Stopping Dynamics of Highly Charges Ions in a Strongly Coupled Plasma ◇

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Delivering ultra-cold ions for precision experiments requires total control of ion properties such as temperature, charge state or position. Previous work [1,2,3,4] has shown that such control can be achieved by using laser-cooled ^{24}Mg^{+} ions as a stopping medium for heavy, highly charged ions (HCI).

Here, we focus on the response of the strongly coupled one-component plasma of ^{24}Mg^{+} ions to the mutual Coulomb interaction with a single highly charged ion passing through the plasma.

The kinetic energy $\mathrm{E_{kin,HCI}}$ of the highly charged ion is reduced during its passage through the plasma via two processes, namely close binary collisions with laser-cooled ions and a collective, long-range interaction with the majority of all plasma ions. While the first process can be analyzed in terms of simple two-particle collisional dynamics, an analysis of the second process has not been conducted until recently.

Detailed simulations [1,2,5] of the stopping dynamics of a single, highly charged ion interacting with a harmonically confined, ultra-cold one-component plasma of ^{24}Mg^{+} ions reveal long-range oscillation patterns visible over the whole plasma bulk both in the direction of the ion motion and transverse to it, see Fig. 1.

This plasma response can be easily explained in terms of a simple fluid model [6] if the velocity of the highly charged ion is high compared to the velocity of the laser-cooled ions. A strongly coupled plasma [7], in which the mutual potential energy of the particles is larger than their total kinetic energy, reacts to a local disturbance similar to a perfect fluid: All particles oscillate at a fixed frequency, the plasma frequency ω_p [7].

This feature is well reproduced in the simulation, where the ion velocity changes periodically with ω_p, exhibiting a pure sinusoidal variation. When interacting with the plasma ions, the HCI pushes those ions above and below its path of flight to the side. The plasma ions are accelerated by the HCI, leaving their equilibrium position. This creates a local polarization of the plasma, which causes the plasma ions to oscillate around their equilibrium position. The phase of this oscillation is set by the arrival of the HCI, thus it is the same for all ions at a certain position z_0.

All ions within a range of $\lambda_\perp = \mathrm{v_{HCI}}/\omega_\mathrm{p}$ move in the same direction, while ions further away change the direction of their motion, relaxing to their equilibrium position. Thus, with decreasing ion velocity $\mathrm{v_{HCI}}$, the oscillation wavelength decreases, as seen in Fig. 1.

In case of the longitudinal oscillation pattern along the Z-axis, similar reasoning can be adopted. Those ions in front of the HCI are pushed forward by the repulsive Coulomb force in a range defined by the adiabatic screening length $\lambda_\mathrm{ad} = \mathrm{v_{HCI}}/\omega_\mathrm{p}$. This is indicated in Fig. 1, where the exponential decrease of the ion velocity in front of the HCI marked by the green line follows $\exp(-z/\lambda_\mathrm{ad})$.Thus, the wavelength of the longitudinal oscillation is given by $\lambda_\parallel = \lambda_\mathrm{ad} = \lambda_\perp$.

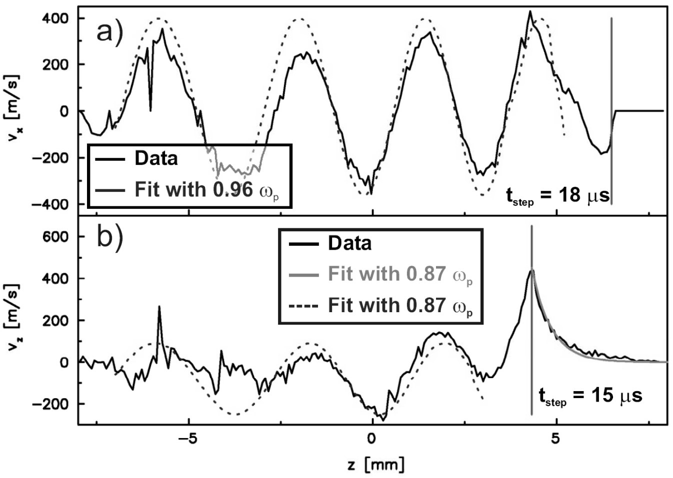

Fig. 1: Upper part: Oscillation of plasma ions perpendicular to the path of the HCI. The wavelength $\lambda_\perp$ of the oscillation is indicated by the blue curve. The velocity values are summed up for all ions above the path of the HCI. Lower Part: Velocity of plasma ions along Z. Besides the wavelength $\lambda_\parallel$ marked in blue, also adiabatic screening is indicated by the green curve. Experimental parameters: $\mathrm{Q_{HCI}} = 20$, $\mathrm{E_{kin,HCI}} = 400$ meV, $\mathrm{T_{Mg}} = 1$ mK, $\mathrm{n_{Mg}} = 3.02 \times 10^{13}\ \mathrm{m^{-3}}$, $\omega_\mathrm{p} = 2\pi \times 0.236$ MHz; $\mathrm{t_{step}}$ denotes the time of flight of the HCI

Concluding, we have shown that the collective oscillation of the ions caused by the repulsive Coulomb interaction of the plasma ions with the HCI can be understood using a simple fluid model approach. In this model, the plasma ions oscillate with the plasma frequency around their equilibrium position when disturbed by the field of the HCI. The phase of the oscillation is determined by the highly charged ions, leading to a coherent oscillation pattern evolving over the complete plasma bulk, following the path of the HCI.

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