

# Stopping Highly Charged Ions in a Laser-cooled Plasma

M. Bussmann, U. Schramm <sup>a</sup>, V.S. Kolhinen, J. Szerypo, M. Sewtz, P.G. Thirolf, and D. Habs

<sup>a</sup> Forschungszentrum Dresden-Rossendorf e. V., Bautzner Landstrasse 128, 01328 Dresden

Future high-precision Penning trap systems [1,2,3,4] for measuring nuclear masses will rely on in-trap experiments using highly charged ions (HCIs).

Neither the strength of the trapping magnetic field  $B$ , nor the measurement time  $t$  or the number  $N_{\text{counts}}$  of repeated measurements can be significantly changed using present experimental methods. Thus, increasing the charge state  $Q_{\text{HCI}}$  of the ion of interest seems the most promising step towards gaining in relative mass accuracy

$$\frac{\Delta m}{m} \propto \frac{m}{t} B N_{\text{counts}}^{1/2} \times \frac{1}{Q_{\text{HCI}}}. \quad (1)$$

In delivering highly charged ions to the precision trap systems, the momentum spread of beams of highly charged ions available for mass spectrometry must be matched to the momentum acceptance of the precision trap system.

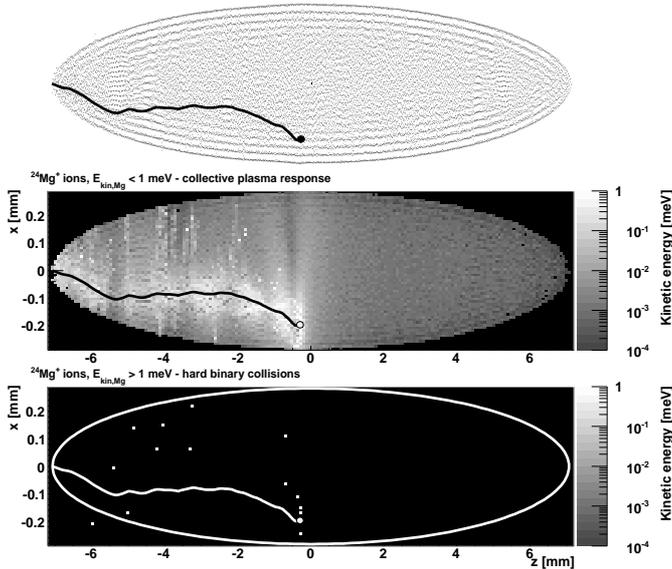


Fig. 1: Three different views of the HCI’s passage through a  $^{24}\text{Mg}^+$  plasma of density  $n_{\text{Mg}} = 4.23 \times 10^{13} \text{ m}^{-3}$ ,  $11.1 \mu\text{s}$  after placing the HCI near the plasma brim, setting its initial energy  $E_{\text{kin,HCI}} = 400 \text{ meV}$  and charge state  $Q_{\text{HCI}} = 40$ . The kinetic energy of the HCI has been completely deposited in the plasma. Upper part: Real space image of a vertical slice through the center of the plasma ellipsoid, marking the path of the HCI and its current position. Both lower parts: Intensity-coded distribution of the kinetic energies of the  $^{24}\text{Mg}^+$  ions, integrated in  $y$ -direction.

A reduction of the momentum spread requires a cooling scheme which

1. does not alter the high charge state of the ion of interest,
2. is efficient and minimizes ion loss,
3. for rare, unstable nuclei provides cooling times comparable to the nuclei’s lifetime and
4. for high-precision measurements allows for a final ion temperature of a few K or even mK.

In the following we present results on a realistic simulation of a new stopping scheme [5] using a laser-cooled, one-component plasma (OCP) of  $N = 10^5$   $^{24}\text{Mg}^+$  ions as a stopping medium.

The  $^{24}\text{Mg}^+$  ions are confined in a three-dimensional harmonic potential as found, for example, in Paul traps, to compensate the mutual Coulomb repulsion. If the mutual Coulomb energy overcomes the kinetic energy of the ions, the OCP becomes strongly coupled, its form resembling a prolate ellipsoid [6]. The plasma density  $n_{\text{Mg}}$  is then only determined by the strength of the harmonic confining potential.

In laser-cooled plasmas a transition from a liquid to a crystalline phase can be observed. In such a Coulomb crystal the ions are ordered at an equidistant spacing, each ion localized at a well defined position in the crystal lattice, which can be controlled by the confining fields and the laser force.

At the beginning of the simulation the HCI is placed near the brim of the plasma ellipsoid, see Fig. 1, upper part. During the simulation its passage through the ultra-cold plasma ( $T_{\text{Mg}} = 1 \text{ mK}$ ) and the complete dynamics of the stopping process are computed, taking into account the interaction of all particles involved. The plasma densities studied in the simulation are typical of trap parameters chosen for confining  $^{24}\text{Mg}^+$  ions in a Paul trap. This allows to obtain both realistic estimates on the stopping times and a detailed view of the plasma dynamics during the stopping process.

Analyzing the plasma dynamics [7] is necessary to determine whether the plasma stays stable during the passage of the HCI and to find matching conditions for fast recooling of the plasma after the HCI has deposited its energy in the plasma bulk.

The simulation results show that plasma stability is guaranteed throughout the stopping process, since a large amount of the HCI’s kinetic energy is deposited over the whole plasma bulk, see Fig. 1, middle part. Furthermore, only a minute number of  $^{24}\text{Mg}^+$  ions is lost in close binary collisions with the HCI, acquiring enough kinetic energy to leave the plasma bulk, see Fig. 1, lower part.

Both processes of energy deposition, either by collective plasma response or hard binary collisions, take away a comparable amount of the total kinetic energy deposited by the HCI, see right part of Fig. 2. If only energy loss due to collective plasma response is considered, already stopping times of a few ten  $\mu\text{s}$  are obtainable for the initial kinetic energies  $E_{\text{kin,HCI}}$  studied here, see Fig. 3. When the HCI is finally stopped in the plasma, it is sympathetically cooled by the laser-cooled  $^{24}\text{Mg}^+$  ions down to a few mK.

Two counter-propagating laser beams are sufficient to maintain the low plasma temperature. The duration of the recooling of the  $^{24}\text{Mg}^+$  ions using these laser beams can be estimated to be comparable to the stopping times found in the simulation.

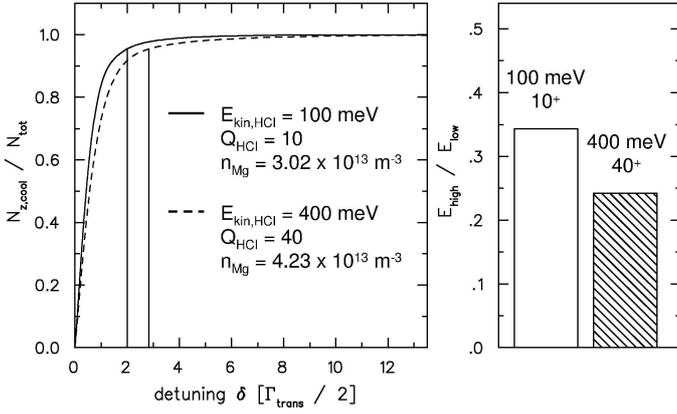


Fig. 2: Left: Number  $N_{z,\text{cool}}$  of ions within the acceptance of the laser force compared to the total number  $N_{\text{tot}} = 10^5$  of  $^{24}\text{Mg}^+$  ions, depending on the laser detuning  $\delta$ , which is given in units of the natural transition line width of  $\Gamma_{\text{trans}} = 2\pi \times 42.7$  MHz for the  $2S_{1/2} \rightarrow 2P_{1/2}$  transition in  $^{24}\text{Mg}^+$ . Vertical lines mark the value of  $\delta$  at which 95.4 % of all ions can be recooled. Right: Ratio of the total kinetic energy  $E_{\text{high}}$  of all ions with  $E_{\text{kin,HCI}} > 1$  meV to the total kinetic energy  $E_{\text{low}}$  of all ions with  $E_{\text{kin,HCI}} < 1$  meV. The hollow box corresponds to the same data set as the solid line in the left part, the hatched box to the dashed line.

This fast recooling is possible since it is not necessary to scan the laser frequency to address most of the momentum space of the ions, a process which works efficiently only on the time scale of several 100 ms up to several seconds. Instead a fixed detuning  $\delta$  of the laser frequency of only a few times the natural transition line width  $\Gamma_{\text{trans}} = 2\pi \times 42.7$  MHz is sufficient to recool almost all of the  $^{24}\text{Mg}^+$  ions, see left part of Fig. 2.

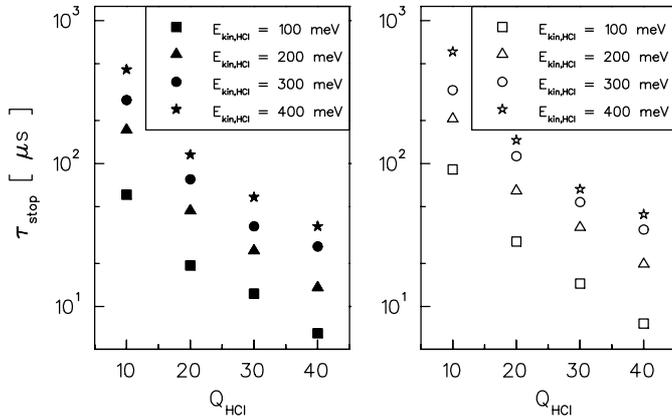


Fig. 3: Stopping time  $\tau_{\text{stop}}$  versus charge state  $Q_{\text{HCl}}$  for various initial energy  $E_{\text{kin,HCI}}$ , taking only into account the energy loss due to collective plasma response. Solid symbols refer to  $n_{\text{Mg}} = 4.23 \times 10^{13} \text{m}^{-3}$ , open symbols to  $n_{\text{Mg}} = 3.02 \times 10^{13} \text{m}^{-3}$ .

Finally, degeneration of the charge state of the HCl due

to ionization or charge exchange processes [8,9,10] is negligible and much weaker if compared to in-trap electron cooling schemes [11]. For example, the two-body charge exchange process  $^{24}\text{Mg}^{1+} + ^{100}\text{X}^{40+} \rightarrow ^{24}\text{Mg}^{2+} + ^{100}\text{X}^{39+}$ , can be estimated theoretically [12] to orders of magnitude longer than the stopping and recooling time, see Fig. 4.

We therefore conclude that it is possible to use a plasma of laser-cooled ions to efficiently stop highly charged ions for future high-precision trap experiments. The cooling scheme outlined here is robust, meaning that ion loss is minute and stable cooling conditions can be provided at low beam intensities.

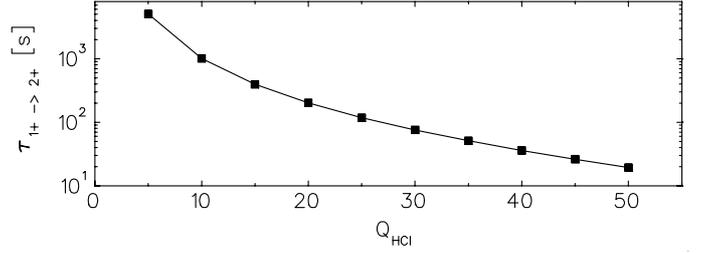


Fig. 4: Average duration  $\tau_{1+ \rightarrow 2+}$  of the two-body charge exchange process  $^{100}\text{X}^{Q+} + ^{24}\text{Mg}^{1+} \rightarrow ^{100}\text{X}^{(Q-1)+} + ^{24}\text{Mg}^{2+}$  for a HCl  $X$  with initial kinetic energy  $E_{\text{kin,HCI}} = 400$  eV in a plasma of density  $n_{\text{Mg}} = 4.23 \times 10^{13} \text{m}^{-3}$ . In this energy range theoretical values have been compared to experimental data, while for lower energies data still is sparse. We thus choose to increase the kinetic energy by a factor 1000 compared to the energy range discussed in this work. For lower initial energies,  $\tau_{1+ \rightarrow 2+}$  increases even further.

The theoretical studies presented here are ongoing and currently focus on developing a fast and efficient extraction scheme to transfer the HCl to the precision trap system. At the MLL, it is foreseen to build a suitable Paul trap system and a cooling laser system which will be used to cool highly charged ions for precision measurements in the MLL-Trap system. The development of this system will be accompanied by extensive plasma dynamics and cooling experiments at the Paul trap system PALLAS [6].

## References

- [1] J. Dilling *et al.*, Int. J. Mass Spectr. **251** (2006) 198
- [2] F. Herfurth *et al.*, Int. J. Mass Spectr. **251** (2006) 266
- [3] R. Ringle *et al.*, Int. J. Mass Spectr. **251** (2006) 300
- [4] D. Habs *et al.*, Eur. Phys. J. **A25** (2005) 57
- [5] M. Bussmann, U. Schramm, D. Habs, V.S. Kolhinen and J. Szerypo, Int. J. Mass Spectr. **251** (2006) 179
- [6] U. Schramm, D. Habs, Prog. Part. Nucl. Phys. **53** (2004) and references therein
- [7] M. Bussmann, U. Schramm and D. Habs, AIP Conf. Proceedings **862** (2006) 221
- [8] T.A. Carlson *et al.*, At. Data Nucl. Data Tables **v.2** (1970) 63
- [9] H. Cederquist *et al.*, Phys. Rev. **A51** (1995) 2191
- [10] B.R. Beck *et al.*, Phys. Rev. Lett. **77** (1996) 1735
- [11] G. Zwicknagel, AIP Conf. Proceedings **862** (2006) 281
- [12] R. E. Olson *et al.*, Phys. Rev. **A14** (1976) 579