DD

CERN-EP 90-18

a

CM-P00060949

1990

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/90-18
8.02.1990

A NEW COOLING MECHANISM FOR HEAVY IONS IN A PENNING TRAP

G. Savard¹, St. Becker¹, G. Bollen¹, H.-J. Kluge¹, R.B. Moore^{2,3}, L. Schweikhard¹,
H. Stolzenberg¹ and U. Wiess¹

¹ Institut für Physik, Universität Mainz, D-6500 Mainz, Fed. Rep.
Germany

² Foster Radiation Laboratory, McGill University, Montreal, Canada

³ ISOLDE collaboration, CERN, Geneva, Switzerland

(IS-130)

ABSTRACT

A new cooling mechanism for heavy ions stored in a Penning trap has been developed. The axial and cyclotron motion are cooled by buffer gas collisions. The outward radial diffusion due to the increase in the radius of the magnetron motion associated with a decrease in magnetron energy is counteracted by an azimuthally quadrupole RF-field at the sum frequency of the magnetron and cyclotron motions. Hence mass selective cooling is achieved.

PACS number: 32.80.Pj, 07.75.+h.

Submitted for publication in Physical Review Letters

As a general rule, high accuracy measurements of the fundamental properties of particles and their interactions are greatly enhanced by confining the motion of the particles to a small volume of phase space in a clean environment and observing the interactions for a long time. Electromagnetic fields applied to charged particles so as to confine them to a finite phase space volume in a very high vacuum can provide such an environment for long periods but the practical requirement of creating particles within such a volume, or transferring them into it from an outside source, usually results in the phase space occupied by the particles being rather large. It can sometimes be reduced by removing particles outside a selected phase space volume but generally it is much more desirable to be able to collapse the phase space volume by cooling the particle motion within the fields.

At high energy, storage ring are beginning to provide cooling of particles in such a confinement. At low energy, electromagnetic traps of the Paul and Penning types have been providing such conditions for quite some time¹. The Paul trap provides such confinement by using an oscillating electric quadrupole field. The Penning trap combines radial confinement in a high magnetic field with axial confinement by a static electric quadrupole field aligned with the magnetic field.

Cooling techniques for such traps have already been developed. Resistive cooling of light particles in a Penning trap has been achieved by picking up, with a tuned circuit, the signal induced by the particle motion relative to the trap electrodes^{2,3}. For heavy ions, this method is not practical since the signals are proportional to the velocity of the stored particles and hence too small, resulting in long cooling times. The cyclotron motion of electrons in Penning traps is also cooled very effectively by synchrotron radiation³. However, this is insignificant for heavy ions. Laser cooling⁴ of ions in traps has been demonstrated but this method can only be applied to some few elements which have suitable optical transitions.

Another approach is the use of buffer gas collisions to remove energy from the ion motion. The effect of buffer gas on ion motion in a trap was presented by Major and Dehmelt⁵ and cooling of ions by buffer gas collisions in a Paul trap is widely used. Such cooling in a Paul trap is possible because of the confining three-dimensional harmonic oscillator potential of such a device.

Simply removing energy from the particle motion in any coordinate causes the particle to move toward the trap center into a smaller phase space volume. However, in the case of the Penning trap removing energy from the particle motion by buffer gas collisions will cause the particle to move away from the trap center. This is because the same electric quadrupole potential that provides the axial confinement of the particle also provides a radially repulsive electric field. In ordinary trap operation the motion is still confined because this radial repulsion causes a slow precession of the particle orbit about the trap center, usually referred to as a “magnetron” motion. However, this magnetron motion is one of the degrees of freedom of the motion and, because of its small kinetic energy and relatively large electric potential energy, has a maximum total energy at the center of the trap. Simply removing energy from the magnetron motion by buffer gas collisions will cause the particle to move down the magnetron energy hill to a larger radius. This can easily be seen from the energy of an ion with quantum numbers n_z , n_- and n_+ (z, magnetron and cyclotron motion) given by³

$$E_{n_z, n_-, n_+} = \hbar\omega_+(n_+ + 1/2) + \hbar\omega_z(n_z + 1/2) - \hbar\omega_-(n_- + 1/2).$$

At high quantum numbers, buffer gas collisions will reduce n_+ and n_z but will increase n_- because of the negative sign of the magnetron energy. Hence the radii of the motions will change according to

$$\rho_{\pm}^2 = \frac{2\hbar(n_{\pm} + 1/2)}{m(\omega_+ - \omega_-)}$$

$$z^2 = \frac{2\hbar(n_z + 1/2)}{m\omega_z}.$$

To perform buffer gas cooling effectively in a Penning trap, a mechanism is needed to restrain this radial blowup of the ion cloud.

The radial motion of an ion in the trap can be described as a linear combination of a reduced cyclotron motion ω_+ of radius ρ_+ and a magnetron motion ω_- of radius ρ_- :

$$x = \rho_+ \sin(\omega_+ t) + \rho_- \sin(\omega_- t)$$

$$y = \rho_+ \cos(\omega_+ t) + \rho_- \cos(\omega_- t)$$

An azimuthal RF dipole field set up in the trap will act on the ω_+ and ω_- motions independently and will transfer energy to the particle only at the two

resonance frequencies ω_+ and ω_- . In the case of a quadrupole field in the xy-plane, $E_x = K y \cos(\omega_d t)$, $E_y = K x \cos(\omega_d t)$, the power absorbed by the ion is given by the product⁶

$$q\vec{v} \cdot \vec{E} = qK \cos(\omega_d t) [\rho_+^2 \omega_+ \cos(2\omega_+ t) + \rho_-^2 \omega_- \cos(2\omega_- t) + \rho_+ \rho_- (\omega_+ + \omega_-) \cos(\omega_+ t + \omega_- t)]$$

The ion can therefore pick up energy from the applied field at the three frequencies $2\omega_+$, $2\omega_-$ and $\omega_+ + \omega_-$. Electric fields at the first two frequencies act on the motions independently but at the third frequency couple both motions. Thus transitions are induced from $|n_-, n_+, n_z\rangle$ to $|n_- \pm 1, n_+ \mp 1, n_z\rangle$ ⁶. For a stored ion with only magnetron motion of initial radius $\rho_- = R_i$, this coupling will decrease ρ_- while increasing ρ_+ until the magnetron motion is transformed completely to cyclotron motion of radius $\rho_+ = R_i$.

However, collisions with the buffer gas will tend to equilibrate the energy of the ion with that of the gas. This will damp the fast components of the ion motion and lead to reduced z-oscillation amplitude and cyclotron radius. Combining such a quadrupole field with buffer gas cooling, at appropriate buffer gas pressure and RF amplitude, will also cause the magnetron radius to decrease. The net result is a combination of cooling and centering of the ion cloud. Since the frequency that has to be applied is $\omega_+ + \omega_- = \omega_c = \frac{qB}{m}$, this method is mass selective.

This phenomenon can be demonstrated by a numerical integration of the equations of motion. The left side of figure 1 shows the motion of a particle in the presence of a buffer gas whose effect is approximated as a damping force proportional to velocity. This should be a reasonable approximation to the actual ion motion under buffer gas cooling since, from ion mobility data⁷, the interaction between heavy ions and a buffer gas such as helium at low energies are primarily that of the ion and the dipole moments it induces in the helium atoms. They are therefore of long range and involve very small changes in the ion energy for each helium atom involved. The action of a buffer gas is then very similar to a viscous drag. The initial cyclotron motion is seen to decay rapidly while the magnetron radius increases steadily until the particle moves out of the trap. The right side of figure 1 shows the effect of adding a RF-quadrupole field coupling the motions. It is clearly seen that the coupling between both motions will slow down the decay of the

cyclotron radius and shrink the magnetron radius resulting in a centering of the particles in the trap. This effect requires the coupling of both motions to be faster than the constant for exponential increase of the magnetron radius while being smaller than the decay constant for the cyclotron motion. Both constants are functions of the buffer gas pressure and of the trapping parameters. For example, the constant for the increase of the magnetron radius is proportional to the trapping voltage and inversely proportional to the square of the magnetic field, it is also inversely proportional to the mass of the stored particles. It therefore requires a strong coupling to cool and center heavy ions in an intermediate magnetic field while only a very weak coupling is required for light particles in a superconducting solenoid.

This cooling technique has been implemented at the on-line mass measurement system for radioactive ions at the ISOLDE mass separator at CERN. The system⁸ is composed of two Penning traps, a high-precision trap placed in the highly homogeneous magnetic field of a superconducting solenoid to perform the mass measurement and a trap used to bunch the DC beam of the ISOLDE mass separator for injection into the high-precision trap. The cooling is performed in the bunching trap so that the extracted bunches occupy a reduced phase-space volume when delivered to the high-precision trap. In addition, the mass selectivity of the cooling allows impurity ions to be removed.

The bunching trap (fig.2) is placed in a magnetic field of 0.7 Tesla with a homogeneity of $10^{-3}/\text{cm}^3$. A trapping potential of 10 Volts is used and the He buffer gas can be put directly into the trap by a teflon tube with the gas flow controlled by a needle-valve. Differential pumping is available between both traps to maintain a vacuum of 10^{-9} mbar as required in the high-precision trap. The ring of the trap is split into four quadrants allowing the excitation of the ion cloud by a quadrupole field. The ions are provided either by the on-line mass separated ion beam of ISOLDE or a test source. The ion beam is implanted on a rhenium foil mounted on a rotor placed in the entrance end electrode of the trap. After the implantation the rotor is turned to have the foil facing the inside of the trap (fig. 2). The implanted atoms are then desorbed and surface ionized by a pulsed current through the foil. The ions are captured in the trap by loss of some axial energy through collisions with buffer gas. Once the ions have been cooled to a small cloud in the center of the trap, a process taking about 200 ms, they are ejected in a

bunch through a hole in the extraction end electrode by applying a 10 Volts pulse to the entrance electrode.

The cooling effect was observed by measuring the energy distribution of the ions ejected from the trap. Without buffer gas and RF excitation, energy distributions of 4 to 5 eV are observed. With buffer gas cooling, energy distributions of about 1 eV are obtained for the ejected ions. From the strength of the electric field used for the ejection pulse, it can be shown that this corresponds to a temperature of the ions inside the trap about equal to that of the buffer gas.

The centering effect of a quadrupole RF excitation of ^{133}Cs in the presence of He buffer gas is shown in figure 3. At resonance, an increase of a factor of 70 is demonstrated for the number of ions per bunch detected by a microchannelplate placed 1.5 meters above the trap. Due to inhomogeneity in the magnetic field and imperfections in the trapping potential, the resonance curve is limited to a $\text{FWHM} = 230 \text{ Hz}$ corresponding to a mass selectivity of about 350.

In conclusion, mass selective buffer gas cooling of heavy ions in a Penning trap has been performed. It allows ions to be cooled to a temperature equivalent to that of the helium buffer gas, while eliminating contaminant ions of other masses present in the trap. Its use on the mass-measurement system for radioactive isotopes at ISOLDE therefore provides better injection conditions into the high-precision Penning trap⁹. The technique also makes it feasible to collect a DC beam in a Penning trap by a mechanism similar to that used for collection in Paul traps¹⁰. We are studying the feasibility of such a system.

This work has been funded by the Bundesminister für Forschung und Technologie under contract No 06 Mz-188-I. One of us (RBM) would like to thank the National Sciences and Engineering Research Council of Canada, McGill Univ. and CERN for support during a sabbatical leave.

REFERENCES

- ¹ H.G. Dehmelt, *Advan. At. Mol. Phys.* 3 (1967) 53.
- ² R.S. Van Dyck Jr., P.B. Schwinberg and H.G. Dehmelt, *Atomic Physics 9* (1984), edited by R.S. Van Dyck Jr. and E.N. Fortson (World Scientific, Singapore).
- ³ L.S. Brown and G. Gabrielse, *Rev. Mod. Phys.* 58 (1986) 233.
- ⁴ D.J. Wineland, W.M. Itano, J.C. Bergquist and R.G. Hulet, *Phys. Rev. A* 36 (1987) 2220.
- ⁵ F.G. Major and H.G. Dehmelt, *Phys. Rev.* 170 (1968) 91.
- ⁶ G. Bollen, R.B. Moore, G. Savard and H. Stolzenberg, submitted to *J. of Appl. Phys.*.
- ⁷ H.W. Ellis, E.W. McDaniel, D.L. Albritton, L.A. Viehland, S.L. Lin and E.A. Mason, *At. and Nucl. Data Tables* 22 (1978) 179.
- ⁸ H. Schnatz, G. Bollen, P. Dabkiewicz, P. Egelhof, F. Kern, H. Kalinowsky, L. Schweikhard, H. Stolzenberg, H.-J. Kluge and the ISOLDE Collaboration, *Nucl. Instr. Meth.* A251 (1986) 17.
- ⁹ H. Stolzenberg, G. Audi, St. Becker, G. Bollen, H.-J. Kluge, R.B. Moore, T. Otto, G. Savard, L. Schweikhard and the ISOLDE Collaboration, "High accuracy direct mass determination of unstable Cs isotopes", in preparation.
- ¹⁰ R.B. Moore and S. Gulick, *Physica Scripta*, T22 (1988) 28.

FIGURE CAPTIONS

Fig. 1 Runge-Kutta integration of the equation of motion in a plane perpendicular to the magnetic field for an ion in a Penning trap. The cross represents the center of the trap, the circle, the initial magnetron radius. On the left, motion of an ion experiencing a viscous drag proportional to velocity. Fast damping of the cyclotron motion and a slow blowup of the magnetron motion are observed. On the right, the effect of an additional resonant quadrupole field at ω_c is shown. Both cyclotron and magnetron radii are decreased.

Fig. 2 Perspective view of the bunching trap used on the mass measurement system at ISOLDE. The minimum distance of the endcaps is 28 mm.

Fig. 3 Number of ions per bunch extracted of the bunching trap as a function of cooling frequency. The resonance for ^{133}Cs is at $\omega_c = 81.2$ kHz for $B=0.7$ T. Helium is used as buffer gas at a pressure of $p=8 \times 10^{-5}$ mbar.

Figure 1

Figure 2

Figure 3