DESIGN OF A POST ACCELERATOR FOR THE RARE ISOTOPE ACCELERATOR FACILITY*

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Abstract

The proposed Rare Isotope Accelerator (RIA) Facility includes a post-accelerator for rare isotopes (RIB linac) which must produce high-quality beams of radioactive ions over the full mass range, including uranium, at energies above the coulomb barrier, and with high transmission and efficiency. The latter requires the RIB linac to accept at injection ions in the 1+ charge state. A concept for such a post accelerator suitable for ions up to mass 132 has been previously presented [1-3]. This paper presents a modified concept which extends the mass range to uranium. The RIB linac will utilize existing superconducting heavy-ion linac technology for all but a small portion of the accelerator system. The exceptional piece, a very-low-charge-state injector section needed for just the first few MV of the RIB accelerator, consists of a pre-buncher followed by several sections of cw, normally-conducting RFQ. Two stages of charge stripping are provided: helium gas stripping at energies of a few keV/u, and additional foil stripping at ~600 keV/u for the heavier ions. In extending the mass range to uranium, however, for best efficiency the helium gas stripping must be performed at different energies for different mass ions. We present numerical simulations of beam dynamics for a design for the complete RIB linac which provides for several stripping options and uses cost-effective solenoid focussing elements in the drift-tube linac.

1 LINAC DESIGN CONCEPT

The RIB accelerator system must have the following properties:

- Efficiently accept and accelerate ions over the full mass range, including uranium.
- Provide an output beam at any energy up to 5-10 MeV/nucleon.
- Maintain a longitudinal emittance of a 0.5 π keV/u·nsec over the full range of energy and mass.

An important technical challenge is to design a linac for low-charge-state ions which can provide low longitudinal emittance (i.e. good time and energy resolution). The ability of the linac to maintain small longitudinal emittance, will be critical in enabling experiments to use time-of-flight techniques while simultaneously having available good energy resolution and adequate beam intensity.

The technology developed for existing superconducting heavy-ion linacs, characterized by excellent performance and a very high degree of modularity, provides a basis for all but a small portion of such a RIB accelerator system. The exceptional piece is a very low charge state injector section. The most efficient generation of beams of rare isotopes requires singly charged ions at initial injection. Very low charge state ions can most efficiently be bunched and accelerated by using several sections of cw, normally-conducting RFQ for the first few MV of the RIB accelerator .

The design goal for the RIB linac is to accelerate heavy ions in the mass range from 6 to 240, starting with ions at charge state 1+. As discussed in references [3,4], the RIB linac provides for charge stripping at two stages: non-equilibrium gas stripping at energies of ~10 keV/u, and an additional foil stripping at ~600 keV/u for the heavier ions.

In operation, radioactive nuclei will be either collected or ionised at charge state 1+ and extracted at a voltage of 100 kV. A state-of-the-art high-acceptance isobar separator with mass resolution m/Δm≈20000 [5] will provide final separation of the desired species. For further acceleration, the velocities of different ions must be matched into the normally-conducting injector RFQ. This is accomplished by mounting the first two sections of RFQ on a variable voltage platform.

For best efficiency over the full mass range, helium gas stripping must be performed at different energies for different mass ions. The linac following this stripping can accelerate ions of charge to mass ratio 1/66 and above. By stripping at 7 keV/u some 55% of an incident ^{132}Sn beam, for example, can be stripped into charge state 2+ and further accelerated. For the heavier ions, higher charge states are required, for which the best stripping efficiency is achieved at higher energy. Figure 1 shows the efficiency of helium stripping [4] as a function of beam energy with charge number as a parameter. The yield of heavy ions is shown at charge state q which is required for the following accelerator section. To cover the full mass range, we propose to provide options for He gas stripping at either of two energies: at 7 keV/u for the lighter ions, and for ions of Z>54, at 20 keV/u. Providing two different options for helium gas stripping ensures a high efficiency of operation over the full mass range, including mass 240. In the proposed RIB linac ions with masses 66 and below do not require this helium gas stripping.

The RIB linac consists of the following main sections (see Fig. 2):

- An injector with three sections of normally-conducting RFQ.
- A superconducting linac which will accelerate ions of q/m > 1/66 to 600 keV/u or more.

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- A carbon-foil stripper at W_n>600 keV/u, when necessary, to provide a q/m>0.12 for the last stage of acceleration. The beam energy at this point depends on the particular charge-to-mass ratio.
- A superconducting linac to accelerate ions of q/m > 29/240 to energies of 6 MeV/u or higher.

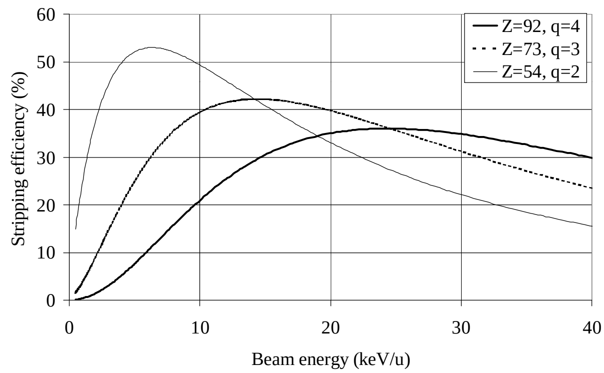

Figure 1: Helium stripping efficiency of heavy ions as a function of beam energy.

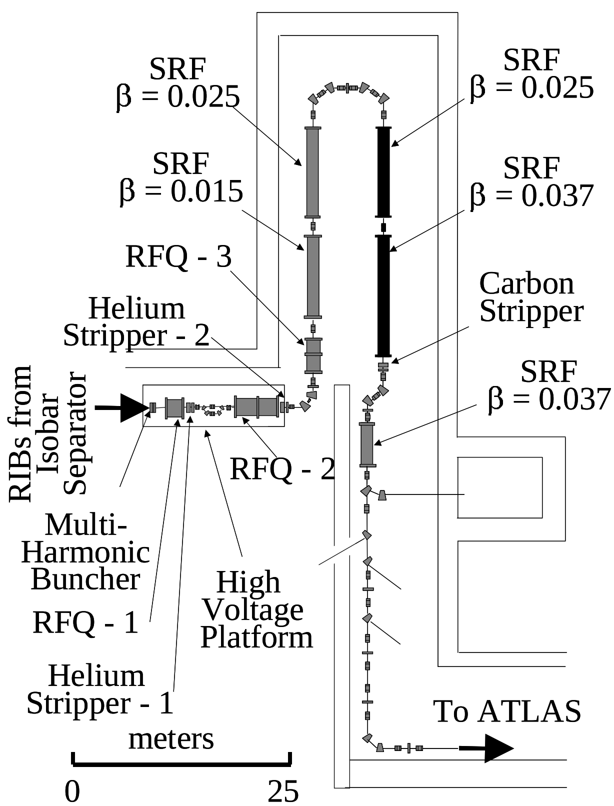

Figure 2: Schematic view of the Rare Isotope Beam linac.

2 NORMAL-CONDUCTING RFQ INJECTOR SECTIONS

The buncher, the first two sections of 12 MHz RFQ, and both He gas-stripper cells will be placed on a 380 kV open-air variable-voltage platform. Placing these elements on a variable voltage platform allows operation with a fixed constant velocity profile for the full mass range of ions, including uranium. The output of the first section is at 7 keV/u, and the beams of 66 < mass < 133 will be charge-stripped at this point. Whether stripped or not, ions of any mass and charge state, including mass 240 at charge state 1+, will be further accelerated by the next section of the 12 MHz RFQ to an energy of 20 keV/u. At this point the beams of mass > 132 will be stripped. The third section of RFQ will operate at 24.25 MHz and accelerate the ions, now at a charge state q/m > 1/66, to an energy of 62 keV/u for injection into the superconducting linac.

The 12 MHz four-harmonic bunching system which is presently in use on the ATLAS accelerator may be most suitable for this application. The RFQ should operate at as low a frequency as is practicable to maximize the transverse focusing strength. As has been demonstrated at Argonne National Laboratory (ANL) the split-coaxial RFQ geometry is appropriate for operation at 12 MHz [6]. The RFQ is designed for a minimum charge-to-mass ratio of 1/240. Ions of higher charge state are accommodated by simply scaling both the platform voltage and the RFQ rf voltage to match. The acceleration of very low masses may require operation at rf voltages below the linear region of the drive amplifiers, and additional low power rf amplifiers may be required in order to properly stabilize phase and amplitude of the accelerating fields. The proposed cw inter-vane voltage of 92 kV with a mean bore radius of 9 mm has been proven entirely practical in extensive tests of the prototype 12 MHz RFQ at ANL.

Numerical simulations of the beam dynamics through the entire chain of RFQ sections have been performed. The proposed design achieves longitudinal emittance as low as 0.2 π keV/u·nsec for 80% of the DC beam entering the buncher. Several rf bunchers are required for matching. Transverse focusing in the transitions can be done with either electrostatic quadrupoles or SC solenoids. The last two sections of the RFQ will be based on a more effective accelerating structure, a hybrid RFQ [7]. Our studies show excellent properties of the hybrid RFQ for acceleration of low charge-state slow heavy ions.

Light ions will exit the HV platform above the input matched velocity of the following ground-potential RFQ. To achieve velocity matching for these ions, a rf cavity with effective voltage ~60 kV is required. Such a voltage can easily be produced, for example, by a normally-conducting folded-quarter-wave resonator with ~1 kW rf power.

3 SUPERCONDUCTING INJECTOR LINAC (BETWEEN THE STRIPPERS)

The low-charge-state injector linac can be based on established interdigital drift-tube SC niobium cavity designs, which can provide typically 1 MV of accelerating potential per cavity in this velocity range. The low charge-state beams, however, require stronger transverse focusing, than is used in existing SC ion linacs. For the charge states considered here (q/m = 1/66) the proper focusing can be reached with the help of strong SC solenoid lenses with fields up to 15 T. Commercial vendors now offer a wide range of high field magnets in the range of 10 to 17 Tesla [8]. These magnets are based on solenoids made of NbTi and Nb_3Sn. A 30 cm length, 3 cm bore, 15 T solenoid, for example, is currently available for ~$55K including power source, leads and controls.

The SRF linac consists of 54 interdigital cavities operating at -20° synchronous phase, and each cavity is followed by a SC solenoid. This linac can accelerate any beam with $q/m \geq 1/66$ over the velocity range $0.0011 \leq \beta \leq 0.04$.

Since the solenoids will operate at appreciably higher fields than in the present-day ATLAS linac, in order to protect the superconducting cavities from the solenoid magnetic fields more magnetic shielding will probably be required. We have allowed for this by assuming the focusing periods to be relatively long. Figure 3 shows the results of numerical ray tracing for a $^{132}Sn^{2+}$ beam of normalized transverse emittance $\varepsilon_T = 0.1\ \pi$ mm·mrad. The longitudinal emittance growth through the linac is negligible. For the simulation, the longitudinal emittance at input was taken to be 0.3 π keV/u·nsec. Using Monte Carlo simulations, we have calculated the longitudinal acceptance of each section of the SRF linac. The acceptance calculated as an ellipse area inserted into the detailed shape of the bucket is an order of magnitude or more larger than the beam emittance. This insures a conservation of longitudinal emittance throughout the SRF linac.

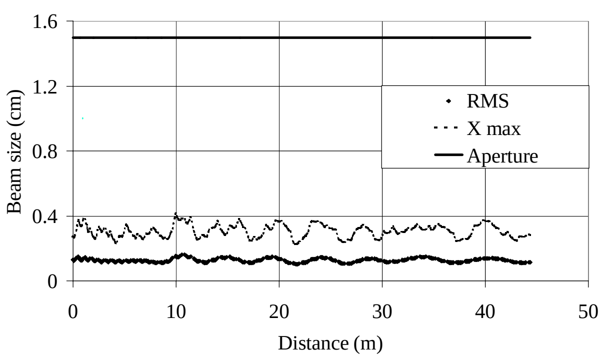

Figure 3: Beam rms size and envelopes along the RIB SRF Linac.

4 ATLAS SECTION

After the second stripper, the desired charge state must be selected and further accelerated to the beam velocity required to match to the ATLAS linac section in order to provide the last stage of acceleration to the desired beam energy. A short 45° jog is planned to select the desired charge state producing an offset in the beamline and additional space in an existing area for experimental beamlines as shown in Fig. 2.

Further acceleration is required in order to bring the beam energy to approximately 1.4 MeV/u and match the velocity acceptance of the β_G=0.06 resonators in ATLAS. An additional eight SRF cavities of β_G =0.037 are required for this stage.

A two-magnet achromatic 90° bend directs the beam into the existing ATLAS linac with transverse focusing and matching into ATLAS using quadrupole doublet lenses in this section of the transport line. The longitudinal beam matching into ATLAS is accomplished with an existing superconducting rebunching resonator in the ATLAS injection beamline.

The new, low-velocity portion of the Rare Isotope Beam linac matches into the existing ATLAS linac at the start of the split-ring resonator section of ATLAS. The existing 12-MV Positive Ion Injector (PII) linac of ATLAS is not planned to be used as part of the RIB linac. The PII section of the present ATLAS linac may still be used for certain experiments requiring stable beam acceleration as part of the total experiment and is also available as an alternative acceleration scheme for rare isotopes if the ECR charge breeder approach is incorporated into the facility at a later date.

The beam energy at the match point into ATLAS for the low-velocity RIB linac will be approximately 1.4 MeV/u. Following this point, the ATLAS linac consists of 12 'low-beta' (β_G =0.06) resonators and 30 'high-beta' (β_G =0.105) resonators of the 'split-ring' class. An existing 'spare' cryostat will be outfitted with new eight quarter-wave resonators designed for β_G =0.15 and installed at the end of ATLAS. With this addition, 38 high-beta resonators will be available and the voltage of the present ATLAS configuration will be enhanced.

5 CONCLUSION

The RIB linac for the RIA facility is mainly based on low velocity SRF cavities and the existing ATLAS linac. Initial acceleration up to 62 keV/u is provided by room temperature RFQ structures. This section of linac accepts singly-charged ions with mass number up to 240. The use of a gas stripper at 7 keV/u or 20 keV/u provides high stripping efficiency and generates beams with charge-to-mass ratio ≥1/66 for further acceleration.

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