

COLLISIONAL COOLING OF NEGATIVE ION BEAMS

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Abstract

Investigations have been conducted to determine the feasibility of using collisional cooling for reducing the energy spreads and, consequently, the emittances of negative-ion beams. We have designed a gas-filled RF-quadrupole ion cooler equipped with provisions for retarding energetic negative ion beams to energies below thresholds for electron detachment at injection and for re-acceleration to high energies after the cooling process. The device has been used to cool O^- and F^- ion beams with initial energy spreads, $\Delta E > 10$ eV to final energy spreads, $\Delta E \sim 2$ eV FWHM. Overall transmission efficiencies of $\sim 14\%$ for F^- beams have been obtained. Experimental results show that electron detachment is the major loss mechanism for negative ions.

1 INTRODUCTION

The Holifield Radioactive Ion Beam Facility (HRIBF), Oak Ridge National Laboratory, uses the Isotope Separator On-Line (ISOL) technique to provide accelerated radioactive ion beams (RIBs) for nuclear physics and nuclear astrophysics research. The radioactive ion beams produced by this method are often mixtures of the radioactive isotope of interest and isobaric contaminants that complicate and sometimes compromise experiments. These contaminant beams must either be eliminated or reduced to tolerable levels. At the HRIBF, a magnetic mass separator with a nominal mass resolving power of $M/\Delta M \cong 20000$ is used for isobaric purification. However, such high resolving power can only be effected with very high quality RIBs – beams with very small emittances and energy spreads. This is challenging at the HRIBF because the 25-MV tandem post accelerator requires the injection of negative-ion beams. Negative-ion beams, usually generated with Cs-sputter negative-ion sources or indirectly by positive-to-negative charge exchange, have inherently large emittances, and consequently, the degree of isobaric purification that can be achieved is limited.

We have investigated the feasibility of using collisional cooling for reducing the emittances and energy spreads of negative-ion beams. Cooling of positive ions with gas-filled radio frequency (RF) ion guides has been reported [1-5]. However, there are inherent difficulties in cooling and transporting negative ions through a gas-

filled RF quadrupole ion-guide. For example, negative ions are much more fragile than their positive-ion counterparts. Consequently, electron detachment can take place through collisions with the buffer gas.

An RF quadrupole ion-guide cooler equipped with provisions for decelerating ion beams to sufficiently low energies prior to cooling and re-accelerating them following the cooling process was designed and constructed. We report first results of cooling high-energy negative-ion beams using the cooler system. Several negative-ion species, including F^- and O^- , were cooled in buffer gases such as He. The transmission efficiencies and fractional losses of these species attributable to electron detachment were also ascertained for the system. The beam cooler and experimental systems are described and results derived from cooling experiments with both negative- and positive-ion beams are presented.

2 DESCRIPTION OF THE COOLER SYSTEM

The cooler and differential pumping system, used for creating the appropriate pressure profile for the injection, cooling, and extraction processes, is shown schematically in Fig. 1. The RF-quadrupole ion guide consists of four parallel cylindrical rods, 8-mm in diameter and 40-cm in length, equally spaced with an

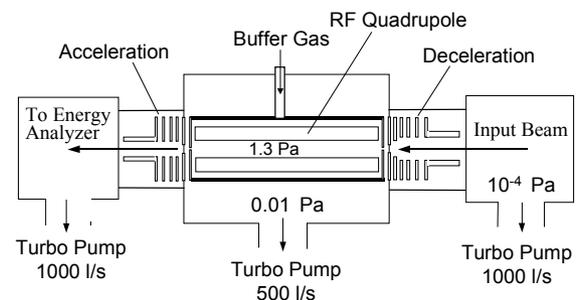


Fig. 1 Schematic depiction of the collisional RF quadrupole ion guide coupled with deceleration and re-acceleration electrodes.

inscribed circle of radius 3.5 mm between electrode surfaces. The quadrupole rod structure is enclosed in a Cu cylinder with end caps, as shown in Fig. 1. Ions are focused into the RF quadrupole through a 3-mm diameter entrance aperture and, after cooling, exit the ion guide

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through a 2-mm diameter aperture. After cooling to near thermal energies, the motion of the ions along the axis is essentially governed by diffusion and thus, it is necessary to provide a longitudinal field to direct them toward the exit aperture. The longitudinal DC field is created along the quadrupole axis with four tapered electrodes located between the quadrupole rods. The deceleration electrode system consists of seven electrodes for gradually decelerating ion beams to very low energies (<100 eV). Following cooling and transmission through the RF quadrupole, the ion beams are extracted through the 2-mm diameter exit aperture and re-accelerated to high energies.

3 EXPERIMENTAL SETUP

The performance of the deceleration/acceleration gas-filled RF ion-guide system was evaluated and characterized at an off-line ion source test facility. Ion sources employed for on-line generation of various negative RIBs were used to generate stable negative-ion complements of the RIB species for use in the cooling experiments. Negative-ion beams were extracted from an ion source, mass selected with a magnetic mass analyzer, and then focused into the cooler system. As schematically shown in Fig. 2, ion beams re-accelerated from the cooler can be directly monitored with a Faraday cup, or deflected into a 45° , parallel-plate electrostatic energy analyzer for determination of the energy distributions of ion beams following the cooling process. The energy distributions in ion beams prior to the cooling process were measured by transporting the beams to the energy analysis system at high energies through the grounded and evacuated cooler system.

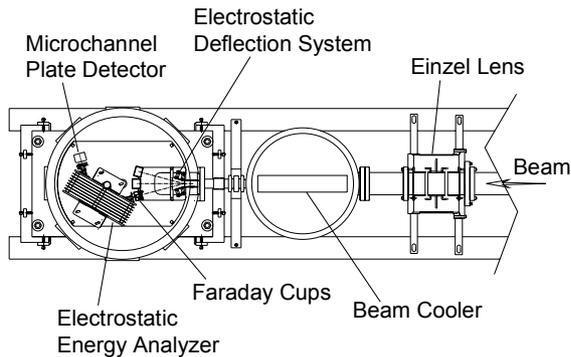


Fig. 2. Schematic depiction of the experimental setup for beam cooling and energy distribution measurements.

4 RESULTS

Cooling experiments with both negative- and positive-ion beams have been performed. F^- and O^- beams were chosen for study because of the large difference in their electron affinities (3.4 eV and 1.46 eV, respectively). Information concerning electron detachment losses through the cooler can be gained by measuring the transmission efficiencies of positive-ion beams under similar cooling conditions. Thus, cooling

experiments with Ar^+ beams were also conducted. All experiments were conducted with mass analyzed, 5-keV ion beams.

4.1 Cooling of F^- and O^- Ion Beams

The effect of cooling on F^- beams is displayed in Fig. 3. The ions were sputter generated in an RF plasma negative-ion source that has a typical emittance of ~ 50 mm mrad (90% contour) for 20-keV beams. F^- beams with intensities of 2 to 30 nA were injected into the cooler by retarding their energies to < 40 eV. He was used as the buffer gas. The RF quadrupole was operated at a frequency of 2.75 MHz and amplitude of $V_{rf} \sim 80$ V. As shown in Fig. 3a, the F^- beams have initial energy spreads of ~ 4 eV FWHM with a high-energy tail that extends beyond 14 eV. Cooled F^- beams with near Gaussian energy distributions and ~ 2.3 eV FWHM were obtained at He pressures of ~ 2.3 Pa inside the quadrupole, as shown in Fig. 3b. The mean energy of the ions emerging from the cooler was found to shift to lower values with increasing He pressure, indicating that their initial energies were dissipated in collisions with the He buffer

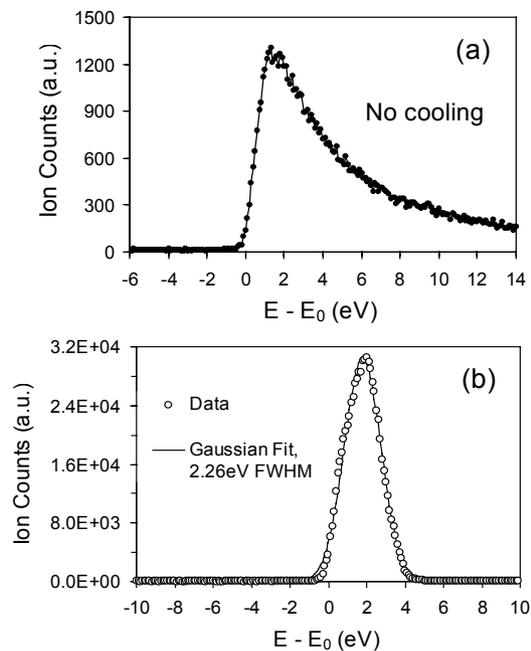


Fig. 3. Measured energy spreads of F^- beams from an RF plasma negative-ion source (a) before and (b) after cooling.

gas. The overall transmission efficiency through the system was 10%-14%. Cooled F^- beams with intensities in excess of 4 nA have been extracted from the cooler.

The experiments were repeated with O^- beams generated in the RF plasma-sputter negative-ion source. The uncooled O^- beams have high-energy tails similar to those of F^- . After passing through the cooler, narrow energy spectra with FWHM of ~ 2.2 eV and ~ 2.3 eV were obtained at He pressures of 2 Pa and 4.3 Pa, respectively. The transmission efficiency for O^- beam was $\sim 5\%$ for 55 nA and $\sim 6\%$ for 55 nA for 17 nA input beams.

4.2 Transmission Efficiency Measurements

Ion-transmission efficiencies were determined by measuring the ratio of ion-beam intensities before and after cooling. The transmission efficiency versus ion injection-energy in the CM frame, E_{cm} , for F^- , O^- , and Ar^+ beams are displayed in Fig. 4. During the measurements, the cooler was operated at He gas pressures of 2 to 2.3 Pa, an RF frequency of 2.75 MHz, and $V_{rf} = 65$ V, 80 V, and 110 V, respectively, for F^- , O^- , and Ar^+ beams. The input beam intensities for these beams were 32 nA, 15 nA, and 4.5 nA, respectively. All three transmission curves display a plateau at very low CM collision energies followed by a monotonic decrease with increasing energy. Maximum transmission efficiencies for F^- and O^- beams and Ar^+ beams are $\sim 12\%$, $\sim 6\%$, and $\sim 50\%$, respectively.

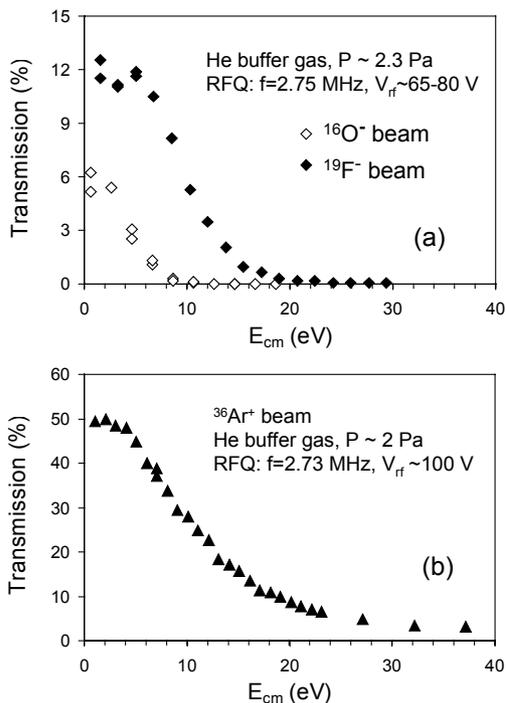


Fig. 4. Measured transmission efficiencies for (a) F^- and O^- ion beams and (b) Ar^+ ion beams as functions of injection ion energy in the CM frame.

5 DISCUSSION AND CONCLUSIONS

Transmission losses at large ion energies have been previously reported in several cooling experiments [2]. For Ar^+ ions the decrease in transmission with increasing ion energies may be due to a combination of two effects: (1). The transmission measurements were conducted at a fixed buffer gas pressure of ~ 2.3 Pa. As the ion energy is increased, the gas pressure is not sufficient for damping the motions of ions and thus, an increasing number of ions will less likely pass through the small exit aperture. (2). At high energies, collisions with buffer gas may lead to scattering losses of ions during transport through the quadrupole.

Comparing the transmission curves for F^- , O^- and Ar^+ suggests that, in addition to similar effects which cause decreases in transmissions for positive ions, negative ions also suffer from electron detachment losses as the ion energy is increased. According to measurements by Hug et al. [6], the threshold energy, E_{th} , in the CM frame for electron detachment of F^- in collisions with He is 6.15 ± 0.15 eV, while a value of $E_{th} \sim 3.8$ eV for electron detachment of O^- in He was reported by Penent, et al. [7]. Above threshold energies, detachment cross sections increase rapidly with collision energy. Our experimental observations are in good agreement with these measurements: transmission efficiencies for negative-ion beams are found to decrease more rapidly than those of positive-ion beams when the ion energy in the CM frame is above 7 eV for F^- , and above 3 eV for O^- ions. As shown in Fig. 4a, the transmission efficiencies for F^- and O^- beams drop to nearly zero at CM energies higher than 22 eV and 12 eV, respectively. Thus, negative-ion losses are likely dominated by electron-detachment processes at ion energies higher than the threshold energy for electron detachment.

As noted in Fig. 4, even at energies below the threshold for electron detachment, the transmission efficiencies for F^- and O^- beams are still much lower than those for Ar^+ beams. Furthermore, the transmission efficiency for F^- is \sim two times higher than that for O^- , which agrees with the reports that the total electron detachment cross sections for $F^- + He$ collisions are \sim two times smaller than those for $O^- + He$ collisions [6,7]. A close examination of the deceleration fields reveals that ion energies in the CM frame are still > 20 eV in the region near the entrance to the quadrupole. These factors suggest that negative-ion losses at very low injection energies are also likely due to electron detachment processes that take place in collisions with residual buffer gas before the ions enter the quadrupole. We believe that higher transmission efficiencies for negative-ion beams can be realized after improvements have been made to the deceleration and differential pumping systems so that electron detachment losses can be minimized.

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