap plus an EBIS device [9] or with an ECR "catcher" [25] to increase the charge states.

Post-Accelerators Based on Linacs.

The Argonne Post-Accelerator Proposal. The Argonne concept for an advanced radioactive beam facility [10] is to build on the present capability of the ATLAS superconducting linacs to deliver beams from protons to uranium with excellent transverse and longitudinal beam quality [26]. The injector stage of the post-accelerator is being designed [27] to start with 1+ ions with masses up to about 200 from ISOL-type ion sources; a schematic layout is shown in Fig. 3. The design of a CW, low-frequency RFQ for the first stage of this injector was presented at this conference [28]. This concept involves stripping of the 1+ ions to 2+ or 3+ after the first stage RFQ. High stripping efficiencies with very low multiple scattering (<1 mr) have been demonstrated for Kr, Xe, and Pb ions using a low-pressure windowless gas cell [29]; charge-state fractions for 1-MeV Pb ions in helium and nitrogen are shown in Fig. 4.

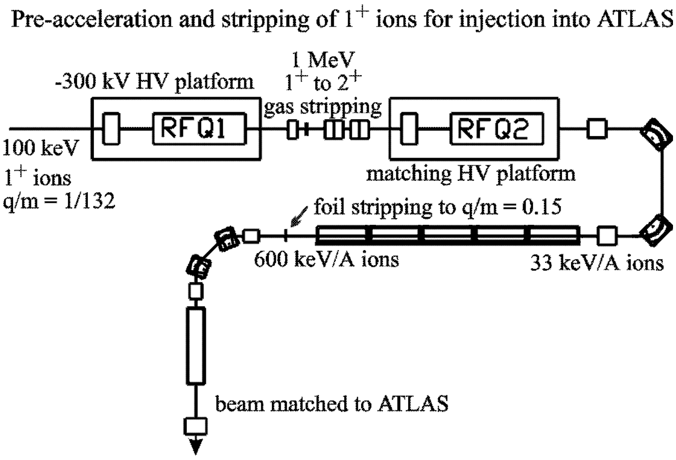

Fig. 3. Block diagram of the ANL concept for a radioactive beam pre-accelerator beginning with 1+, mass 132 ions from an ISOL-type ion source.

RFQ + IH-Linac Combinations. Several radioactive beam facilities [19, 30, 9, 31] are using normally conducting low-frequency RFQ structures followed by IH-linacs to take advantage of the high shunt impedances obtainable with such structures. Two of these [19, 31] will operate CW.

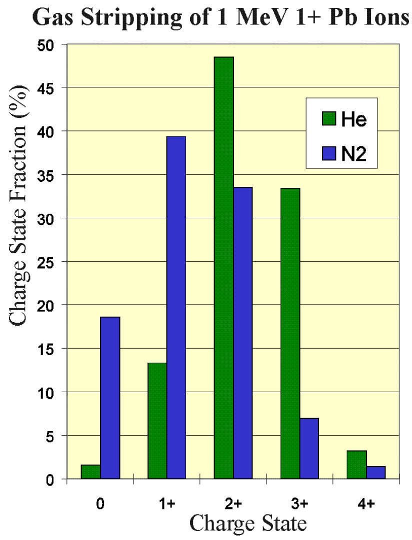

Fig. 4. Charge state distributions for 1-MeV ^{208}Pb ions in thin helium and nitrogen gas, illustrating the enhancement of 3+ ions from helium relative to nitrogen [26].

Other Post-Accelerator Options.

Cyclotrons. The SPIRAL [18], ARENAS [5], and PIAFE [8] projects will all use cyclotrons as the radioactive beam post-accelerators. The CIME cyclotron, currently nearing completion at GANIL for the SPIRAL project is shown schematically in Fig. 5. A specific advantage of cyclotrons over linacs is that being isochronous and with high turn numbers they are m/q selective with resolutions up to 10,000. A disadvantage is that, to achieve high beam energies, ions with relatively high q/m values are required.

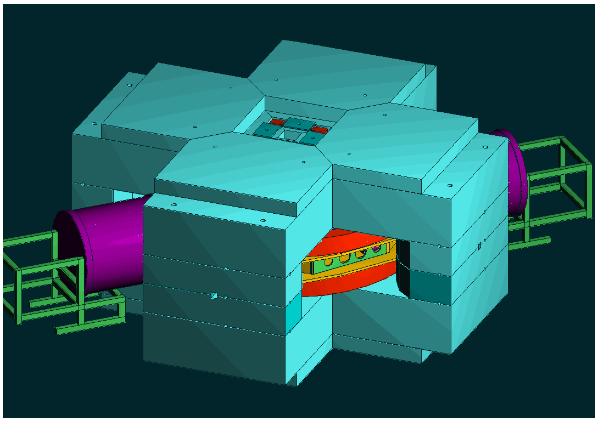
Fig. 5. CAD layout of the CIME k = 265 MeV cyclotron currently under construction at GANIL as the post accelerator for the SPIRAL radioactive beam project.

Tandems. The HRIBF facility at Oak Ridge is using the existing 25 MV tandem as the post accelerator [20]. It produces beams with low transverse emittance at energies useful for nuclear physics over a broad mass range for any ion species which can be either directly extracted as or charge exchanged into a negative ion.

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