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Simulations of the energy loss of ions at the stopping-power maximum in a laser-induced plasma

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Abstract. Simulations have been performed to study the energy loss of carbon ions in a hot, laser-generated plasma in the velocity region of the stopping-power maximum. In this parameter range, discrepancies of up to 30% exist between the various stopping theories and hardly any experimental data are available. The considered plasma, created by irradiating a thin carbon foil with two high-energy laser beams, is fully-ionized with a temperature of nearly 200 eV. To study the interaction at the maximum stopping power, Monte-Carlo calculations of the ion charge state in the plasma are carried out at a projectile energy of 0.5 MeV per nucleon. The predictions of various stopping-power theories are compared and experimental campaigns are planned for a first-time theory benchmarking in this low-velocity range.

1. Introduction

Ion stopping in plasmas is a central issue of high-energy-density physics and inertial confinement fusion. Here, not only is the precise description of the ion-plasma interaction important for all ion-based fusion concepts, as heavy-ion fusion or ion-driven fast ignition. Even more importantly, it is also essential for the understanding of alpha-particle heating in the burning DT fuel that determines the yield of a specific fusion reactor to a large extent.

When the velocity of the projectiles v_p is significantly higher than the thermal velocity of the plasma electrons v_{th} , the stopping power (energy deposited per unit length) of the ions in the plasma can be described by perturbative approaches based on a first Born approximation. Examples are the well-known Bethe formula, or the standard stopping model (SSM) for intermediate projectile velocities [1]. Until now most stopping experiments were carried out at $v_p \gg v_{th}$ and can be interpreted within the SSM frame.



Theoretical difficulties arise however for $v_p \approx v_{th}$, where the stopping power reaches its maximum. For such velocities, the ion-plasma interaction involves both strong collisions and collective plasma excitations, and the coupling between the projectile and the plasma is maximal. Here, large discrepancies appear between the various theories, reaching up to 30-50 % between perturbative predictions and data from nonperturbative approaches like the T-Matrix or the combined schemes [2, 3].

By now the scarce available experimental data [4] have not enabled to benchmark the theoretical predictions. In this work, simulations have been performed to study the energy loss at maximum stopping power, in a hot laser-induced plasma, as a preparation for an upcoming experimental benchmarking of the stopping theories.

2. Theoretical considerations

The considered setup enables to study the ion-plasma interaction in reproducible and well-controlled conditions, while simulation codes permit to access the plasma and projectile parameters at all times.

2.1. Plasma target

The plasma target is identical to the one employed at GSI in Darmstadt as described in Ref. [5]: a $100 \mu\text{g}/\text{cm}^2$ planar graphite foil is irradiated from both sides by laser beams at 532 nm wavelength, 30 J energy, 7 ns pulse length at FWHM and 1 mm focus spot diameter obtained by using random phase plates for spatial beam smoothing. In this way, a hot carbon plasma with an electron density $n_e \leq 10^{21} \text{ cm}^{-3}$ and an electron temperature $T_e \leq 200 \text{ eV}$ is generated. This plasma is (i) fully-ionized by the time the laser irradiation ends, (ii) precisely reproducible and quasi-uniform in the direction transversal to the ion axis owing to the used irradiation scheme and (iii) fully characterized via the combined data from hydrodynamic simulations obtained with the two-dimensional RALEF2D code [6] and from time-resolved multi-frame interferometry

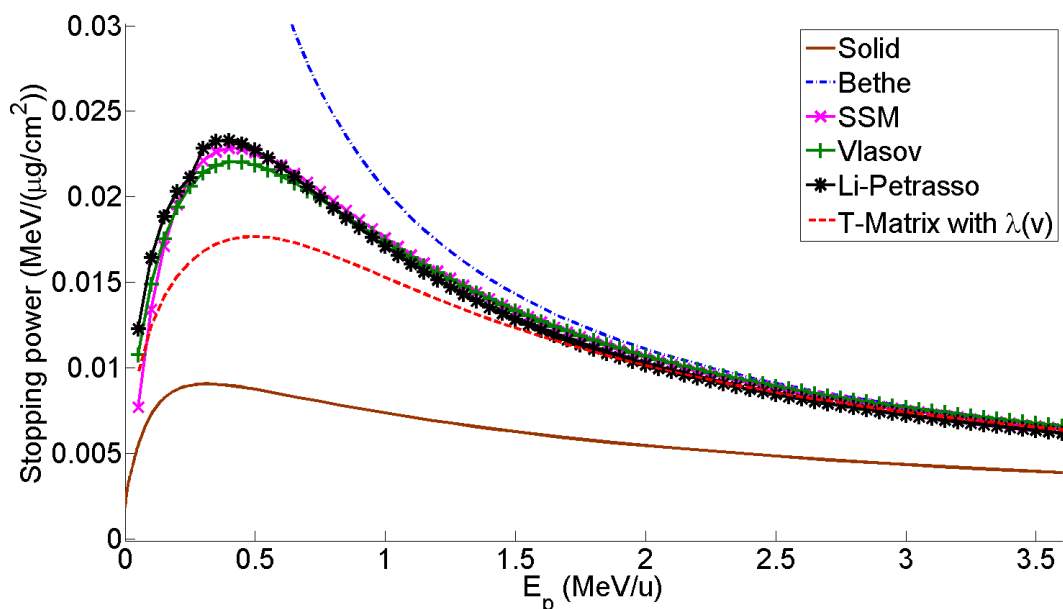


Figure 1. Comparison of the stopping power of C^{6+} ions in a fully ionized plasma with a density of $5 \times 10^{21} \text{ cm}^{-3}$ and a temperature of 150 eV as predicted by different theories as a function of the projectile energy. The stopping power in solid matter is shown for comparison.

measurements of the plasma electron density [7]. Therefore, this plasma target constitutes a well-suited test bed for precise ion energy-loss measurements and studies.

2.2. Projectile ions

In order to fix the charge-state of the projectiles in the plasma and, thus, to simplify the interpretation of the energy-loss results, carbon was chosen as projectile ion species as these ions are expected to be nearly fully stripped in a fully ionized carbon plasma. This was predicted by using a Monte Carlo code describing the charge transfer processes (ionization and recombination) of the projectile ions in the plasma [8] and showed that more than 90% of the beam ions are fully ionised in the hot plasma. The required projectile energy to access $v_p \approx v_{th}$ for $T_e = 200$ eV is 0.5 MeV/u. The Coulomb parameter of the interaction for C^{6+} ions at 0.5 MeV/u energy is $\eta = Z_p e^2 / \hbar v_r > 1$ with Z_p being the projectile charge and v_r the relative projectile-electron velocity. This value suggests that the perturbative approaches may be inadequate.

2.3. Stopping predictions

Stopping-power calculations are shown in Fig. 1 as a function of the projectile energy for several theories. The predictions of three perturbative theories, based on a first Born approximation, are shown: (i) the SSM, relying on a modified Bethe formula with the Bloch, Barkas and Chandrasekhar corrections [1], (ii) the dielectric theory obtained from the linearized Vlasov-Poisson equations [9], describing the stopping power resulting from large impact-parameter events in a collisionless plasma, and (iii) the Li-Petrasso stopping model, structurally similar to the SSM but including higher-order collisions [10]. Here, these perturbative approaches appear very consistent with each other. Their common high-velocity limit, the well-known Bethe formula, significantly overevaluates the stopping-power maximum. However, the nonperturbative T-Matrix approach [11], describing binary collisions with a simple model for dynamic screening, predicts a 30% smaller stopping power than the perturbation approaches.

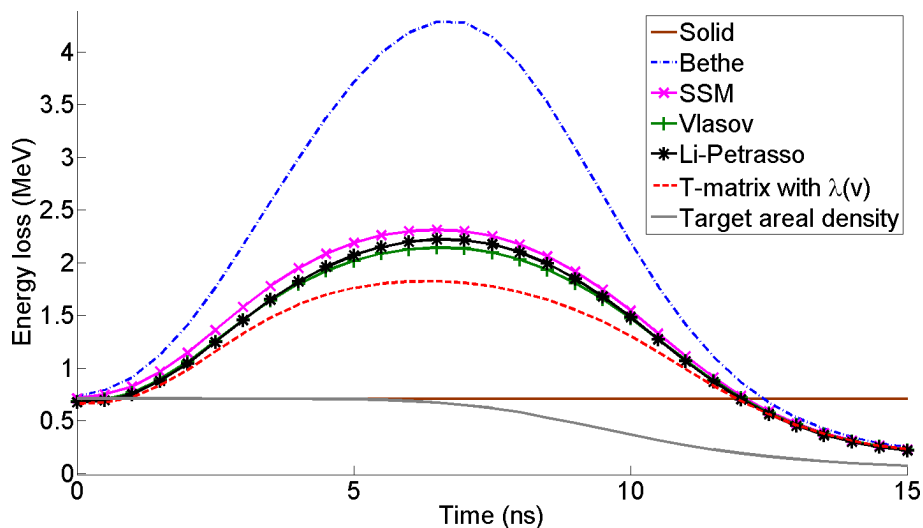


Figure 2. Comparison of the energy-loss predictions in the studied configuration. The time 0 marks the start of the target heating. The energy loss in solid matter is shown for comparison, as well as the target areal density, normalized to the latter, as indicator of the plasma expansion.

The resulting energy loss in the considered beam-plasma configuration was obtained by combining the simulated plasma parameters, taking both the longitudinal and transversal parameter gradient profiles into account, with the corresponding charge-state distributions

of the ion beam in plasma. It is shown in Fig. 2 over the first 15 nanoseconds of the interaction. Uncertainties on the simulated plasma parameters that arise from the comparison with interferometry data [5] lead to a 5% error on the calculated energy loss.

As expected, the energy loss increases in plasma due to the more efficient energy transfer to free electrons and the increase in the projectile charge state. A maximum is reached when the plasma becomes fully ionized at around 7 ns. Later, the energy loss decreases due to the starting three-dimensional plasma expansion, characterized by the decrease in the target areal density. Between 6 and 13 ns, where the temperature is highest, $v_p \approx v_{th}$ and discrepancies between the theories similar to those of Fig. 1 appear. In particular, the optimal energy resolution required in the experiment to benchmark the theories can be determined as 100 keV.

3. Planned experiment

The experiment is planned at GSI-Darmstadt, where two high-energy lasers can be used in combination with a high-frequency pulsed ion beam. To reach a projectile energy of 0.5 MeV/u, a beam of 3.6 MeV/u carbon ions is decelerated by passing through a 45 μm thick carbon foil as shown in Fig. 3. The ions are detected after a time-of-flight (TOF) distance of 0.5 m allowing an energy resolution of 60 keV with a Chemical Vapour Deposition (CVD)-diamond device as TOF-detector [12], which enables to distinguish between different stopping theories.

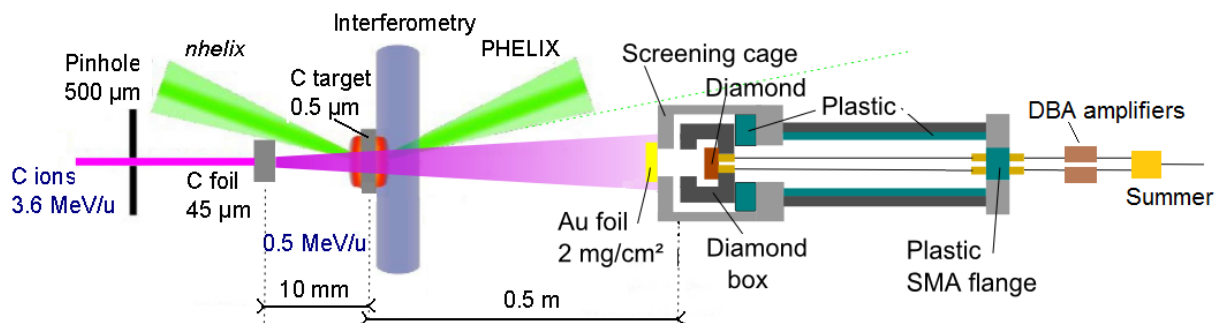


Figure 3. Schematics of the experimental setup.

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