SINGLY-CHARGED HEAVY-ION BEAM STUDIES ON A 12 MHZ RFQ

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Abstract

Detailed experimental measurements of singly-charged ^{132}Xe and ^{84}Kr beams accelerated through the ANL 12 MHz RFQ for inter-vane voltages up to the design value of 100 kV have been performed. As part of an injector to a RIB linac for RIA (Rare Isotope Accelerator) the RFQ would accelerate low energy, low charge-to-mass ratio ion beams with high efficiency (ie. CW operation) while simultaneously introducing negligible transverse or longitudinal emittance growth. We will present results of a series of measurements using ^{132}Xe and ^{84}Kr beams ranging in energy from 220 to 450 keV injected into the RFQ using the ANL 4 MV Dynamitron and a recently added RF chopper used to simulate pre-bunched beams. Small beam chop widths of a few nanoseconds at the entrance permit detailed tests of the RFQ acceptance and emittance properties. Measured ^{132}Xe and ^{84}Kr energies at the RFQ exit are in agreement with model calculations. The long term thermal stability of the RFQ at the highest inter-vane voltages (~100 kV) will also be discussed.

1 INTRODUCTION

The efficient generation of rare isotope beams requires singly charged ions at the injector to a RIB (Radioactive Ion Beam) linac [1] for RIA [2]. A RIB linac will accelerate heavy ions in the mass range 6 to 240, initially with charge state 1+. Low charge state ions may be efficiently accelerated using sections of cw, normally-conducting RFQ [3,4]. The current RFQ was designed for acceleration of singly-charged ions with masses up to 132, however, after re-fitting with new vanes suitable for mass 240, it will be used in the first section of a RIB linac. The vanes will be redesigned according to the highest stable fields reported here.

2 EXPERIMENTAL APPARATUS

The main components of the experimental apparatus are shown in Figure 1. The RFQ construction, including the use of drift tubes and the entrance and the exit, is described elsewhere [4]. The goal of these experiments was to test cw operation of the RFQ with real beams and to examine the energy and time structure of the transmitted beams. Here a 6 MHz rf chopper is used in place of a buncher and a simple Rutherford scattering measurement from a thin Au target into a silicon detector was chosen for particle detection at the RFQ exit. A pair of Faraday cups before and after the RFQ was used for beam transmission measurements.

2.1 Beam Chopper

The 12 MHz RFQ was designed to accept prebunched beams from a multiharmonic buncher. Here a less expensive pre-existing chopper initially operated at 48 MHz was modified to run at 6 MHz and installed upstream of the RFQ. The modified chopper and beam parameters are shown in Table 1.

The chopper operation was optimized by measuring beams at the RFQ entrance. The vertical slits were adjusted for a 4 mm aperture and beam current was measured as a function of the chopper voltage using a cup just downstream of the slits. The chopper voltage was chosen to minimize longitudinal emittance at the entrance of the RFQ and resulted in a bunch width of ~15 nsec. For some measurements the width was reduced further by narrowing the slit aperture.

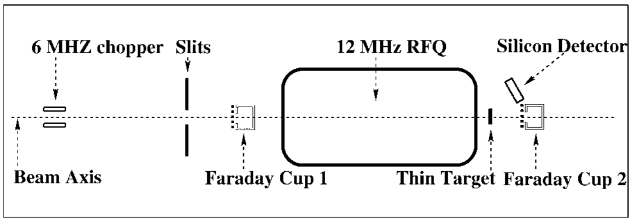

Figure 1: Schematic view of the test apparatus.

Table 1: Chopper and injected beam parameters

Operating frequency	6 MHz
Deflection plate length	6 cm
Inter-plate distance	12.7 mm
Peak-to-peak voltage	~2000 V
Chopper to slit distance	100 cm
Slit width	≤ 4 mm
Phase width at RFQ entrance	$\leq 70^{O}$ at 12 MHz
Calculated longitudinal emittance	~0.6 π keV nsec
Measured horizontal emittance	4.9 π·mm·mrad
Measured vertical emittance	12.8 π·mm·mrad

Beam emittance in the vertical plane more than doubled due to the applied chopper voltage, however, the resulting emittance is still much smaller than the acceptance of the RFQ (150 π·mm·mrad). A set of horizontal slits were adjusted so that a single isotope, in this case ^{132}Xe, was transmitted. Beam emittances from the Dynamitron were measured to be small. Table 1 lists the transverse beam emittances downstream of the chopper slits for a 350 keV xenon beam. Beam simulations through the chopper have been performed and indicate that 8% of particles survive beyond a 4 mm width slit and form a bunched structure at the entrance of the RFQ. Measured results shown in Figure 2, for the expected transmission through the chopper are in good agreement with simulations and confirm that the chopper may be used to produce short beam bunches at the RFQ entrance.

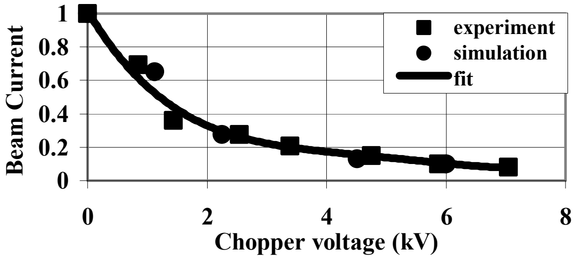

Figure 2: Relative beam current after chopper slits versus chopper voltage.

3 BEAMS AT THE RFQ OUTPUT

Measurements near the beam axis were difficult due to a large x-ray and electron flux produced by the RFQ particularly for high vane voltages needed to accelerate xenon. Therefore, many measurements were made with a krypton beam. The first of two techniques was based on a custom silicon surface barrier detector from ORTEC with essentially no surface dead layer. The accelerated beam is scattered elastically through a 20 μg/cm^2 Au foil into the detector placed 10-15^{O} off the beam axis to avoid background. An ORTEC 142 preamplifer generated energy and time signals that were amplified, digitized and recorded by a data acquisition computer.

Bunch widths were calibrated with a resolution of approximately 1 ns. The detector energy calibration was performed using a monochromatic beam directly from the Dynamitron and the RFQ off. The 300 keV detector resolution was relatively poor but more than sufficient to cleanly identify accelerated particles. A typical time-versus-energy spectrum showing bunches spaced by 160 ns centered at the expected energy of 1 MeV is shown in Figure 3, top panel. The energy width is dominated by the detector resolution as these low energies. The bottom panel is the time projection indicating bunch widths of ~15 nanoseconds.

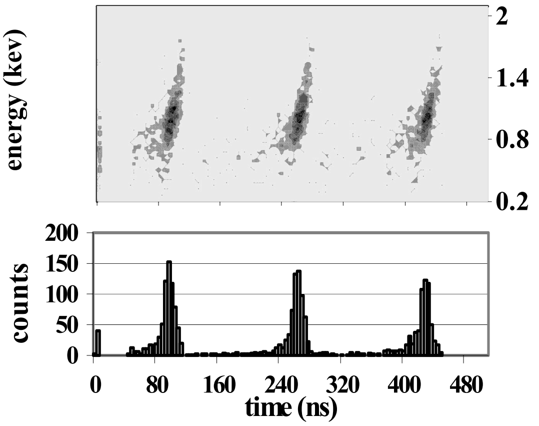

Figure 3: Time-of-flight versus energy (top) and the time projection (bottom) for accelerated ^{84}Kr at the RFQ exit.

The second of the two techniques was based on a Faraday cup and a carbon stopping foil of areal density 80 mg/cm^2. The target thickness was chosen to stop unaccelerated particles while transmitting accelerated particles so that the cup current with and without the foil gives a measure of the amount of beam captured and accelerated by the RFQ. The passage of heavy-ions through the foil also results in beam straggling and electron stripping. The first effect was mitigated by placing the Faraday cup immediately after the foil. The increase in beam current due to the stripping was unimportant since generally only relative beam currents were meaningful. Secondary electrons from the target were suppressed by applying a positive bias of 300 V to the target. The expected target stopping powers were verified by bombarding the target with monochromatic beams of known energy from the Dynamitron.

The relative capture for short bunched beams was measured as a function of both the Dynamitron beam energy and the RFQ vane voltage by recording cup currents with and without the stopping foil. Results for one beam energy, a 220 keV krypton beam, injected into the RFQ are shown in Figure 4. and indicate a saturation of beam capture as the vane voltage is increased. Simulations for krypton at an injection energy of 220 keV indicate that capture efficiency saturates at an intervane voltage of 63 kV; see Figure 4. These data were compared with the intervane voltage taken from a calibrated rf coupling loop and results agree to within 10%. The calibration based on capture efficiency is used here.

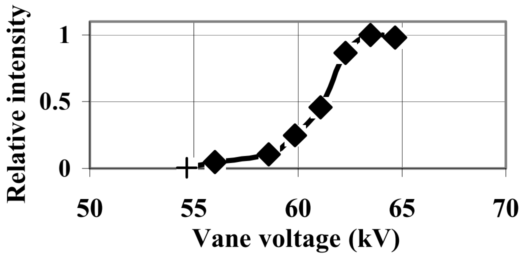

Figure 4: Beam current for accelerated krypton versus vane voltage indicating a saturation of beam capture at the design intervane voltage of 63 kV.

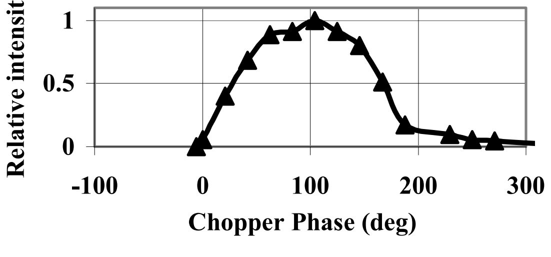

Figure 5: Accelerated krypton beam current versus chopper phase. The phase width is a combination of the RFQ phase acceptance (~100^{O}) and the injected bunch width (45^{O}). The value of ~100^{O} is expected for an RFQ operated at 30^{O} synchronous phase.

To measure the phase acceptance of the RFQ, the chopper was turned on and set for a chop width of ~10 ns. The chopper phase was varied and the accelerated beam current was measured at the second Faraday cup. This was done for several values of the injected beam energy and a typical phase scan curve is shown in Figure 5. The phase width of ~140^{O} is in good agreement with the expected value, approximately equal to three times the synchronous phase (30^{O}) plus a correction for the phase width of the input beam (45^{O}).

4 BUNCH WIDTH MEASUREMENTS

Due to the excellent time resolution of the silicon detectors bunch widths for accelerated heavy-ions were measured with good accuracy as a function of chopper and RFQ voltage settings. The purpose of these measurements is again to check the expected behavior of the RFQ as vane voltages and injected bunch phases are adjusted. Figure 6. shows measured time widths for three settings of the vane voltage. The minimum transmitted bunch width of 6 nsec (26°) at FWHM occurs at design accelerating voltage of 63 keV. The width remains relatively unchanged as the voltage is increased further. Figure 7 shows bunch widths for beam exiting RFQ as a function of chopper phase for a fixed vane voltage.

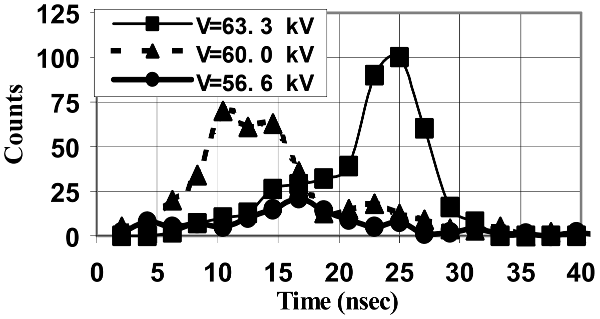

Figure 6: Bunch time widths for three values of RFQ vane voltage

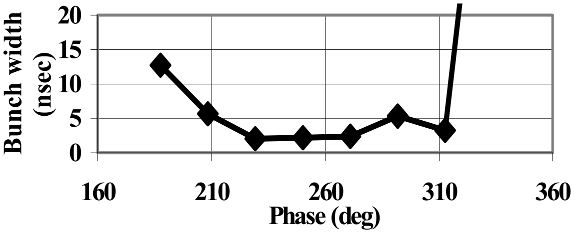

Figure 7: Average bunch width versus chopper phase.

5 THERMAL STABILITY

The thermal and mechanical stability of the RFQ was explored by applying a known rf power and allowing the system to equilibrate thermally while monitoring the resonant frequency, cooling water temp, x-ray yield, vacuum pressure, and vane tip spark rate. Equilibration times were ~1 hour each time the rf power was increased by 1 kW. Stable operation over long periods (~300 hours) was observed for intervane voltages up to 90 kV. An increase in x-ray yield for higher rf powers was observed as shown in Figure 8 and is likely bremsstrahlung resulting from field emission. The observed Δf=-80 kHz shift at 17 kW of rf power coincides with the increased x-ray yield and may be explained by vane heating seen only for voltages greater than 90 kV. The effects of heating will be reduced in new vane tips redesigned to include direct internal water cooling while keeping the present cooling water used in the aluminum supporting arms.

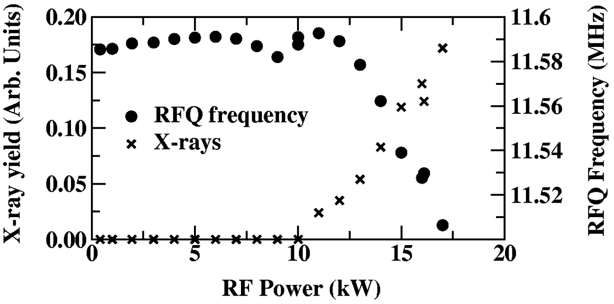

Figure 8: RFQ resonant frequency (circles) and x-ray yield (crosses) versus RF power. Stable operation and a constant Q were observed for voltages up to 90 kV. Points at 17 kW rf power correspond to a vane voltage of 95 kV.

6 CONCLUSION AND OUTLOOK

Properties of the accelerated singly-charged heavy-ion beams were measured using silicon detector and Faraday cup measurements. A 6 MHz chopper was implemented for bunching of the injected beam and accelerated beams were measured at the exit of the RFQ and used for a calibration of the intervane voltage. The behavior of the RFQ versus vane voltage and injected bunch phase are all in agreement with simulations. After initial conditioning, no multipacting was observed over then entire voltage range and the Q was constant and stable for voltages up to 90 kV.

This essentially completes development of the 12 MHz RFQ. New vane tips will be designed to include direct water cooling and the RFQ will be used for acceleration of masses up to A=240 in the entrance section of a RIB linac for RIA.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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