Ion energy loss in plasma beyond the linear interaction regime

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The ion-stopping experiments U281 and U282, as continuations of U274, were performed at the Z6 area of GSI where the UNILAC and PHELIX facilities are available for combined experiments. In this way, two unexplored regimes of heavy ion-plasma interaction, both relevant for Inertial Confinement Fusion (ICF), have been investigated.

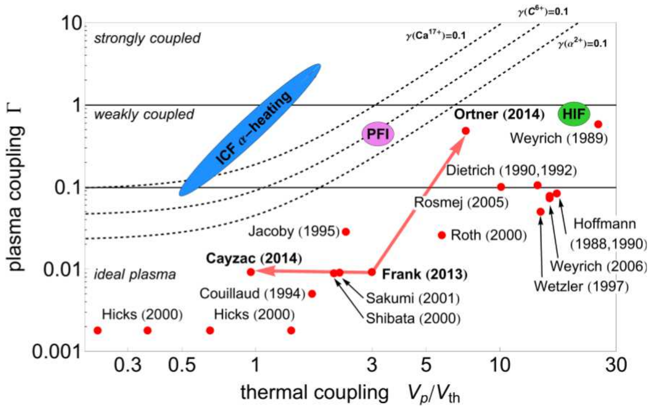

Figure 1: Overview of reported ion energy-loss experiments in plasma as a function of the velocity ratio $\frac{v_p}{v_{th}}$ and the plasma nonideality parameter Γ.

As illustrated in Fig.1, until now most experiments have been performed with projectile velocities much larger than the thermal velocity of the plasma electrons, i.e for $v_p \gg v_{th}$ and in ideal plasmas with the plasma coupling parameter $\Gamma \ll 1$. This so-called linear beam-plasma interaction regime is now well-understood and characterized.
Both described experiments deviate from that linear case. In the first experiment, in the wake of Ref.[1], measurements were performed at the stopping-power maximum in a hot and fully ionized plasma. It corresponds to low-velocity stopping with $v_p \approx v_{th}$. The plasma is ideal but the nonlinearity is important. There, the theoretical stopping-power predictions exhibit large discrepancies and no conclusive experimental data exist. A test of the theories would be highly relevant for alpha-particle stopping in ICF [2].
In the second experiment, following Ref.[3], the energy loss was measured at a higher projectile velocity $v_p \approx 10\, v_{th}$ but in a cold and partially ionized plasma, which is nonideal with $\Gamma \approx 0.5$. This case is highly relevant for heavy-ion fusion (HIF) and proton fast ignition (PFI) in ICF, where the stopping is also incompletely understood.
In the experiment at the stopping maximum, the energy loss of nitrogen ions was measured at a projectile energy of 0.5 MeV/u in a 150–200 eV hot and fully ionized carbon plasma generated with two high-energy laser beams. The experimental setup was optimized in comparison with Ref.[1] by the implementation of an improved random phase plate (RPP) and better-controlled plasma conditions. A preliminary analysis shows energy-loss data significantly below the theoretical predictions, which confirms the results of Ref.[1]. For the interpretation, a more precise calculation of the projectile charge state has been made possible by using cross-section data from non-equilibrium charge-distribution measurements of the beam after 2–40 μg/cm^2 thick carbon foils. Moreover, parametric studies of the plasma simulations pointed out the systematic calculation errors due to the necessary assumption that the plasma is in local thermodynamical equilibrium [2].
In the second experiment, the energy loss and the charge-state distribution of calcium ions at 3.6 MeV/u were measured in a weakly nonideal plasma induced by indirect laser heating [4]. For this purpose, intense laser light was converted in a sub-millimeter sized gold hohlraum into x-ray radiation which then volumetrically heated a carbon foil into a dense plasma state with a temperature of 5–15 eV and an ionization degree of 1.5–3. The data show an increase of the energy loss of 80% compared to the solid state, which is significantly higher than the theoretical predictions. In addition, the mean charge state shows no increase compared to solid carbon within the error bars, as expected from Monte-Carlo simulations [5].

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References

[1] W. Cayzac et al., GSI report (2013)
[2] W. Cayzac et al., in preparation
[3] A. Ortner et al., GSI report (2013)
[4] A. Ortner et al., Nucl. Instr. Meth. Phys. Res. B **343**, 123-131 (2015)
[5] A. Ortner et al., accepted for publication in Phys. Rev. E

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