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IN FLIGHT CAPTURE OF AN ION BEAM IN A PAUL TRAP

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Abstract

A system for collecting 60 keV ion beams was set up at the ISOLDE-3 radionuclide mass-separator facility at CERN. Electric field retardation was used to bring the ions to 20 eV for injection into a Paul trap. Tests were made with $^{132}\text{Xe}^+$ and $^{79}\text{Br}^-$ ions. A trap potential well depth of about 30 V could be created. At this well depth a collection efficiency of about 0.2% was obtained for a xenon beam of emittance about 2π mm-mrad and energy spread estimated to be of a few eV. The efficiency for bromine ions was less but still appreciable. The efficiencies achieved indicate that a sizable fraction of the ions arriving at the correct RF window for acceptance by the trap were being collected. To the limit of the apparatus, the efficiency was increasing in proportion to the third power of the RF amplitude applied to the trap, indicating that it was proportional to the phase space volume of the trap.

These results are now being used to design a larger Paul trap collection system for installation at the ISOLDE-BOOSTER facility. By including a prebunching system to fit an incoming DC beam to the RF acceptance, it is expected that almost complete collection of weak mass separated high velocity beams can be achieved.

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1. INTRODUCTION

The usefulness of electromagnetic traps is greatly enhanced if charged particles can be introduced into them from outside. This has been vividly demonstrated in the recent high-accuracy mass measurements on radionuclides at ISOLDE using a tandem Penning trap configuration, the most recent of which are published in this volume[1]. In that work the ions which are observed under cyclotron resonance in a high-precision trap are prepared in another trap and transferred from that trap to the other[2]. The principal reason for this scheme is that radionuclides cannot be prepared as ions within the precision trap itself without significantly compromising its performance as a mass spectrometer.

Other workers have also found significant advantages in the ability to introduce charged particles into a trap from the outside. Gabrielse et al. [3] have injected antiprotons into a Penning trap to measure their inertial mass. Louris et al. [4] and Berkel et al. [5] have injected low velocity ions into Paul trap mass spectrometers for research in chemistry. This enables the use of Paul traps with negative ions which cannot be produced by the usual techniques of soft electron pick-up in such traps because of the high kinetic energy that free electrons obtain in the RF field. It is expected that the advantages of being able to separate the charged particle production from the system used for observing the particles will make such schemes more widely used in the future.

For some work it is necessary to be able to capture high-energy charged particles into a trap. This is particularly true, of course, for the antiprotons which are delivered from the LEAR facility at CERN at about 5 MeV. In this case the particles are introduced into the trap by energy degradation through a metal foil forming one of the electrodes of the trap, followed by deceleration in a temporary strong electric field. The very low transfer efficiencies of such a technique are acceptable in that work because it is very desirable to have only very few antiprotons in the trap.

For the radionuclide mass measurements cited above, where the radionuclides are delivered as ions at typically 60 kV, the ions are implanted onto a foil which is subsequently maneuvered to form part of one of the electrodes of the trap and reionized by heating. This is based on a scheme first published by Coutandin and Werth[6]. Such a scheme is limited, of course, to surface ionizable elements and even for those has efficiencies which are never greater than about 0.1 %. However, for these experiments, high efficiency and element non-specificity are very desirable. Part of the program at ISOLDE is therefore the development of a system for efficient in-flight capture of high velocity ion beams. The scheme chosen is electric field retardation followed by phased injection into a Paul trap. This paper presents the principles used in the design of the

system and reports on a prototype that has been developed. Results that have been obtained are presented.

2. THEORY

The possibility of injecting ions into a Paul trap from outside the electric field was the subject of a patent submitted by Dawson and Whetten [7]. Subsequently Kishore and Ghosh [8] carried out a theoretical analysis of a possible injection scheme in which the trap was turned on after the particles entered it. This was followed by an equivalent analysis from Todd et al [9] using phase-space dynamics. They confirmed that there were RF phase windows through which external ions could be injected into a Paul trap that was momentarily shut off. Schuessler and O [10] obtained a similar result from accurate integration of various ion trajectories over many RF cycles but with the important discovery that there were narrow RF windows for ion capture even when the RF field is on during entry of ions into the trap. These results inspired us to consider the problem of transferring ions from outside into a trap as analogous to loading a synchrotron storage ring with a linear injector.

Collecting a beam of particles into any confined region of space involves transferring an ensemble of particles from one region to another of six-dimensional phase space. The volume of the ensemble in phase space is

$$S = \int dx \, dy \, dz \, dp_x \, dp_y \, dp_z \quad (1)$$

where dx , dy and dz specify an elemental ordinary volume and dp_x , dp_y and dp_z specify an elemental volume in momentum space. By Liouville's theorem, the integrated six-dimensional volume is conserved in any transformation involving conservative force fields, such as would normally be applied for in-flight capture.

In practical systems for charged particle manipulation one generally tries to avoid aberrations. In aberration-free, or "linear", systems, the subintegrals

$$S_x \equiv \int dx dp_x, \quad S_y \equiv \int dy dp_y, \quad S_z \equiv \int dz dp_z \quad (2)$$

are individually conserved. In the particular case of the limits of integration being constants the overall phase space volume becomes

$$S = S_x S_y S_z \quad (3)$$

In beam optics, where z is usually regarded as the coordinate in the beam direction, the transverse components of the phase space volume are often expressed in terms of "emittance". This is defined as the area occupied by the particles in a diagram in which their angular divergences from the central beam axis are plotted against their displacements from the beam axis. The connection between the emittances ξ and the transverse phase space volume components for a beam of particles with central momentum p_0 is

$$S_x = p_0 \xi_x ; S_y = p_0 \xi_y \quad (4)$$

The conservation of a phase space component in a system which allows independent motions in the three spatial coordinates causes the emittance diagrams to shrink if the central momentum increases, even if there is no interdependence introduced between the three coordinate directions. To have an emittance measure which is preserved under a simple acceleration, such as is intended for beams from ion sources, the emittance is often expressed as a "normalized emittance" which is defined as

$$\xi_n = \gamma \beta \xi \quad (5)$$

where γ is the ratio of the relativistic mass m of the particles to their rest mass m_0 and β is the ratio of their velocity to the velocity of light at momentum p_0 . Thus the normalized emittance in a given coordinate is directly related by a multiplication constant to the phase space area in that coordinate;

$$S_x = m_0 c \xi_{nx} \quad (6)$$

where m_0 is the rest mass of the beam particle and c is the velocity of light.

The longitudinal phase space component of a length l of beam which has a momentum spread Δp is

$$S_z = \Delta p l \quad (7)$$

The phase space volume of a length of beam is thus determined from its normalized emittances in the two coordinates of its transverse plane and its momentum spread;

$$S = m_0^2 c^2 \xi_{nx} \xi_{ny} \Delta p l \quad (8)$$

In a particle trap the individual particle motions in each coordinate, to first order, will be simple harmonic. In the phase diagram for each coordinate, the particles will therefore all move clockwise in trajectories which are all ellipses of the same shape and aligned with the momentum-displacement axes. All will have the same orbital period in this diagram but individual phases and amplitudes. This will result in a phase space area occupied by the collection being that of the ellipse for the particle with the maximum amplitude of oscillation. For example, in the x coordinate this would be

$$S_x = \pi m \omega_x x_{\max}^2 \quad (9)$$

where ω_x is the angular frequency of the x oscillation and $x_{\max}$ is the maximum amplitude of that oscillation. Since the motions in the three coordinates of an ideal trap are completely independent, the phase space volume will be the triple product of the phase space areas. For a Paul trap which has cylindrical symmetry about a z axis, the x and the y motions will have the same frequency and maximum values, which may be expressed as ω_r and $r_{\max}$. The phase space volume of such a trap is then

$$S = (\pi m)^3 \omega_r^2 \omega_z r_{\max}^4 z_{\max}^2 \quad (10)$$

Comparing (8) and (10) gives the maximum length of beam that can be stored following in-flight capture in a Paul trap. A typical RFQ trap, such as is used for mass spectrometry in chemistry, will allow oscillation amplitudes of up to about 1 cm and can be operated so as to have equal axial and radial oscillation frequencies of up to 250 kHz for mass 100 ions. The normalized emittance of a beam of such ions from a quality separator such as ISOLDE is typically $7 \times 10^{-3} \pi$ -mm-mrad in each transverse coordinate

and the energy spread is less than 6 eV in 60 keV. The velocity of mass 100 ions at 60 kV is about 3×10^5 m/s. The beam segment that could be theoretically collected in such a trap is about 200 km or 0.5s.

This analysis has not included space charge effects. The number of ions in the phase space limit of a trap could easily exceed the space charge limit which, for the trap described above, has been shown by Dehmelt to be about 10^6 [11]. However, the purpose of the collection system for the mass measurements at ISOLDE is to be able to deal effectively with the very weak beams of short-lived radioisotopes. Also, for highly precise measurements the precision Penning trap should never have more than about 100 ions delivered to it. The space charge limit of the collection trap is therefore not a concern in this work.

A capacity for 0.5 s of beam would appear to be more than sufficient for collecting ions in a Paul trap. However, there is a problem in the manipulation of the shape of the beam phase space into that which matches the trap. The relative sizes of the phase space projections into the three coordinate planes are very different for the two cases. The phase space volume of the ions within the trap is evenly projected into these planes; about 500 eV- μ s in each from a phase space volume of 1.25×10^8 (eV- μ s)³. However, in the incoming beam the ions occupy only about 7 eV- μ s in each of the two transverse components but about 2.5×10^6 eV- μ s in the longitudinal component.

The problem this presents is similar to that of multiple stacking of injected beams in synchrotron storage rings. There each incoming beam length that fills the circumference of the ring must be placed in different regions of the phase space volume of the ring. Such "stacking" can typically be achieved for up to 100 orbits, or a total beam length of 100 times the storage ring circumference. However, about 5000 axial strings of beams would have to be stacked to completely fill a trap. Thus, while there is a great deal of phase space available in the radial direction in a trap, the fine threading of the beam required to fill this space does not seem feasible.

However, the problem can be considerably reduced by buffer gas cooling of the ions that are already in the trap. Such cooling was originally studied by Dehmelt [11] and is now commonly applied. In a study at McGill, parallel to the work reported here, significant reduction in the phase space volume of stored ion clouds have been observed after 10 ms in 1 Pa of He at room temperature [12]. The reduction in the phase space area of the axial motion is especially important since any such reduction will prohibit particles from reaching an end electrode or from leaving the trap through the hole it entered, both of which are at the extremes of the phase space area. If because of buffer gas cooling only 10 ms of stacking is required, the number of stacks is reduced to about

100. This appears feasible. Another approach, of course, is to increase the size of the trap so that fewer stacks are required to achieve the same phase space volume.

Thus, in principle, it should be possible to obtain close to 100% collection of an externally injected beam in a Paul trap. However, except for a monstrously large trap, it will involve transferring successive axial segments of the beam into different sections of radial phase-space within the trap. This will require coupling of the axial motion to the radial motion. In the work of others cited above, the traps were assumed to have pure electric quadrupole fields which, of course, provide no coupling of the axial and radial motions. Small acceptances and small RF phase windows are then to be expected. Injecting ions into the large phase space of the trap that is available at larger radii will require the higher order multipoles in the electric field that provide the necessary coupling of the axial and radial motions.

Unfortunately, accurate calculations of the effects of higher order multipoles on the behaviour of ions in a Paul trap containing buffer gas are difficult. This is particularly so over the period of 10 ms required for the buffer gas cooling to reduce the phase space volume. We therefore built a typical Paul trap to experimentally determine its phase space acceptance of an external beam. The results of this test were used to design an appropriate deceleration system for testing collection from higher energy sources.

3. APPARATUS

The apparatus built to test external injection of ions into a Paul trap has been described in the proceedings of the International Workshop on Stored and Trapped Particles in Stockholm, 1987 [13] and only its essential features will be repeated here. It included a pulsed source of variable energy ^{133}Cs ions that was mounted on-axis with the trap just outside a hole of 8 mm diameter in one end electrode of the trap. The extent of the ion collection after a given time was determined by suddenly pulling the ion cloud out of the trap through the gauze forming the other end electrode and observing them with an electron-multiplier.

With this apparatus the first reported experimental injection of external ions into a Paul trap was achieved. Collection efficiencies of up to 50% were reached for pulses of ions of energy about 1 eV. This was with a trapping pseudopotential well depth (i.e. the energy of an ion with axial oscillation of amplitude equal to the half the separation of the end electrodes) of about 10 eV. The ion pulses were about 3 μs duration and separated by the natural axial oscillation period of the ions in the trap (about 20 μs) and there was a

deliberately applied axial energy damping field containing a strong sextupole component correctly phased relative to the RF and the ion injection pulse.

One significance of this work was the demonstration that bunching the incoming ions and manipulating the higher order electric multipoles in a Paul trap can lead to quite efficient capture of incoming ions. However, more important for the goal of capturing high velocity ions it was also shown that the efficiency was still greater than 1% for a pulsed beam at 20 eV. This is believed to be due to a time window in the RF cycle when entering ions experience a deceleration from the RF field that puts them into an "orbit" in which they must undergo several axial oscillations before the right combination of RF micromotion and axial oscillation allows them to reach an electrode or the hole through which they entered. At the same time there is a strong coupling between the axial and radial motions from the higher order multipoles in the vicinity of the entrance hole. There will then be many more oscillations before the right combination of axial motion, RF micromotion and radial motion brings the ion to one of the trap electrodes or back to the entry hole for possible escape.

This has been simulated with calculations of trajectories for a few tens of axial oscillation cycles and the results show that there is indeed an energy dependent time window during which ions can enter the trap and undergo many oscillations before hitting an electrode. The window predicted by the computer simulations is shown in Fig. 1 and is consistent with the observed collection efficiencies. Essentially it is the same sort of window as seen by Schuessler but about a factor of ten wider in time because of the effects of the higher-order multipoles in our trap.

This result was quite encouraging since it seemed that by making the trap larger and deeper and by prebunching the incoming beam to the appropriate RF phase of the trap, an efficient collection system could be built for ions that enter the trap at several tens of eV. We therefore undertook the design and testing of a deceleration system to bring ISOLDE 60keV ions down to these energies and to inject them into a trap system designed to operate on a voltage pedestal of about 60 kV.

This was a rather ambitious undertaking. Deceleration systems for beams such as those of ISOLDE have been designed for implantation studies[14] but the goals have been usually for deceleration to about 1 keV or energy reductions of about a factor of 50. Deceleration to tens of eV requires much more attention to the aberrations of the system. Unfortunately, assessing the effects of aberrations when decelerating by a large energy factor to a short focal distance requires very precise calculations of the ion trajectories. The required precisions are not easily achieved by numerical integration of the equations of motion through a mapped set of field values using ordinary interpolation techniques. This is because of the very large errors that are inherent in first-order (plane)

interpolation of fields in the tight geometry involved and because of the prohibitive computation time required for higher order interpolation.

The approach we have taken is to fit the calculated values of the electric field to a set of axially symmetric multipoles and to use this set of multipoles to calculate the fields used in the numerical integrations. The multipoles beyond the quadrupole, of course, are those which cause aberrations in the focus. By tailoring the geometry of the deceleration system we have found it possible to make the effects of higher order multipoles negligible for decelerations from 60 keV to about 100 eV. The geometry used is shown in Fig. 2. It is significant, we think, that to reduce the aberrations to the required level, the internal diameter of the decelerating electrodes had to be always at least ten times that of the beam being decelerated. At about the 100 eV level, the beam was deliberately allowed to enter a strongly non-linear field region causing a coupling of the radial and axial motions during entry into the trap.

The system that has been built is shown schematically in Fig. 3. This was set up at the ISOLDE 3 facility last summer. The first beam to be collected was that of 60 keV $^{132}\text{Xe}^+$ ions. This was chosen because of its easy availability from the ISOLDE facility and because the atomic mass is close to that of the $^{133}\text{Cs}^+$ ions from our test source. It also had the attraction of being an atomic species that could not be collected and trapped by the present surface reionizing system used in the mass measurements.

4. RESULTS AND DISCUSSION

Testing of the deceleration system showed that about 20% of the raw ISOLDE-3 beam could be delivered through beam aperture stops used to limit the emittance to the calculated acceptance of the decelerating system (about 2π mm-mrad in each transverse coordinate of the beam). The design calculations were verified in that very careful alignment of the beam onto the system axis resulted in over 50% of the beam after the apertures being decelerated so as to enter the trap at no greater than 20 eV.

In preparing for capture of the 60 keV beam we found it very useful to monitor the current through the deceleration ground electrode. Figure 4 shows this current during deceleration of the $^{132}\text{Xe}^+$ to various voltages. The curves labelled (a) are for 0.8 nA of beam passing through the aperture stops and with a poor vacuum shortly after closing the system. Curve (b) is for 0.6 nA and the better vacuum achieved overnight. These curves are interesting in that they not only indicate the quality of the vacuum but also give a very clear signal when the trap ground is at the potential corresponding to the beam

energy. Thus no communication is needed between the voltage supply for the ISOLDE ion source and our trapping system, an important practical point when dealing with the high voltages involved in this work. Furthermore, the sharp breaks in the curves at the start and finish of the rise showed that the energy spread of the ISOLDE beam could not be more than a few eV.

The slowly rising current in the retardation ground electrode at lower trap potentials is probably due to the electrons produced by the interaction of the xenon beam with the background gas in the system, which is mostly helium used for ion cooling in the trap. The current associated with the motion of these electrons to the trap is supplied primarily through the deceleration ground electrode which directly faces the trap. At the point that the deceleration potential is equal to the beam energy there is a sudden increase in current due to the reflection of most of the xenon ions. These ions not only cause their own current through the ground electrode but also liberate electrons upon impact with it. According to our measurements from testing secondary emission from a beam current monitor, 60 keV Xe ions each liberate an average of about 10 electrons from an aluminum surface such as used for the ground electrode. These electrons are also accelerated up to the trap potential with their associated current also being supplied primarily by the deceleration ground electrode.

This phenomenon made it particularly easy to set the trap at the potential appropriate for beam collection. Subsequent tuning of the trap parameters to those used for the most efficient capture of cesium from our test source resulted immediately in capture of the xenon ions.

Tests were then carried out on the collection efficiency as a function of trap operating parameters. These were measured by extracting the trap contents after a preset filling time and observing the ion pulse with an electron-multiplier. For these observations, the extracted ions were immediately brought back to approximately 60 keV by having them enter the ground transport electrode. The gain of the electron-multiplier for the 60 keV ions was calibrated by observing a weak 60 keV DC xenon beam passed through the trap with no potentials on it and measuring the current falling on the cathode surface. This current was measured by connecting the electron-multiplier as a whole through a picoammeter to ground, using a series 9 V positive bias to capture any secondary electrons emitted from the cathode surface. The current gain was then obtained by operating the electron-multiplier properly and measuring the anode current with the same ion beam. This was done for several ion beam currents to test for possible saturation effects in the electron-multiplier. A gain of 15 000 was obtained.

Various parameters were adjusted for maximizing the efficiency. First the extraction pulse level and timing was set so as to ensure full extraction of the ion cloud. Then the

trap potential and injection electrode voltages were adjusted. Typically the best efficiencies were obtained when the ions entered the trap at an energy centered on 20 eV. Adjustment of the helium buffer gas gave the best collection efficiency at an estimated 0.1 Pa.

The most important parameters determining the collection efficiency were the RF voltage and frequency. The ideal frequency was correlated very strongly to the amplitude. The amplitude of RF is therefore the dominant factor in determining the collection efficiency that could be obtained. The variation of collection efficiency with this amplitude is shown in Fig. 5. The efficiency shown is the fraction of ions passing through the aperture stop that are collected and delivered as a pulse to the electron-multiplier.

The results show that with 1150 V RF amplitude on the trap, the maximum voltage that could be applied, over 0.2% collection efficiency was obtained. This, and the fact that the collection efficiency was rising rapidly with RF amplitude, is very encouraging. Not only was the efficiency of the present foil implantation collection system exceeded but it was exceeded with an ion that could not be produced by surface ionization. In a demonstration of the versatility of the system, it was reconfigured by merely reversing the polarity of all the voltages so that shortly after the xenon collection a beam of negative bromine ions was collected. In the short time that was available the collection efficiency could not be determined but it appeared to be less than for the xenon beam. This could be due to the ease with which negative bromine ions are neutralized compared to positive xenon ions in the relatively poor vacuum of our system at the time of the test.

The collection efficiency of 0.2% for a DC beam appears to us to be a reasonable figure for the phase space volume of our trap and the percentage of time for which the RF window of our trap is open for injection. As for what could be expected at higher RF amplitudes, it is interesting to compare the results shown in Fig. 5 with a cubic dependence on the RF amplitude. Over the limited range of observations it is impossible to draw firm conclusions but the data is certainly consistent with such a dependence. It therefore appears that the efficiency is rising in proportion to the phase space volume of the trap which, with the tuning we used on the trap parameters to get maximum efficiency at each voltage, should be proportional to the cube of the RF amplitude. Such a dependence should continue until the RF window is saturated (expected to occur at about 5 to 10% efficiency).

We are now designing a version of this trap to incorporate in the mass measurement system at the ISOLDE-BOOSTER facility. As presently planned this trap will have about three times as great an end electrode separation and should be capable of being operated at up to 10kV RF. This should increase the phase space volume of the trap by a

factor of about 200 and should bring the efficiency to close to 100% for ions that are arriving at the trap in the RF phase window. Prebunching the incoming DC beam into that phase window should therefore allow almost complete collection of any ISOLDE-BOOSTER beam.

5. CONCLUSION

We have shown that efficient collection of high voltage beams in a Paul trap is possible by using electrostatic retardation of ions before trap injection. The versatility of the system is shown by collection of both $^{132}\text{Xe}^+$ and $^{59}\text{Br}^-$. Collection efficiency of over 0.2% is possible in a relatively modest trap without bunching of the beam into the RF acceptance window. Over the range of operating parameters used, the collection efficiency was proportional to the cubic power of the RF amplitude on the trap.

This indicates that considerably higher collection efficiencies are possible with larger traps, larger aperture decelerating systems and RF bunching of the incoming beam. The design of such a trap is presently being undertaken for installation at the ISOLDE-BOOSTER facility.

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FIGURE CAPTIONS

- Fig. 1 Computed estimates of the energy-time aperture for ^{133}Cs ion of a Paul trap with z_0 (half the separation between end electrodes) of 12 mm. The trap operating parameters are 360 V_{pp} at 250 kHz giving a pseudopotential well depth of about 10 eV.
- Fig. 2 The configuration of the system for decelerating 60 keV heavy ions to several tens of eV.
- Fig. 3 The configuration of the Paul trap collection system as installed on the ISOLDE-3 beam line at CERN. The dimensions are not to scale, the trap and deceleration system being enlarged for clarity.
- Fig. 4 Current through the deceleration ground electrode as a function of trap potential (60kV in Fig. 2). Curves (a) are for 0.8 nA of beam current passing through the deceleration aperture grid and a poor vacuum. Curve (b) is for 0.6 nA and a better vacuum.
- Fig. 5 Overall trapping efficiency as a function of amplitude of RF voltage applied to the ring electrode of the Paul trap.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5