Beam Tests of the 12 MHz RFQ RIB Injector for ATLAS

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Abstract. In recent tests without beam, the Argonne 12 MHz split-coaxial radio-frequency quadrupole (RFQ) achieved a cw intervane voltage of more than 100 kV, the design operating voltage for the device. This voltage is sufficient for the RFQ to function as the first stage of a RIB injector for the Argonne Tandem Linear Accelerator System (ATLAS). Previously reported beam dynamics calculations for the structure predict longitudinal emittance growth of only a few keV·ns for beams of mass 132 and above with transverse emittance of 0.27 π mm·mrad (normalized). Such beam quality is not typical of RFQ devices. The work reported here is preparation for tests with beams of mass up to 132. Beam diagnostic stations are being developed to measure the energy gain and beam quality of heavy ions accelerated by the RFQ using the Dynamitron accelerator facility at the ANL Physics Division as the injector. Beam diagnostic development includes provisions for performing the measurements with both a Si charged-particle detector and an electrostatic energy spectrometer system.

INTRODUCTION

A prototype RFQ accelerator [1] suitable for the initial stage of a secondary-beam accelerator system for an ISOL-type source of radioactive ions has recently been completed. Initial tests of this RFQ [2] have already shown that the RFQ is capable of running cw at an intervane voltage of 102 kV, a value above the design operational level of 100 kV, with an rf input power of 17 kW.

The RFQ is planned to be the initial element of a preaccelerator injector system for radioactive ions into the existing ATLAS accelerators [3,4] and, because of the excellent beam quality of ATLAS, the RFQ will determine the beam quality of the facility. In particular, the longitudinal emittance growth needs to be much smaller than that of typical RFQ implementations.

The ISOL-type ion sources appropriate for RIB produce ions having a low charge state ($q = 1$). The benchmark beam used for the RFQ design was radioactive ^{132}Sn both because of interest in this beam in the nuclear physics research community, and also because mass $A = 132$ represented a considerable increase in mass beyond previously developed RIB injectors for singly-charged ions ($A = 30$).

Numerical simulation of the RFQ beam dynamics for $A/q = 132$ ions [1] indicate a longitudinal emittance growth of only 1.4 π keV·ns through the RFQ structure. Experimental tests are needed to verify these calculations. These tests are to be made with stable beams, using ions of similar mass-to-charge ratio $A/q \leq 132$.

EXPERIMENTAL SETUP

Beam tests of the RFQ are being set up at the 4 MV Dynamitron facility at the ANL Physics Division. The Dynamitron is capable of operating at voltages in the range of about 0.2–4 MV and can deliver high-current positive-ion beams of a variety of species and charge states. A dedicated beam line is under construction which will couple the post-Dynamitron beam transport system to the RFQ. A schematic view of the Dynamitron and existing beam transport system relative to the position of the RFQ is shown in Fig. 1. To inject beam into the RFQ, ions exiting the Dynamitron are first deflected $-8°$ (relative to the initial ion trajectory) by a magnetic dipole ($M1$) magnet and then by $-25°$ with a second $M1$ magnet. Horizontal and vertical steering can be obtained using $M1$ deflectors internal to the Dynamitron, but additional steering is available from a set of three $M1$ magnets located along the beam line (see Fig. 1). Transverse focusing in this beam line section is provided by a single magnetic quadrupole doublet lens located about 3.9 m from the RFQ entrance. Electric quadrupole triplet lenses will eventually be added near the RFQ entrance and exit to provide the proper radial matching needed for $A = 132$, low-velocity beams.

Beam diagnostics systems for both the pre- and post-RFQ beam lines are currently under development. A planned layout of the initial systems and their relation to the RFQ is shown in Fig. 2. As shown in the figure, there will be three beam diagnostics and control systems before beam is injected into the RFQ. A Faraday cup will be used to measure beam current, and a wire scanner will be used to measure the transverse profiles of the beam. Adjustable slits will be used to control the intensity and position of the beam entering the RFQ. Ions accelerated by the RFQ will encounter similar diagnostic systems, as shown in Fig. 2. At this point, however, we require additional diagnostics capable of measuring ion energy and arrival times. For this purpose, two diagnostic systems are under development which will be discussed in detail in the next section.

DIAGNOSTICS FOR ACCELERATED BEAM

Beam diagnostic stations are being designed to measure the energy and beam quality of heavy ions ($A/q \leq 132$) accelerated by the RFQ. Energy measurements of heavy ions in the relatively low-energy regime such as that expected from the initial acceleration of exotic beams pose particular challenges which need to be addressed during the diagnostic design process. Therefore, a system of two complementary diagnostic stations is being developed (see Fig. 2).

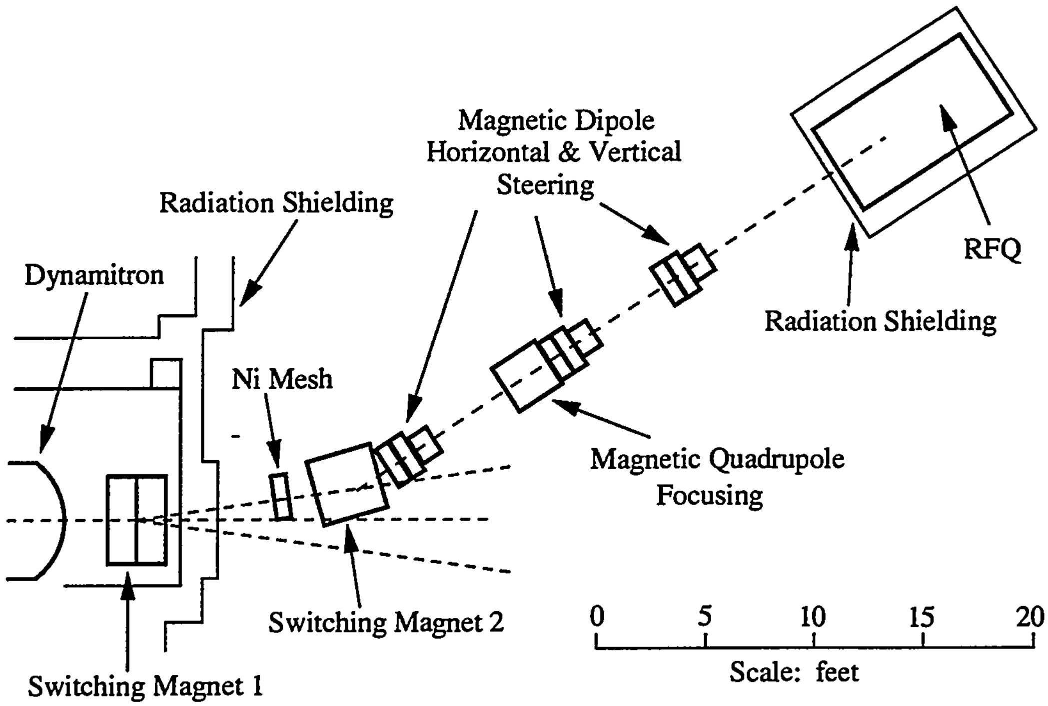

FIGURE 1. Schematic showing an overhead view of the current beam transport system between the Dynamitron injector accelerator and the RFQ.

The first diagnostic station (labeled Diag 1 in Fig. 2), which will be placed approximately 74 cm from the RFQ exit, consists of a Faraday cup to measure beam transmission through the RFQ, and a silicon (Si) charged-particle detector to measure the beam energy and arrival times. Both devices are retractable to both intercept the beam and to allow the beam to pass through when desired. The choice of including a Si detector was based on the relative ease of performing pulse-height (energy) spectrometry on a beam of incident heavy ions with the option of deriving a high resolution (< 1 ns), fast timing signal which would be useful for longitudinal emittance measurements. However, difficulties arise from the beam characteristics of this particular application and from constraints inherent to the Si detector itself. Considering the relatively low beam energies expected following RFQ acceleration, there will be a significant pulse-height signal defect from the output of the Si detector due to energy losses occurring in the front surface electrode and Si crystal dead layer. Detectors using an ion-implanted, ≈ 500 Å thick boron front-surface electrode contact should suffice for this application. Moreover, the large amount of charge carriers liberated by the heavy ion beam may degrade the energy resolution, but utilizing a detector with a minimal Si depletion depth and increasing the bias voltage will enhance the electric field strength and hence the charge collection capabilities.

The beam flux incident on the Si detector must be kept to a minimum, such that

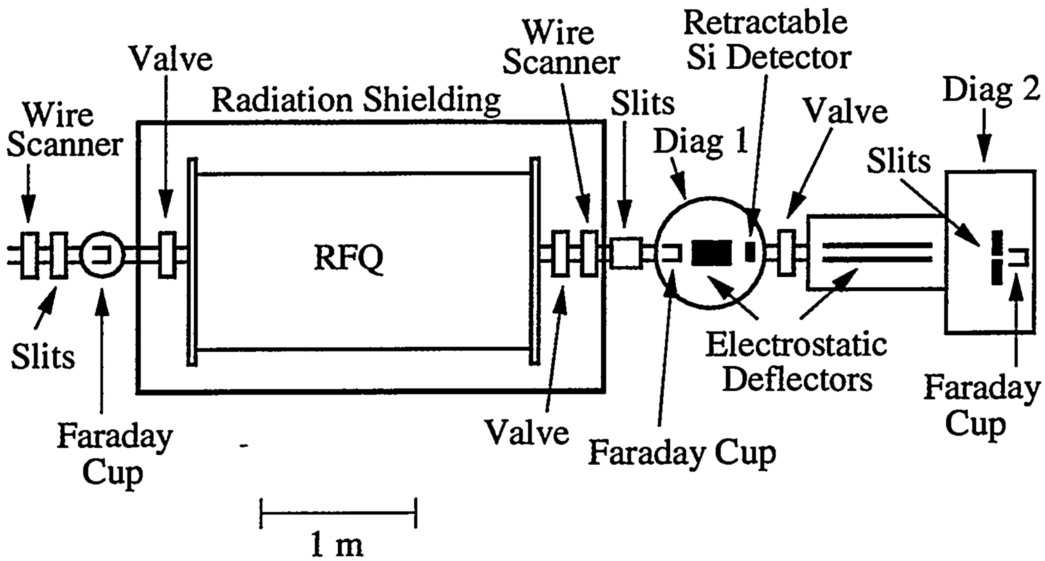

FIGURE 2. Schematic showing an overhead view of the proposed beam diagnostic stations used at the entrance and exit sections of the RFQ.

less than about 1000 heavy ions are incident on the detector each second to avoid Si crystal damage. Initially, the detector will be placed at 0° relative to the beam direction since very low-energy ions will be used and since proper beam current reduction can be achieved with the inclusion of beam degraders, apertures, and slits. One such set of degraders includes the overlap of five electroformed nickel meshes, each having wires that are 0.00020 in. thick spaced 0.00020 in. apart, forming a grid of 2000 wires per inch. The meshes are placed between the two switching magnets (see Fig. 1) to ensure that only ions not suffering from an energy loss upon passage through the meshes will be injected into the RFQ. Preliminary tests with a ^{132}Xe beam have shown that these meshes reduce beam intensity by a factor of 10^3. Overall, intensity reductions on the order of 10^8 were achieved by adding a $\frac{1}{16}$ in. diameter aperture and a pair of adjustable jaw slits. Future experiments could reduce beam intensities by performing elastic scattering from a very thin ($\sim 30\mu$g/cm^2) gold foil placed near the Si detector.

A separate but complementary diagnostic system, shown as Diag 2 in Fig. 2, is also under development. It comprises an electrostatic energy spectrometer system in which a set of parallel plates, with a given potential difference between them, will deflect a charged-particle beam according to the energy and charge of the ions. The location and intensity of deflected beam is then quantified by a Faraday cup positioned at a point offset from the undeflected beam axis. Slits are placed in front of the Faraday cup to limit the uncertainty in the beam position. If the Faraday cup position is held fixed, then the beam energy may be deduced by measuring the beam current on the Faraday cup as a function of a varying potential difference between the plates and comparing the results with that expected from theoretical predictions. Such a system has the advantage of performing an energy measurement rather easily regardless of the incoming beam intensity, however it lacks timing information unless a time-of-flight system is coupled to the fore mentioned diagnostics. Use of this system is also motivated from the fact that the electrostatic plates and their vacuum housing have already been fabricated, installed, and optically aligned from use in past atomic physics experiments.

EXPERIMENTS WITH BEAM

As mentioned in the Introduction, a wide variety of beams which satisfy the condition of $A/q \leq 132$ may be accelerated by the RFQ. Ions having A/q values less than 132 are accommodated by simply scaling the RFQ vane voltage and by maintaining the appropriate ion injection velocity profile. However, since it is the goal of the prototype RFQ to successfully accelerate $A/q = 132$ radioactive ions, this discussion will focus primarily on experiments intended to test this capability. In order to simulate the conditions expected from radioactive ^{132}Sn beams, the RFQ will need to operate at an intervane voltage of 100 kV, and in cw mode with the intent to preserve beam intensity. Only routine high-voltage conditioning of the RFQ appears to be needed for this based on the results of earlier tests [2].

Stable beams of singly-charged ^{132}Xe ions may be used to simulate the conditions expected for ^{132}Sn beam extracted from an ISOL-type ion source. Beam dynamics calculations which have investigated the acceleration of ^{132}Sn [1] have shown that ions with $A/q = 132$ will be accelerated by the RFQ to a velocity of $0.0049c$ (corresponding to an energy of 1508 keV) if they are injected with an initial velocity of $0.0025c$ (corresponding to an energy of 378 keV). Identical injection velocities can be obtained for ^{132}Xe ions using a Dynamitron terminal potential of 378 kV.

The RFQ was designed with external bunching primarily to enhance beam quality, but also to increase efficiency by using the full length of the RFQ for acceleration. Initial beam tests will inject dc (unbunched) beams into the RFQ and hence result in reduced beam transmission. However, beam simulations predict that about 30% of the incoming ions will lie in the proper rf phase bucket to emerge from the RFQ having the maximal energy gain. Longitudinal matching will be provided in the future from a bunching system similar to the 12 MHz gridded-gap, four-harmonic system presently in use for the ATLAS accelerators [5].

Preliminary measurements of accelerated beam will focus on verifying the energy gain expected for $A/q = 132$ ions from theoretical calculations. Both diagnostic systems mentioned earlier could be used to independently check this result. Standard spectroscopic techniques could be used to obtain an ion energy spectrum using the Si charged-particle detector. The electrostatic energy spectrometer system would also be effective for measuring the energy of these $A/q = 132$ ions, as demonstrated by the results of a simulation using the SIMION code shown in Fig. 3. The calculations utilized the existing dimensions of the pair of plates, as shown in the figure, and assumed a drift space of 46 cm based on an existing vacuum chamber coupled

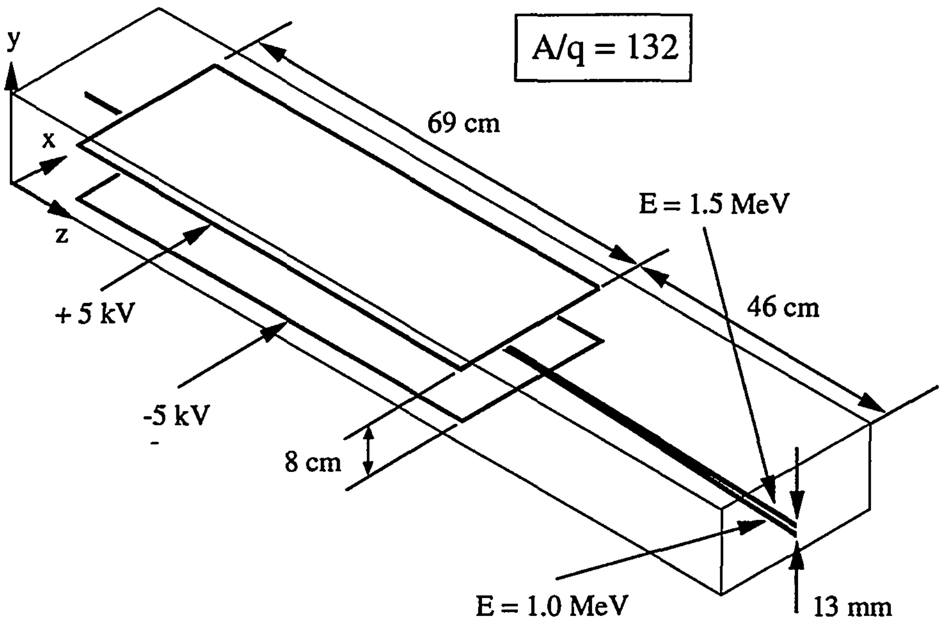

FIGURE 3. Results of a SIMION simulation indicating the flight paths of 1.0 MeV and 1.5 MeV beams, each having $A/q = 132$ and diameters of 6 mm, through a potential difference of 10 kV between a pair of electrostatic deflector plates having the dimensions as indicated. The y-direction deflection difference of 13 mm refers to the centroid position of each beam.

to the chamber which houses the plates. Monoenergetic 1.0 MeV and a 1.5 MeV beams, each with $A/q = 132$ and 6 mm in diameter, were allowed to travel through the electric field generated by the plates and the field-free drift space. When a potential difference of 10 kV is applied between the plates, the calculations show that the centroid positions of the two beams are separated by 13 mm at the termination of the drift space, indicating that energy resolutions on the order of 500 keV can be expected from this system. This is comparable to the typical energy resolutions of Si detectors performing heavy-ion spectroscopy.

Further tests will probe the transverse and longitudinal emittances of the beam and compare them to the predicted results [1]. Of particular interest is the quality of the longitudinal emittance, since calculations with a bunched ^{132}Sn beam show that a value of 6.1 π keV·ns is predicted at the RFQ exit, assuming an input longitudinal emittance of 4.7 π keV·ns. These values are substantially smaller than typical RFQ implementations, but are required to maintain the beam quality of the existing ATLAS accelerators. Figure 4 shows the numerically simulated longitudinal emittance of 200 ^{132}Sn ions which were accelerated by the RFQ after being injected in 1 ns bunches. From the figure, it is clear that the energy spread $\Delta E \approx 20$ keV of the bunch is much smaller than the intrinsic resolutions of both the Si detector and electrostatic energy spectrometer systems mentioned above. In fact, for the energy spectrometer to achieve the same separation as shown in Fig. 3

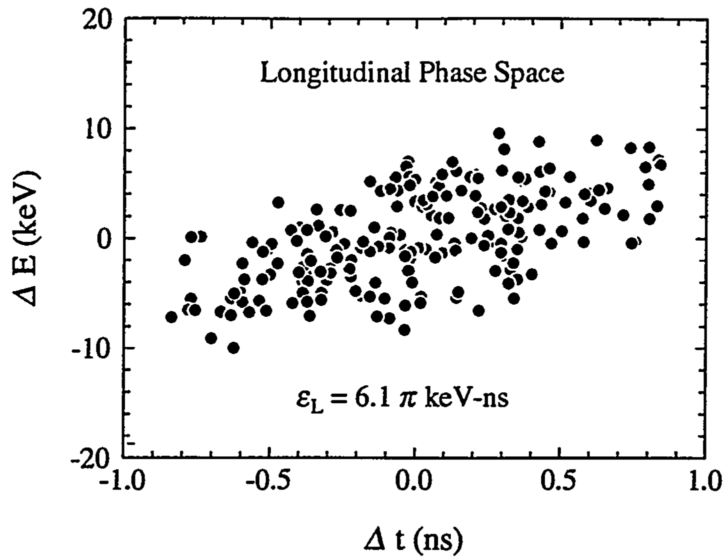

FIGURE 4. Numerically simulated longitudinal phase space of 200 ^{132}Sn ions at the exit of the RFQ [1].

(13 mm) of beams differing in energy by only 20 keV, then calculations show that a plate potential difference of 30 kV and a drift space of 6.8 m is required. A more physically reasonable way to measure the longitudinal emittance would make use of the timing information of the beam. A time width of $\Delta t \approx 2$ ns is predicted for each beam bunch at the RFQ exit, as seen from Fig. 4, which is within the timing resolution of many Si detectors. Therefore, precise timing correlations can be measured between beam bursts and rf pulses from the RFQ. Moreover, this same timing technique may be used to accurately determine the velocity and hence the energy of the beam. A comparison of the time differences between beam and rf pulses as measured by the Si detector at two different positions along the beam axis could give a very accurate determination of ion velocities. Since the exit velocity of the mass 132 ions of interest are about 1.47 $\times 10^6$ m/s, or 0.147 cm/ns, changes on the order of nanoseconds can be seen in the time correlation between beam and rf pulses for ion flight path differences on the order of millimeters, making this technique quite reasonable to implement. The energy spectrometer may also be used for this measurement if a time-of-flight system is incorporated. One possibility involves the installation of a fast Faraday cup in the Diag 2 chamber of Fig. 2.

SUMMARY

Preparations for beam tests of the Argonne 12 MHz RFQ are in progress. Since the RFQ is intended to be the initial component of a pre-accelerator injector system of radioactive beams into the existing ATLAS accelerators, the tests will proceed with the intent to simulate the conditions of the benchmark beam of exotic ^{132}Sn.

Tests without beam demonstrated that the RFQ is capable of sustaining an operating intervane voltage of 100 kV cw and is thus capable of accelerating $A/q = 132$ ions. Stable beams of singly-charged ^{132}Xe ions will eventually be used as the ultimate test of the ability to accelerate ^{132}Sn beam. For this purpose, a dedicated beam line is under construction at the 4 MV Dynamitron facility at the ANL Physics Division consisting of beam transport systems and diagnostics.

In order to measure the energy of beam accelerated by the RFQ, two separate diagnostic systems are under development. One system consists of a Si charged-particle detector from which energy resolutions of about 500 keV are typical for heavy ions. Although this intrinsic resolution is larger than that expected for the energy width of bunched $A/q = 132$ beams, the subnanosecond timing resolutions of these detectors makes it possible to directly and accurately measure the time widths and, as a result, infer energy spreads as well. This will be particularly useful in the determination of the longitudinal emittance of the beams. Another diagnostic system consisting of a pair of electrostatic deflector plates and a Faraday cup forms an energy spectrometer that has an energy resolution similar to that of the Si detector system. Adding a time-of-flight system to these diagnostics would be necessary to determine longitudinal emittances, however.

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