

# SIMULATION OF COOLING MECHANISMS OF HIGHLY-CHARGED IONS IN THE HITRAP COOLER TRAP

G. Maero\*, F. Herfurth, O. K. Kester, H.-J. Kluge, S. Koszudowski, W. Quint,  
GSI, Darmstadt, Germany  
S. Schwarz, NSCL, East Lansing, Michigan, USA

## Abstract

The use of heavy and highly-charged ions gives access to unprecedented investigations in the field of atomic physics. The HITRAP facility at GSI will be able to slow down and cool ion species up to bare uranium to the temperature of 4 K. The Cooler Trap, a confinement device for large numbers of particles, is designed to store and cool bunches of  $10^5$  highly-charged ions. Electron cooling with  $10^{10}$  simultaneously trapped electrons and successive resistive cooling lead to extraction in both pulsed and quasi-continuous mode with a duty cycle of 10 s. After an introduction to HITRAP and overview of the setup, the dynamics of the processes investigated via a Particle-In-Cell (PIC) code are shown, with emphasis on the peculiarities of our case, namely the space charge effects and the modelling of the cooling techniques.

## INTRODUCTION - SCIENTIFIC GOALS

At the HITRAP facility in GSI, a series of precision experiments will be possible via the use of heavy and highly-charged ions; species up to  $U^{92+}$  can be produced and delivered by the accelerator complex, and radioactive nuclides can be provided by the Fragment Separator (FRS). Heavy atoms that have been previously stripped of all or most of their electrons allow indeed studies on residual electrons in the so-called high-field regime, where tests on the theory of quantum electrodynamics (QED) can reach new levels of accuracy; among these experiments we can mention the *g-factor* measurement of the bound electron or the width of the ground-state hyperfine splitting in H-like ions. Other planned experiments include nuclear mass measurements, collision studies and more [1].

The HITRAP setup will also be part of the Facility for Low-energy Antiproton and Ion Research (FLAIR); there  $\bar{p}$  will allow fundamental symmetry tests.

## THE HITRAP FACILITY

The HITRAP facility is located in the Reinjection Tunnel between the Experimental Storage Ring (ESR) and the Heavy Ion Synchrotron (SIS); ions are accelerated and partially stripped in the Universal Linear Accelerator (UNILAC) and taken up to 400 MeV/u in the SIS. The particles lose all electrons on a thin target; deceleration to 4 MeV/u

in the ESR allows their injection in the HITRAP decelerating section, where a double-drift buncher shapes them for improved acceptance into a IH-Linac operated in deceleration mode. A RadioFrequency Quadrupole (RFQ) structure further slows the bunch from 0.5 MeV/u to 6 KeV/u, after which the ions can be stored in the Cooler Trap that cools them down to 4 K and ejects them in pulsed or quasi-continuous mode. A bending magnet and a vertical beam line guide the beam to the platform on top of the tunnel, where a distribution beam line delivers the cold ions to the various experiments.

## THE COOLER TRAP

The Cooler Trap, currently in the construction stage, is the element where the ion beam is not only decelerated but also cooled and shaped in such a form to fit the experiments' requirements. It consists of a cryogenic, cylindrical Penning trap, i.e. a series of cylindrical electrodes immersed in a longitudinally directed magnetic field provided by a superconducting solenoid. The latter, with a strength of 6 T and a maximum inhomogeneity below 0.1% over a volume of 10-mm diameter and 400-mm length, allows for the radial confinement via the Lorentz'  $\vec{v} \times \vec{B}$  force. The longitudinal trapping of the  $10^5$  ions is obtained by lifting the last electrode's potential, so that the bunch is reflected back at the end of the trap. If the first electrode's potential is raised before the ions reach the entrance, the bunch is trapped. The energy and length of the incoming bunch (6 KeV/u  $\approx$  15.5 KV/q,  $\approx$  400 ns) dictate the length of the electrode stack (400 mm excluding the outermost trapping electrodes) and the trapping potential, that is about 20 KV.

The manipulation of the potential of the 21 equally-shaped internal electrodes gives the possibility to create nested traps where simultaneous confinement of ions and electrons is achieved. Indeed, as many as  $10^{10}$  electrons, created in a pulsed laser source located in the downstream beam line, are injected in order to perform electron cooling (see Fig. 1). Due to the presence of a strong magnetic field, the electrons maintain the low temperature of the cryogenic environment (4 K) losing energy via synchrotron radiation with a time constant  $\tau_s = 3\pi\epsilon_0 \frac{m^3 c^3}{e^4 B^2} \approx 0.1$  s [2]. The axial bounce of the ion cloud through the electron-filled regions lowers the ions' energy via Coulomb collision [4]; to avoid radiative recombination as the electrons' and ions' energies get closer, the process must be stopped at some point and a different cooling scheme has to be introduced:

\* G.Maero@gsi.de

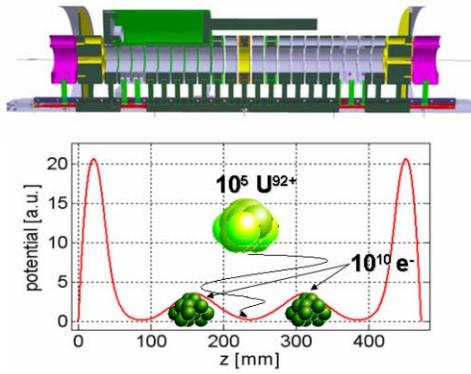


Figure 1: Section of the Cooler Trap, a large-scale storing device with an inner diameter of 35 mm and a length of 400 mm of trapping region. Inner electrodes are 17-mm long and are separated by 2-mm gaps. The box for cryogenic electronics is placed in the upper-left part. A sketch of the nested-trap configuration is shown below.

resistive cooling. Ions are collected in the central region of the trap, where radially-split electrodes allow detection of motion frequencies and manipulation of the cloud via resonant excitation (e.g. ‘rotating wall’ radial compression [5]). Then resistive cooling with an external RLC circuit (whose quality factor is about 800) at the resonant axial oscillation frequency  $\omega_z$  takes place. This provides the cooling of the axial motion only, RF coupling to the radial motions is obviously foreseen; the ions’ energy is brought down to the level of the environment temperature, that is why the trap is in thermal contact with the magnet cold head at 4 K.

Some questions have already become apparent, and will be dealt with in the next section:

- the survival probability to radiative recombination;
- the space charge and its effects (frequency shifts and frequency range broadening);
- the time constants of the abovementioned processes.

## THEORY AND SIMULATION OF COOLING PROCESSES

### Electron Cooling

For electron cooling in a trap, electrons are not renewed like in a storage ring, but cooled via synchrotron radiation in the magnetic field; nevertheless the energy exchange by Coulomb collisions with the ions produces a strong feedback depending on particle densities. The dependence is not trivial: to model the phenomenon, the energy lost by hot ions is considered as instantaneously converted into the temperature of an isotropic  $e^-$  distribution. On the other hand, the latter will be the result of this positive contribution and the radiation decay; furthermore, the stopping force affecting the ions is density-dependent, too. Hence

a denser electron cloud will have a stronger stopping and consequently the electrons will heat up more (typical numbers show a rise from the initial meV range to a few eV), leading then to a slower cooling of the ions. Therefore the cooling times do not reduce linearly with the electron density.

To summarize, from former investigations it appears possible to cool the ion bunch in about 1 s, keeping radiative recombination losses within 10 ÷ 15% [2], [3].

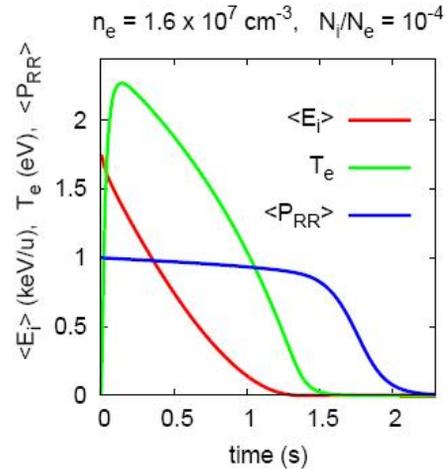


Figure 2: Example of electron cooling:  $10^5 U^{92+}$  ions are cooled in about 1 s without significant losses by recombination ( $\langle P_{RR} \rangle$  is the ion survival probability). The strong heating and successive cooling of the  $e^-$  temperature  $T_e$  by synchrotron radiation is also evident [3].

### The Particle-In-Cell Code

A Particle-In-Cell (PIC) code is used to investigate the issues of space charge and resistive cooling. A PIC code essentially solves the Poisson equation, i.e. calculates the electrostatic potential with assigned boundary conditions including the charge of the ions. Then the particles are advanced in time with a suitable propagation algorithm within the obtained electrostatic potential and the given  $\vec{B}$  field, and the process is looped ad libitum [6].

The Poisson equation is solved in an rz-symmetric geometry with a Fast-Fourier-Transform (FFT) method [7]. The charge of each particle is smeared on a radial ring when it is included in the charge distribution, but the motion is treated in full 3d. The  $\vec{B}$  field creates an additional problem, as an ion of charge  $q$  performs cyclotron oscillations of frequency  $\omega_c = qB/m$  and common advancement algorithms, as leapfrog or time-adaptive Runge-Kutta routines, would require too small time steps  $\Delta t$  to keep a sufficient level of accuracy, depending on the  $B$  strength. On the contrary, a Velocity Verlet (VV) scheme, adapted to the specific case of ions in electromagnetic fields, allows for a B-independent choice of  $\Delta t$  s [8]. Our simulations show that with  $\Delta t = 5^{-9}$  s one gets an energy nonconservation

$\Delta E/E \approx 10^{-4}$  after a simulation time of 50 ms for  $B = 6$  T, while using a leapfrog algorithm the particle is radially lost much before.

Since the simulation of  $10^5$  trajectories would be too expensive in terms of computing time, the method of charge scaling is used: a limited number of simulation ‘superparticles’ is chosen, carrying the total amount of charge of the real bunch when the charge distribution has to be calculated for the Poisson equation, but behaving as normal particles when advanced in time with the VV routine.  $500 \div 1000$  superparticles are already enough to reproduce well the statistical properties of the cloud.

### Resistive Cooling

A particle placed in the vicinity of a conductor induces a surface charge density on the conductor itself; if the latter is kept at a fixed potential, one can cancel the apparent contradiction with the creation of a so-called ‘image charge’ of opposite sign, so that the global effect is null at the conductor’s surface. If an ion is placed between two conducting elements, the image charge induced on the first will have an effect on the second, generating a second image and so on and so forth, so that a whole series of images is created. An analytical calculation of the image sequence is possible for simple cases, like for instance that of an ion placed between two parallel plates (a capacitor) [9]; the net difference  $\Delta q^{(N)} = q_{im}^L - q_{im}^R$  between the charge collected on the two plates (when the series of images is truncated at the  $N - th$  order) varies depending on the ion’s axial position (see Fig. 3) and connecting the plates to an external circuit this turns out to be an ‘image current’ oscillating with the ion bounce, that can be detected with LC elements (resonant or ‘bolometric’ detection [10]), or damped in amplitude if the LC (‘tank’) circuit has a dissipative component (resistive cooling).

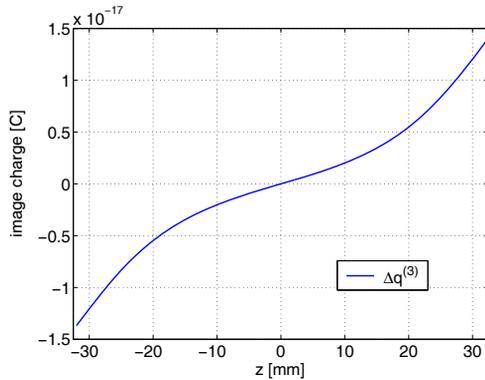


Figure 3: Net image charge  $\Delta q^{(N)}$  accumulated on two parallel plates at a distance  $d = 64$  mm, versus the position of a  $U^{92+}$  ion. The charge is calculated up to the third image ( $N = 3$ ).

In the Cooler Trap the detection and cooling are performed creating a nested trap in the center of the electrode

stack and connecting the two electrodes adjacent to the central one to the tank circuit; we have calculated the image charge that is collected on the cylindrical surface following the same approach as described for the capacitor [9], i.e. writing the Gauss’ law for a cylinder; integration on an axially-finite region  $[z_1 - z, z_2 - z]$  where  $z$  is the particle position with respect the center of the trap and  $z_1, z_2$  are the axial coordinates of the desired electrode, the result yields

$$q_{ring} = \frac{qR^2}{2} \int_{z_1-z}^{z_2-z} \frac{1}{(R^2 + z'^2)^{3/2}} dz' = \frac{qR^2}{2} \left[ \frac{z' \left(1 + \frac{z'^2}{R^2}\right)^{3/2}}{(R^2 + z'^2)^{3/2} \left(1 + \frac{z'^2}{R^2}\right)^{1/2}} \right]_{z_1-z}^{z_2-z}, \quad (1)$$

and again the net  $\Delta q_{ring}$  is the difference between the charge on the two collecting electrodes (see Fig. 4).

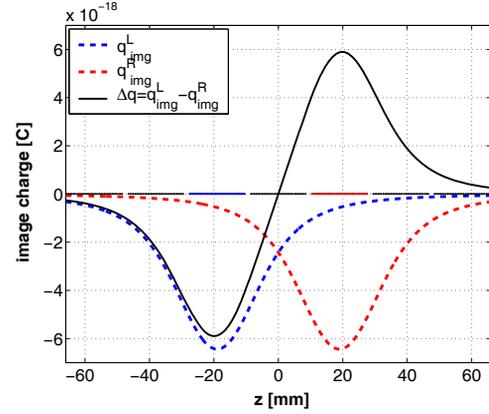


Figure 4: Net image charge accumulated on the electrodes of a multi-ring trap versus the position of a  $U^{92+}$  ion. The charge on the two pick-up electrodes and the difference (net charge) is shown. The geometrical parameters reproduce the Cooler Trap characteristics.

It can be shown that the damping of the ion motion (i.e. its energy) is exponential [11], with a decay constant  $\tau = mD_{eff}^2 / (Rq^2)$ , where  $R$  is the resistance of the tank circuit and  $D$  the *effective electrode distance*, that would be the equivalent distance between the parallel plates in the capacitor case. This guides us to the implementation in the PIC code: the instantaneous image current is  $I$  gives a voltage drop on the external resistance  $\Delta V = RI$ , and the cooling is fed back via a restoring force  $F_z = qE_z \approx -q\Delta V / D_{eff}$  acting on the particle. In our case, with an effective resistance of  $72.7 \text{ M}\Omega$ , the theoretical value is  $\tau = 110$  ms; simulations give a pretty good agreement (125 ms) if we imagine to have parallel plates at the ends of the central nested trap, while using the cylindrical rings as pick-ups affects the detected signal and gives a cooling time constant of 250 ms.

## Space Charge

The picture changes significantly moving from a single particle to a cloud of  $10^5$  ions. First of all, they will fill the potential well, flattening its bottom (see Fig. 5). As a consequence, the axial motion will not have a fixed eigenfrequency  $\omega_z = (qV/(md^2))^{1/2}$  (with  $d$  a geometrical trap parameter) anymore. The energy spread of the particles will result in an energy-dependent range of frequencies. The estimate of this effect is crucial, since the resistive cooling will be performed via an RLC circuit, whose effective resistance has a peak at the characteristic frequency  $\omega_{LC} = 1/(2\pi)(LC)^{-1/2}$ ; this means that full cooling will be reached only by ions within the bandwidth of the tank, that is inversely proportional to its Q value. Simulations of an ion column (1 mm radius,  $\approx 10$  eV energy) in a potential well of 100 V show that as the number of ions increases,  $\omega_z$  shifts from the eigenvalue of 383.15 KHz and the frequency range  $\Delta\omega/\omega = (\omega' - \omega)/\omega$  broadens (see Table 1).

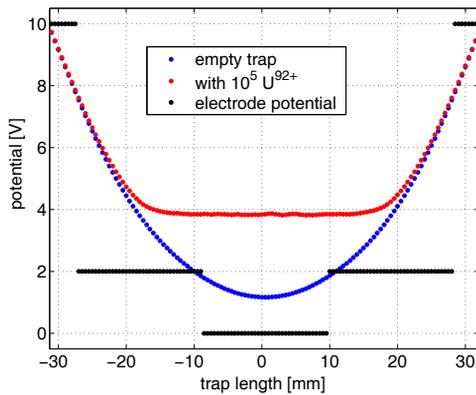


Figure 5: Space-charge effect of column of  $10^5$  bare Uranium ions with a radius of 1 mm. The potential on the longitudinal axis is visibly flattened. The voltage applied to the electrodes is also shown.

Table 1: Axial frequency shifts

No. ions	$\bar{\omega}'$	$-\Delta\omega/\omega$	$\sigma(\omega)$
$10^3$	379.72 KHz	$8.95 \cdot 10^{-3}$	1.77 KHz
$10^4$	374.91 KHz	$2.15 \cdot 10^{-2}$	6.93 KHz
$10^5$	362.05 KHz	$5.51 \cdot 10^{-2}$	24.70 KHz

As far as resistive cooling is concerned, it can be shown that considerations similar to the single-particle case apply to the center-of-mass (CoM) motion, that should be damped at the abovementioned rates; however other internal motions (e.g. a ‘breathing’-like expansion and contraction of the cloud around the center) could be totally or almost invisible in the present coupling scheme and therefore much slower to damp. It has been suggested that natural or artificial imperfections could render them apparent (for instance, recombined ions would displace the CoM with respect to the center of charge) [9]. Cooling of a cloud of

$C^{5+}$  ions has been experimentally proved, but there is not a complete theoretical understanding of the phenomenon yet [12]. Again, investigation of these processes is of high interest and it is being considered within our PIC code. Since the potential is distorted by the space charge, the restoring force cannot be inserted as done above for one ion, but it should be fed back directly into the boundary conditions as a potential difference due to the drop on the external circuit. The implementation is under way.

## CONCLUSIONS

We have shown that a PIC code is a powerful tool for investigations of ion dynamics in a Penning trap. Further improvements of the code are under way as they are not only required within the HITRAP project, but of interest in the whole trap community for the development of new setups and understanding of experimental results.

## REFERENCES

- [1] F. Herfurth, K. Blaum, S. Eliseev, O. Kester, H.-J. Kluge, S. Koszudowski, C. Kozhuharov, G. Maero, D. Neidherr, W. Quint, S. Schwarz, S. Stahl, G. Vorobjev, “The HITRAP project at GSI: trapping and cooling of highly-charged ions in a Penning trap”, *Hyp. Int.* 173 (2006) 93.
- [2] H. Nersisyan, C. Toepffer and G. Zwicknagel, “Interactions between charged particles in a magnetic field”, Springer (2007) 151.
- [3] G. Zwicknagel, “Electron cooling of highly charged ions in Penning traps”, *AIP Conf. Proc.* 862 (2006) 281.
- [4] H. Poth, “Electron Cooling: Theory, Experiment, Application”, *Phys. Rep.* 196 (1990) 135.
- [5] F. Ames, G. Bollen, P. Delahaye, O. Forstner, G. Huber, O. Kester, K. Reisinger and P. Smith, “Cooling of radioactive ions with the Penning Trap REXTRAP”, *Nucl. Instr. Meth. Phys. Res. A* 538 (2005) 17.
- [6] D.W. Mitchell and R.D. Smith, “Two dimensional many particle simulation of trapped ions”, *Int. J. Mass Spectrom. Ion Proc.* 166/167 (1997) 271.
- [7] R.W. Hockney, “A fast direct solution of Poisson’s equation using Fourier analysis”, *J. Ass. Comp. Mach.* 12 (1965) 95.
- [8] Q. Spreiter and M. Walter, “Classical Molecular Dynamics simulation with the Velocity Verlet algorithm at strong external magnetic fields”, *J. Comp. Phys.* 152 (1999) 102.
- [9] D.F.A. Winters, M. Vogel, D.M. Segal and R.C. Thompson, “Electronic detection of charged particle effects in a Penning trap”, *J. Phys. B* 39 (2006) 3131.
- [10] H. G. Dehmelt, F. L. Walls, “Bolometric technique for the rf spectroscopy of stored ions”, *Phys. Rev. Lett.* 21 (1968) 127.
- [11] M.H. Holzscheiter, “Cooling of particles stored in electromagnetic traps”, *Phys. Scripta* 22 (1988) 73.
- [12] H. Häffner, T. Beier, S. Djekić, H. Hermanspahn, H.-J. Kluge, W. Quint, S. Stahl, J. Verdú, T. Valenzuela and G. Werth, “Double Penning trap technique for precise g factor determinations in highly charged ions”, *Eur. Phys. J. D* 22 (2003) 163.