Electrostatic Trap for keV Ion Beams

H. F. Krause, C. R. Vane, and S. Datz

Physics Division, Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831 USA

Abstract. A reflecting ion beam electrostatic trap has been constructed and tested for the purpose of studying molecular ion physics. A trap of this type offers a large field-free region, wide mass range, and beam directionality that simplifies the detection of stored ions or breakup products. In our configuration, pulsed ions extracted from an ion source (5–10 μs) are accelerated to keV energies and magnetically analyzed before injection into the trap. After the ions enter the trap, high-voltage electrostatic entrance and exit mirrors and Einzel lenses (operated by fast switches) cause the ions to oscillate between the mirrors in nearly parallel trajectories. Neutralized ions, detected by a channel plate located beyond the exit mirror, indicate the time dependence of the stored ion population. Voltages and pulsed timing of the beam and trap are controlled by computer (38 parameters). The computer can quickly find the optimum trapping conditions in successive fills using the detected neutral yield. Numerous atomic and molecular ions (energy of 1.3–3.0 keV and m <100 amu) have been stored with a beam capture efficiency up to 2%. The storage lifetime, limited by neutralizing collisions with background gas, is typically 2–5 sec at a pressure of 2×10^{-10} Torr.

INTRODUCTION

A wide variety of techniques have been used to trap and study positive and negative ions [1]. Typically, very low-energy ions (E < 10 eV) are confined in a small volume using static electric and magnetic fields or time dependent fields. In most cases, the ions are born inside the trapping volume and there is no preferred direction of motion for the ions stored. These cold ion traps have led to major advances in physics and chemistry, such as in high-precision spectroscopy and mass measurements, fundamental constants and cold ion collision physics.

Another very successful approach to ion trapping has been the storage ring method that is based on accelerator technology [1-3]. Here, the ions are produced by an intense ion source and accelerated, and the beam is charge-state/mass analyzed before it is injected into the storage device. The large variety of positive and negative ion sources available (e.g., gas discharge, electron impact, sputter, ECR, electrospray ion sources) allows a much greater variety of ionic species to be studied than is possible in most cold ion traps. The directionality of the stored beam simplifies the detection of the stored species or decay products. Large medium- and high-energy storage rings (~30-m circumference), with the help of electron and laser-beam coolers, have produced major advances in the study of low-energy electron-ion collisions (e.g., dielectronic recombination and molecular ion fragmentation dynamics) and in nuclear physics.

A much smaller "table-top" electrostatic storage ring (6-m circumference), ELISA, which stores 25-keV atomic and molecular ions, has been developed recently [4]. It offers some of the basic features of the large storage rings mentioned above at a much lower price. It also offers a much larger mass range than is possible for the large magnetic rings because it is electrostatic.

The reflecting ion beam electrostatic trap (RIBET) described below, similar to [5-6], stores ions at low keV energies. A trap of this type, analogous to an optical resonator, offers many of the features of ELISA (e.g., a large field-free region, wide mass range, and beam directionality that simplifies the detection of stored ions and breakup products) in a much smaller and less expensive package. The large selection of ion sources available to storage rings can also be used with this trap. Its functionality is complementary to a storage ring like ELISA, and to low-energy ion traps where the ions have no preferred direction of motion.

ELECTROSTATIC TRAP ARRANGEMENT

The ion trap and the downstream detection chamber, shown in Fig. 1, operate as follows. Ions formed in a Colutron discharge ion source are pulse extracted, accelerated, focused, magnetically momentum analyzed, and then refocused before injection into the trap about 3 m from the ion source (E = 1.3–3.0 keV, $\delta E/E \sim 10^{-3}$). The ion beam is small and nearly parallel (1–2 mm dia., $d\vartheta \sim 0.3$ mrad) as it enters the trap and no entrance collimator slit is used. As an ion fill pulse is launched (width ~7 μs for projectile mass of 40 amu), high voltage is applied to the exit electrostatic mirror electrodes and its companion Einzel lens using a fast switch (shown at the right side of the trap). Incident ions pass through the grounded entrance mirror electrodes and its companion Einzel lens (left side) and the ions are

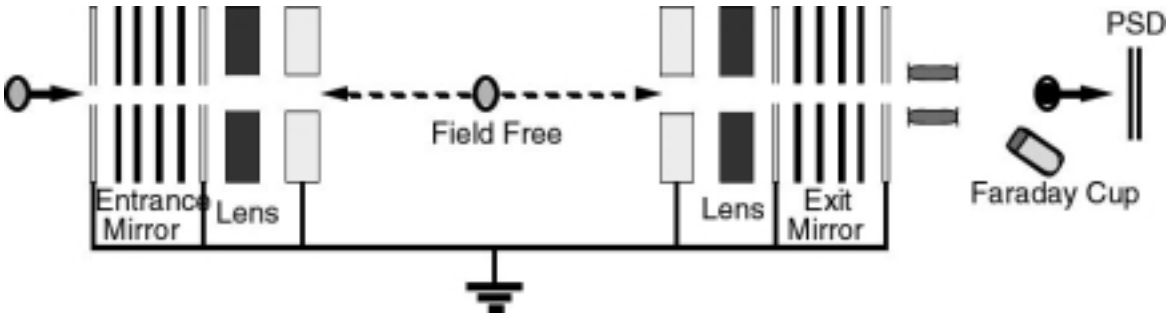

Figure 1. Sketch showing RIBET and the downstream detection chamber. High voltages are applied to mirror and lens elements that are shaded; text explains the voltage distribution.

reflected once from the exit mirror. As the leading edge of the reflected ion pulse approaches the entrance mirror, high voltages are applied to the Einzel lens and mirror electrodes that trap the ions. The ions oscillate back and forth between the mirrors until (i) ions undergo a charge-changing collision with residual gas and leave the trap or (ii) the confining potential on either electrostatic mirror is removed. Neutrals (keV energy) formed inside the trap leave through the ends; the neutrals traveling in the downstream direction are detected on a two-dimensional position sensitive detector (PSD). Electrostatic deflection plates and a Faraday cup, located between the trap and the channel plate, are used to measure the ion beam intensity and ensure that only exiting neutrals are measured throughout the trapping cycle.

An ion trap of this type, like any storage device, requires vacuum consistent with the desired storage time. The vacuum in our trap and adjacent differentially pumped chambers are maintained primarily by large Ti sublimation pumps with some assistance from ion pumps. Three differentially pumped stages between the ion source chamber and the ion trap chamber, consisting of turbomolecular, cryopump and another ion- and sublimation pumped stage, allow the trap vacuum to be maintained at or below 1×10^{-10} Torr range when the gas discharge source is used. Our trap chamber has been operated only at room temperature, but it could be cooled to much lower temperatures to prepare internally cold ions.

The voltages required to trap ions depend on the incident ion beam energy, and these voltages must be applied by fast high voltage switches. To trap 2.85-keV ions of any mass in our geometry (trap length, L = 38 cm) a maximum mirror voltage of 4.55 kV and trap Einzel lens voltages of 2.4 kV are used. The four mirror voltages at each end of the trap, sandwiched between grounded electrodes, decrease a factor of 2 stepping from outer to inner electrodes to provide a "soft bounce" for the stored ions. Because the voltages at the exit end are applied long before the ion fill pulse arrives at the trap (tens of μs), we drive all exit mirror electrodes through a 4×10^5 Ohm resistive divider circuit using one fast switch (Directed Energy, Inc., PVX-4130, 6 kV). At the entrance end, where higher speed is desirable, one fast switch drives the lowest three voltages through a resistive divider chain V_{max} = 2.22 kV; the measured rise time is about 2 μs using a total resistance chain of 2×10^5 Ohms and a short drive cable. The mirror element with the highest potential is driven by its own fast switch ($t_r \sim 0.2$ μs for a pure capacitive load). The entrance Einzel lens is also driven by a separate fast switch. Scaling experiments have shown that all voltages applied to the trap are approximately proportional to the ion energy in the 1.3–3.0-keV range (for masses below 100 amu). Ion energy scaling below 1.3 keV was not tested because the injected ion beam intensity and the detection efficiency for fast neutrals drops rapidly as the ion speed decreases below about 8×10^6 cm/s.

Operation of the trap is greatly simplified by computer control. All voltages (except ion source) and pulsed timing for the beam and trap are controlled by an Apple Macintosh computer through two CAMAC crates. The 38 control parameters consist of 24 digital-analog converters (DAC), 6 programmable pulser/latches and 8 programmable timing registers. The DACs control beam energy, beam focusing and x, y steering, the magnetic field for momentum analysis, and all high-voltage power supplies that control trap mirror and lens voltages. The programmable pulser/latches (LeCroy 4448) set the ion beam pulse length and timing delays for operating the trap mirrors and lenses and the latched signals control all fast high-voltage switches used for trapping, dumping, and the signals needed by other data acquisition computers. The CAMAC timing registers control the storage cycle length and any other devices (lasers, buncher etc.) that might be time-sequenced within a storage cycle. The control system software allows the user to vary any control parameter in a programmed manner in a series of successive trap fills, and it learns the preferred scan

ranges for each parameter. This software allows the computer to quickly find the optimum trapping conditions in successive fills using the detected neutral yield (built-in optimizer software). Trapping parameters for any ion are stored and can be recalled so that ions and/or beam energy can be changed within seconds. The trap can also be monitored and operated from a remote location (using a telephone connection) using methods previously discussed [7].

TRAPPING PERFORMANCE

The storage lifetime for 2.85-keV Ar_{40}^{+} ions (no long-lived excited electronic states) is shown for a hold time of 10 sec in Fig. 2. Here, the scaler signal from the PSD, read and reset every 10 ms, was accumulated for 200 storage cycles. In the simplest approximation we expect the stored ion loss rate to be proportional to the number of stored ions, $dN/dt = -RN$. If we assume that collisions between the stored ion and residual gas limit the lifetime, then the total ion loss rate is $R = \Sigma n\sigma v$, where n is the number density of residual gas in the trap (predominantly H_2 at this vacuum), σ is the effective total loss cross section (primarily charge exchange), and v is the ion speed; the sum is over all individual loss processes. We expect a time-dependent neutral signal of the form $N(t)=N_0\exp[-Rt]$. The measured signal shown in Fig. 2 (small dark count subtracted) agrees with this expectation. In fact, the semi-log plot shows a linear loss in the 0–10 sec range where the stored ion intensity decreased a factor of 100. The storage lifetime, $\tau = 1.7$ sec for a trap pressure of 4.2×10^{-10} Torr, was shown to be inversely proportional to trap pressure, in agreement with the model (e.g., $\tau = 7.1$ sec at 1×10^{-10} Torr). The implied effective loss cross section derived from the lifetime, 4×10^{-15} cm^2, is the correct order of magnitude for charge exchange cross sections of 2.8-keV argon ions on H_2 or N_2. The effective loss rate in the mirrors involving slow ion charge-exchange collisions is probably smaller than for full energy ions because asymmetric charge exchange cross sections are much smaller and the effective path length in mirrors is much less than that experienced by the 2.8 keV ions. This would not be true in the case of a stored ion that can undergo symmetric or resonant charge exchange.

An estimate of the beam trapping fraction can also be derived using the data in Fig. 2. In the experiment, an 8 nA DC Ar^{+} beam measured after the trap was pulsed for 7 µs to load the trap (~3.4×10^5 ions injected/fill) and about 1.64×10^3 neutrals/fill were detected on the PSD. Using an estimated detection efficiency of 0.8 for 2.8 keV Ar neutrals and recognizing that half of the fast neutrals that leave the trap are not traveling toward the detector, the estimated beam trapping efficiency is about 1.2%. This efficiency, dependent on the number of ions injected, could easily be in error by a factor of two. This estimate also ignores all low-velocity ions and neutrals lost in the end mirrors, which are undetectable. Our measurements indicate that the beam trapping fraction is reduced by another factor of 8-10 if the trap entrance Einzel lens is at full voltage when an ion pulse is injected (i.e., if this lens is not pulse synchronized with the entrance mirror).

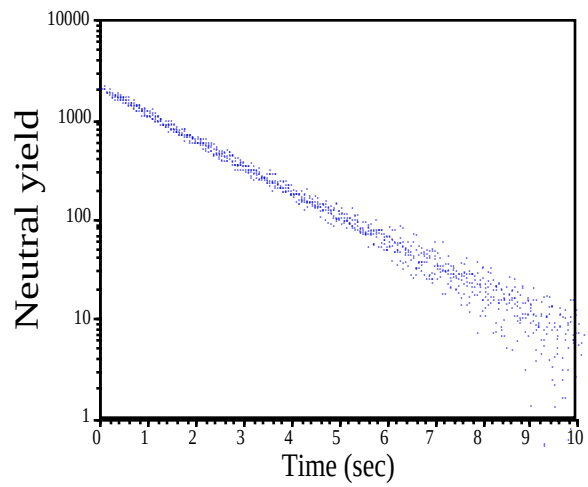

Figure 2. Stored ion population vs. storage time for 2.85 keV Ar^{+} ions at a trap pressure of 4.2×10^{-10} Torr.

Similar long-term storage and loss results have been obtained for projectile ions of different masses and for beam energies in the range 1.3 -2.8 keV. These include: N^{+}, Ne^{+}, S^{+}, N_2^{+}, CO^{+}, Cl^{+}, CCl^{+}, S_2^{+}, and Cl_2^{+}. We have also stored Ar_{40}^{2+} without difficulty (same q/m and trapping conditions as Ne_{20}^{+}). Because the trap is electrostatic, projectiles of the same energy but different mass are trapped using essentially the same trapping voltages. But the timing of fast switches (ion beam pulse length and entrance trap door delay) must be adjusted for each mass to optimize trap filling at different ion speeds. Minor adjustments are usually made to maximize the trapped ion fraction in jumps between the lowest and highest masses tested (e.g., 20 and 70, respectively) and upstream of the trap to adjust for beams of different emittance, size, misalignment, etc. While the storage lifetime for different ions at fixed energy depends on the ion (because of varying charge exchange cross sections with the residual gas and different speeds), the beam trapping efficiency appears to be roughly mass independent in

our tested mass range. Generally, the maximum storage lifetime for each tested ion was observed at the lowest projectile energy. This is probably because (i) each stored ion travels a shorter distance/second at the lowest speed and (ii) the cross section for charge loss in the case of cations decreases at lower energy when asymmetric charge exchange is dominant.

When a much more intense beam was trapped (e.g., 100 nA DC beam of Ar^+ pulsed for 7 μs), corresponding to about 4.2×10^6 ions/fill, a non-linear loss rate of stored ions was observed at the beginning of the storage cycle. The increased loss rate may be a consequence of space charge blow-up within the trapping volume, in the mirror regions or near focal regions in the field-free zone. Other pulse length experiments suggest that non-linear losses are minimal up to about 8×10^5 injected ions when those ions are uniformly distributed in time (longest injection pulse length possible). In fact, a major disadvantage of a short beam trap is the relatively short maximum filling time, especially for fast light ions; higher intensity ion beams of fast ions are required to maximize the fill.

Trapping efficiency vs. the voltage applied to trap Einzel lenses, which illustrates the "trapping window", is shown in Fig. 3. Here we see two regions where the efficiency is optimized. The minimum between the peaks corresponds approximately to the voltage where the incident beam is focused at the center of the trap (f = L/2, where L is the trap length). When the focus of each lens lies at the center of the trap, the next reflection produces a parallel beam in the mirror reflection. Parallel trajectories probably lead to higher losses when the ions are being decelerated in the mirrors. The efficiency drops to zero left of the lower voltage peak and to right of the upper peak where the lens voltages correspond approximately to a parallel beam and f = L/4, respectively. The maximum trapping efficiency occurs where the image of each lens is convergent in the mirror regions and where the electro-optic magnification does not lead to a collision with the trap's electrostatic elements.

The angular distribution of neutrals leaving the trap has also been measured on the PSD. The two-dimensional angular distribution (rotationally symmetric about the centroid) is nearly Gaussian with an angular width of 3.8 mrad (FWHM) when the injected beam is 1-mm dia. This width agrees with the trap Einzel lens geometry and trap focal conditions for the beam size used. Measurements also show that the angular distribution (shape or width) does not depend on the ion, storage time or the beam energy.

CONCLUSION

In summary, we have demonstrated that RIBET can be easily used to store cation beams of mass below

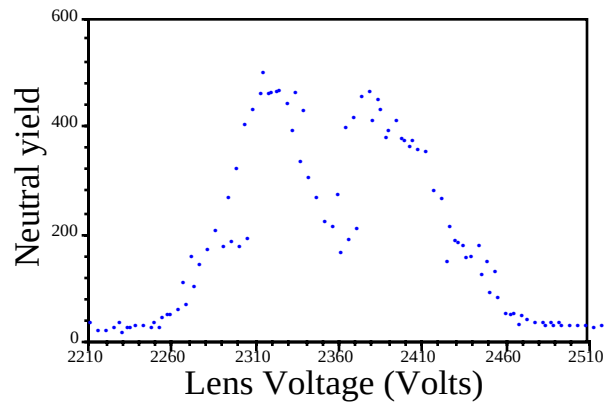

Figure 3. Trapped ion signal vs. the trap lens voltages for 2.85 keV Ar^+ ions. The trapping window is essentially identical for any mass ion at the same beam energy (see text).

about 100 amu throughout the 1.3–3.0-keV range. Part of this regime is well below the 4.2-keV ion beam energy used by Zajfman and co-workers [5-6] in a similar trap. Typical stored ion intensity in RIBET is orders of magnitude smaller than is possible in large storage rings, but so are the complexity and cost. These ion beam traps can be used for studying the lifetime for long-lived electronically excited states of atomic and molecular ions [8-10], cooling internal states of hot atomic and molecular ionic species having a permanent electric dipole moment for spectroscopic experiments, studying slow decay mechanisms of anion or cation cluster ions, and possibly as an ion source for internally relaxed ions for use in other experiments. The large field-free region (~25 cm) is a characteristic that may be especially important for some experiments.

Research sponsored by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Science, under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC.

REFERENCES

1. For overviews on ion trapping see full issues of Physica Scripta; **T22** (1988) and **T59** (1995).
2. Mokler, P.H. and Stohlker, Th., *Ad. At. Mol. Phys.* **36**, 297 (1997).
3. Andersen, L.H., Andersen, T., and Hvelplund, P., *Ad. At. Mol. Phys*. **38**, 155 (1997).
4. Møller, S. P., *Nucl. Instrum. Meth. Phys. Res*., **A 394**, 281 (1997).
5. Zajfman, D., et al., *Phys. Rev. **A*** **55**, R1577.
6. Dahan, M., et al. *Rev. Sci. Instrum.* **69**, 76 (1998).
7. Krause, H. F. et al., *Nucl. Instrum. Meth. Phys. Res*. **B 124**, 128 (1997).
8. Wolf, A. et al., *Phys. Rev. **A*** **59**, 267 (1999)
9. Knoll, L., et. al. **Phys. Rev. A 60**, 1710 (1999)
10. Wester, R., et al., *J. Chem. Phys.* **110**, 11830, (1999).