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BEAM TESTS OF THE 12 MHz RFQ RIB INJECTOR FOR ATLAS

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Abstract

Beam tests of the ANL 12 MHz Radio-Frequency Quadrupole (RFQ), designed for use as the initial element of an injector system for radioactive beams into the existing ATLAS accelerators, are in progress. Recent high-voltage tests of the RFQ without beam achieved the design intervane voltage of 100 kV cw, enabling beam tests with *A/q* as large as 132 using beams from the ANL Physics Division 4 MV Dynamitron accelerator facility. Although the RFQ was designed for bunched beams, initial tests have been performed with unbunched beams. Experiments with stable, unbunched beams of singly-charged ^{132}Xe and ^{84}Kr measured the output beam energy distribution as a function of the RFQ operating voltage. The observed energies are in excellent agreement with numerical beam simulations.

1 INTRODUCTION

A prototype split-coaxial 12 MHz cw RFQ accelerator [1] has been constructed. The RFQ will form the initial element of a preaccelerator system [2,3] for injecting radioactive ion beams into the existing ATLAS accelerators at ANL. Early tests of the RFQ [4] have achieved stable operation at a cw intervane voltage of 102 kV with an rf input power of 17 kW. More recently, with further conditioning cw operation as high as 108 kV has been achieved, a voltage well above the design value of 100 kV.

Following these voltage tests, we have injected the RFQ with singly-charged ions of mass up to 132, the highest *A/q* beam the RFQ was designed to accelerate. The RFQ was designed to be injected with pre-bunched beams. Tests to date have been with injection of dc, unbunched beams. As shown below, much information can be obtained from accelerating an unbunched beam. For example, both experiment and numerical simulation show that about 15% of an injected dc beam is accelerated.

The following reports the results of energy measurements performed on RFQ-accelerated beams of unbunched ^{132}Xe and ^{84}Kr and compares the results to the predictions resulting from numerical simulation of the RFQ beam dynamics.

2 EXPERIMENTAL SETUP

Beam tests of the RFQ were performed at the ANL Physics Division 4 MV Dynamitron accelerator facility. At present, we inject unbunched beam into the RFQ and do not include transverse matching elements at the entrance and exit of the RFQ. A schematic overhead view showing the Dynamitron injector, RFQ, and beam diagnostic system is shown in Fig. 1. A more comprehensive description of the system is given in previous work [5].

Beam energies were measured using a silicon (Si) charged-particle detector placed 1.4 m away from the RFQ exit. The energies were measured following either direct implantation, with the detector placed at 0° relative to the beam direction, or following elastic scattering from a very thin foil (23 µg/cm^2 Au with a 5.3 µg/cm^2 C backing). In the elastic scattering mode, the detector was placed at 10° relative to the beam direction. Energy calibrations were performed for beams of both ^{132}Xe and ^{84}Kr with energies determined by the Dynamitron terminal voltage, without the use of the RFQ, and were found to be linear throughout the energy range of interest.

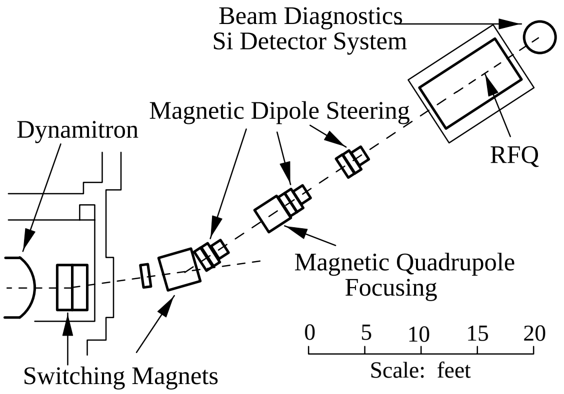

Figure 1: Schematic overhead view of the RFQ beamline at the Dynamitron injector facility.

3 NUMERICAL SIMULATIONS

Numerical simulation of unbunched beams of A/q = 132 and 84 accelerated by the RFQ was performed using the ANL BeamTrak code. The ANL BeamTrak code fully tracks the position and velocity of each individual particle of a bunch through the entire RFQ structure.

An unbunched beam was simulated by considering a bunch 86 ns wide at the entrance of the RFQ, uniformly filling a complete rf period of the RFQ. An actual dc beam would consist of a superposition of a series of such bunches. A single 86 ns bunch is, however, completely representative of such a superposed ensemble.

In what follows, we show the results of simulation in terms of the coordinate and velocity distribution of the particles relative to the “bunch” centroid. Figure 2 shows the longitudinal phase space of a bunch of 500 A/q = 132 particles, representing a singly-charged ^{132}Xe beam. The bunch has an initial time width of 86 ns and

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mean energy of 378 keV, and is then simulated travelling through the RFQ at an intervane voltage of 99 kV. The figure shows the bunch after exiting the RFQ and drifting until the leading edge intercepts the detector, located 1.4 m past the RFQ exit. Note that at this point in time, while most of the particles (each represented by a cross) have been unaccelerated or even partially decelerated, about 15% are accelerated. These accelerated particles form a bunch with an energy nearly 700 keV higher and a time lead of 800 ns relative to the centroid of the entire 500 particle segment of the original segment of dc beam. Note that since the centroid energy of the entire pseudo-bunch is 685 keV, the accelerated portion of the beam arrives at the detector at a total energy of 1368 keV. At this point in time, the original 86 ns wide bunch has spread out, and extends over nearly 1.6 µs.

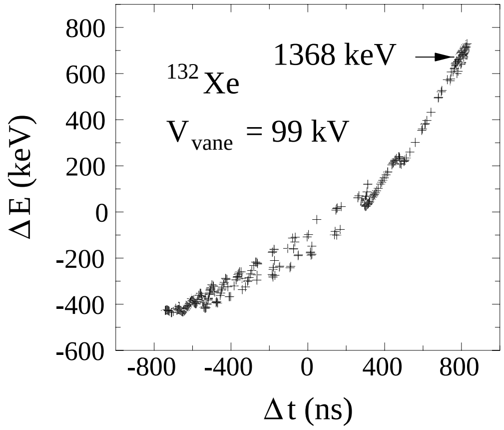

Figure 2: Numerically simulated longitudinal phase space of 500 ^{132}Xe particles at the RFQ exit. The centroid energy of accelerated beam is 1368 keV.

An energy spectrum can be obtained from the simulated-beam longitudinal phase space by projecting the number of particles that fall within a specified range on the energy axis. Performing this projection and using an energy bin size of 50 keV results in the histogram displayed in Fig. 3, where the y-axis corresponds to the sum total of particles counted in each 50 keV bin, for the distribution shown in Fig. 2. Two distinct peaks can be observed in Fig. 3. The first, and most intense, is peaked near 300 keV. This peak has a high-energy "tail" with a smaller peak visible near 700 keV. The most distinct peak is well resolved from the first and is located near 1360 keV. This spectrum can be compared to the experimental spectrum generated from Si detector data (see Section 4.1).

Simulations have also been performed for a ^{84}Kr beam. In this case, the initial energy of the bunch is 241 keV in order to maintain the velocity profile defined by the RFQ vane modulations. The RFQ peak voltage, which scales with *A/q*, must be set at 65 kV for this beam. The simulation results are qualitatively similar to the ^{132}Xe case. Both the longitudinal phase space and theoretical energy spectrum representing a bunch of 500 singly-charged ^{84}Kr particles at the RFQ exit indicated a clear peak near 860 keV, the accelerated portion of the beam, which was well separated and resolved from the remainder of the beam.

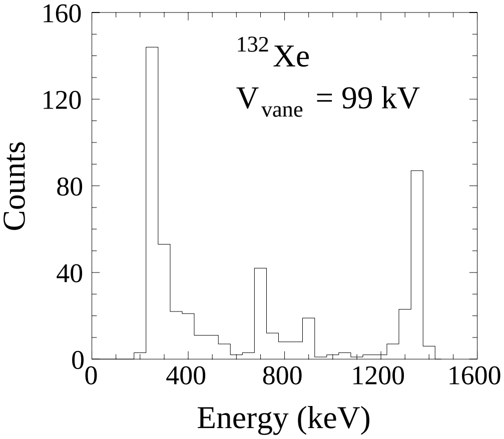

Figure 3: Energy spectrum of 500 ^{132}Xe particles at the RFQ exit projected from the simulated-beam longitudinal phase space of Fig. 2.

4 EXPERIMENTAL RESULTS

4.1 Beam tests with ^{132}Xe

Beam tests with ^{132}Xe were performed by injecting an unbunched 378 keV beam from the Dynamitron into the RFQ operating at voltages in the range of 80-99 kV. Ion energies were measured using the elastic scattering method described in Section 2. This method allows the detector to be shielded from the high background of x rays and electrons emitted by the RFQ.

Energy spectra of accelerated ^{132}Xe ions for RFQ operating voltages of 99 kV and 85 kV are shown in the top and bottom panels of Fig. 4, respectively. In each spectrum, two distinct peaks can be seen, in agreement with the simulations (see Fig. 3). The lowest-energy peak (displayed off-scale in Fig. 4) is mostly unaccelerated beam, although a portion of this peak (about 20%) is known to be a background of x rays and/or electrons which were also observed with the RFQ at these voltages, but with no injected beam. The precise position of the accelerated beam peak near 1400 keV is dependent on the RFQ operating voltage, and shifts from 1404 keV(top) to 1330 keV (bottom) with decreasing voltage. Centroid energies were determined by performing background-corrected Gaussian fits to the line shapes of each peak.

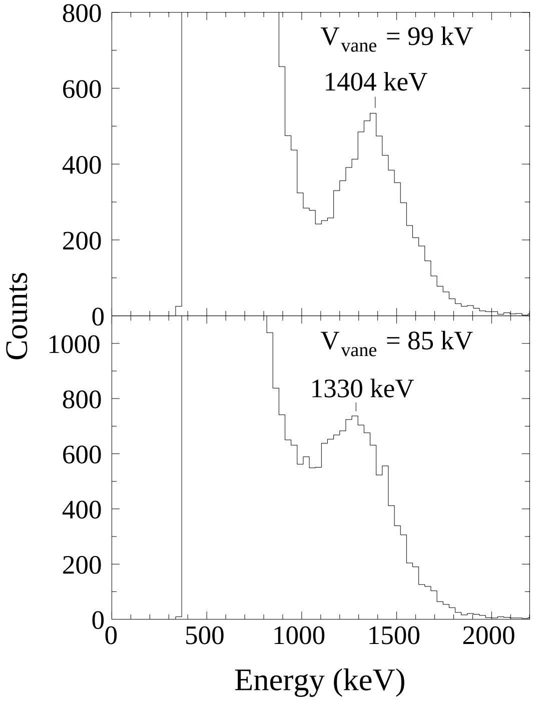

Figure 4: Experimental spectra of accelerated ^{132}Xe ions using an RFQ operating voltage of 99 kV (top) and 85 kV (bottom).

The energy of accelerated ^{132}Xe beam was measured for five different RFQ operating voltages, as seen in Fig. 5, which compares the results to the predictions from the numerical simulations described in Section 3. The beam energy gain remains nearly constant as the operating voltage is reduced below the design value of 100 kV, until 85 kV is reached, below which the beam energy drops sharply. This is due to the RFQ being designed for -30° synchronous phase. As the RFQ voltage is decreased, the accelerated particles slide back in phase to maintain velocity, until reaching 0° phase at which point they can no longer be fully accelerated. Measurements could not be extended below an RFQ voltage of 80 kV because the accelerated-beam peak then becomes indistinguishable from background.

4.2 *Beam tests with ^{84}Kr*

Similar beam tests were performed with ^{84}Kr by injecting an unbunched 241 keV beam from the Dynamitron into the RFQ operating at voltages in the range of 56-76 kV. Ion energies were measured with the detector placed directly at 0° relative to the beam direction, without the use of a scattering foil.

Both the theoretical and experimental energy spectra obtained for ^{84}Kr were qualitatively very similar to those obtained for ^{132}Xe. In this case, the accelerated beam component comprised about 20% of the total output beam, with its energy peaking at about 885 keV.

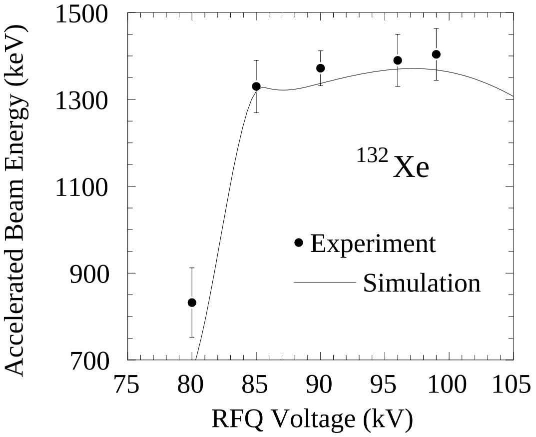

Figure 5: Experimental (filled circles) and theoretical (solid curve) accelerated ^{132}Xe beam energies as a function of RFQ voltage.

5 SUMMARY

Initial beam tests of the Argonne 12 MHz RFQ using ^{132}Xe and ^{84}Kr have been performed. The measured beam energies at the output of the RFQ are in excellent agreement with the results of numerical simulation. Future experiments will make use of the subnanosecond timing resolutions of Si detectors to measure the longitudinal emittance of accelerated beam.

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