Hot plasma's reduced stopping power compared with cold gas for proton projectiles

L. González-Gallego, M.D. Barriga-Carrasco, J. Vázquez-Moyano, J.M. Rojas-Artuñedo

E.T.S.I. Industrial, Universidad de Castilla-La Mancha, E-13071 Ciudad Real, Spain

Introduction

Interactions between ion beams and plasmas are researched in many fields [1, 2, 3]. When ions pass through plasmas, they loss energy that is transferred into the target. To estimate the energy, the concept of stopping power is introduced. If a well knowledge of the interaction between plasma and charged particles is achieved, it can be used in energetic applications, for instance inertial confinement fusion (ICF). Atomic units are used, $m_e = \hbar = e = 1$. m_e is the electron mass, e is the electron charge and $\hbar$ is the Dirac constant.

Theoretical method

The stopping power of a plasma is estimated by the contribution of free electrons and bound electrons (when is partially ionized) of the plasma [4, 5]. Then, its total stopping power is:

$$\frac{dE}{dx} = Sp_{\text{total}} = Sp_{\text{fe}} + Sp_{\text{be}} = \frac{4\pi}{v^2} Q^2 n_{at} \left(qL_{fe} + L_{be} \right), \tag{1}$$

where E is the projectile energy, x is its distance travelled, v is its velocity and Q is its charge. n_{at} is the plasma atomic density, q is the plasma mean ionization, L_{fe} is the free electron stopping number and L_{be} is the bound electron stopping number.

Free electron stopping number L_{fe} is calculated by means of the dielectric formalism, through RPA dielectric function ε_{RPA} [6, 7, 8], obtained in terms of the wave number k and frequency ω. The free electronic contribution of a plasma with free electron density $n_{fe} = q \cdot n_{at}$ is obtained as:

$$L_{fe}(v) = \frac{1}{2\pi^2 n_{fe}} \int_0^\infty \frac{dk}{k} \int_0^{kv} \omega d\omega \, \text{Im} \left[-\frac{1}{\varepsilon_{RPA}(k,\omega)} \right]. \tag{2}$$

Bound electron contribution is estimated as the sum of the bound stopping number L_{be} of each plasma species at ground state [5, 9], $L_{be} = \sum_s \left(L_{be,s} \cdot p_s \right)$, where p_s is the relative abundance of plasma ions. The bound stopping number for a s specie is $L_{be,s} = \sum_i \left(L_{be,s,i} \cdot N_{s,i} \right)$, where $L_{be,s,i}$ and $N_{s,i}$ are the stopping number and bound electron number, respectively, for the i shell of the ions species s in the plasma. The total bound electron density in the plasma, with

$N_s = \sum_i N_{s,i}$, is computed as $n_{be} = n_{at} \cdot \sum_s (N_s \cdot p_s)$. $L_{be,s,i}$ for s specie and i shell is get using an interpolation between high and low velocities [4, 7]:

$$L_{be,i}(v) = \begin{cases} L_{H,i}(v) = \ln\left(\frac{2v^2}{I_i}\right) - \frac{2K_i}{v^2} & \text{for } v > v_{int,i} \\ L_{B,i}(v_p) = \frac{\alpha_i v^3}{1+G_i v^2} & \text{for } v \leq v_{int,i} \end{cases} \tag{3}$$

where $I_i = [(2K_i)/(\langle r_i^2 \rangle)]^{0.5}$, defined from the energy of the discrete and continuum spectrum of the ion taking into account the the quadratic mean radius $\langle r_i^2 \rangle$, is the mean excitation energy [4, 10]; $\alpha_i = 1.067 K_i^{1/2}/I_i^2$ is the hydrogenic approximation friction coefficient at low velocities; K_i is the kinetic energy of the electron and $v_{int,i} = (3K_i + 1.5I_i)^{0.5}$ is an intermediate velocity that links the two projectile velocity cases. Lastly, G_i can be calculated when $L_{H,i}(v_{int,i}) = L_{B,i}(v_{int,i})$.

Discussion

An experiment about stopping power of hot plasmas from [11] is reproduced with our theoretical model and codes [4, 5, 12]. In this experiment reduced stopping power has been observed, which is a higher stopping power value of plasma than gas. There are two experiments: the first performed using ELFIE laser, from the Laboratoire pour l'Utilisation des Laser Intenses (LULI); the second one, using TITAN laser from Jupiter Laser Facility. Two plasmas were tested with proton beams: hydrogen and argon.

The first case studied is a **hydrogen plasma** and 4.1 a.u. protons. In Figure 1, the dependence of the Sp with temperature can be seen, decreasing with temperature. The plasma is fully ionized but room temperature. For the initial energy, for the highest temperatures, the cold gas curve has higher stopping power value than the plasma curves. This is the reduced stopping power we are searching for. If the initial proton energy is changed, the stopping power could be enhanced or reduced. The dependence on density is shown in Figure 2, where the mass stopping power decreases with density, and for all the densities studied, the stopping curves are under the

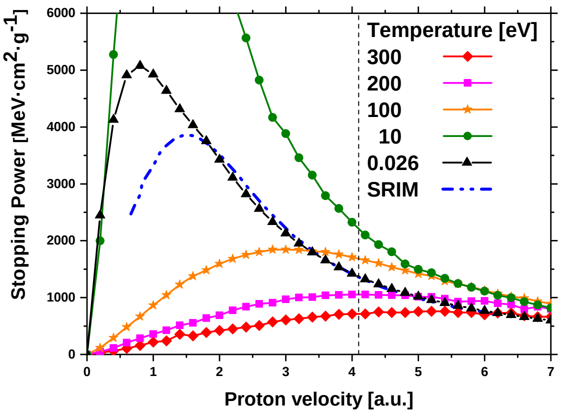

Figure 1: *Hydrogen stopping power at different temperatures. The hydrogen plasma, $\rho = 1$ mg/cm^3, is fully ionized ($q = 1$), except at room temperature ($q = 0$). SRIM data are also included. The input beam energy of the experiment is 4.1 a.u., vertical dashed line.*

cold gas curve for the experimental protons. In Figure 3 it is seen that a greater number of protons have lower energy after passing through cold gas than in hot plasma, as the higher values of the cold gas curve are at the left of the hot plasma curve (so protons have less energy). This suggests that the protons losses more energy in the gas that in the plasma, meaning there is reduced stopping power.

The **argon plasma** for the second case is partially ionized and the experimental proton energy is higher. It is seen in Figure 4 that for that energy, all the plasma stopping power curves are above the cold gas one, as usual, showing enhanced stopping power. However, if the energy were smaller, reduced stopping power could be observed. Our model was compared with Mehlhorn one [13], being equal for free stopping power (dielectric formalism) but different at bound one calculation (different method only valid for heavy ions). This last one fails for the low temperature curves using Mehlhourn model as the plasma is ionized, but for higher temperatures, as the ion is more ionized, the method agrees with our curves. Contrary to hydrogen case, for argon plasma in Figure 5 most protons are found at lower energies after passing through hot plasma than cold gas, so they have deposited more energy in the plasma than in cold gas, meaning that the stopping power of the plasma is enhanced.

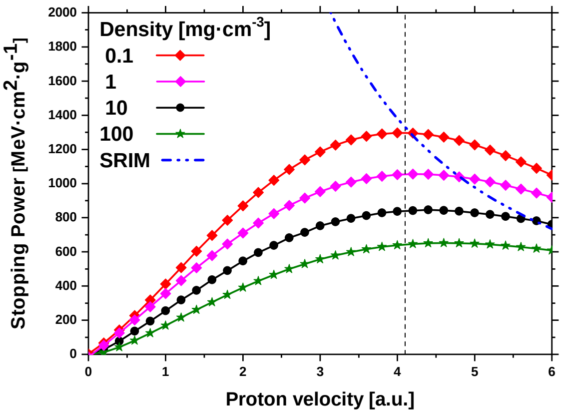

Figure 2: *Hydrogen stopping power for different densities at temperature $T = 200$ eV, $q = 1$. SRIM data are also included. The input beam energy of the experiment is 4.1 a.u.*

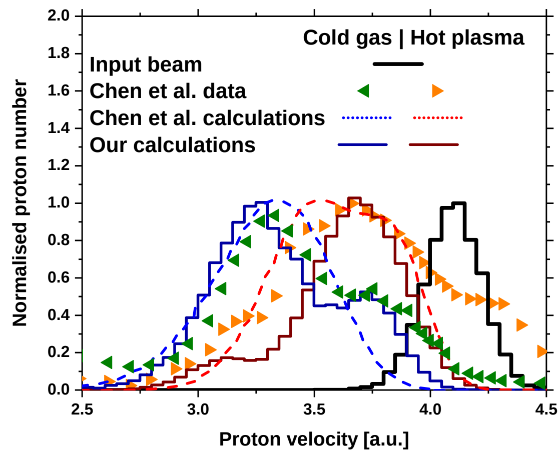

Figure 3: *ELFIE experiment data, experimentalists results and our results for a 4.1 a.u. proton beam traversing the hydrogen gas and plasma.*

Conclusions

The main reason for this study was finding theoretically the reduced stopping power found in experiments using our model. First, a theoretical analysis has been performed for several cases in hydrogen and argon, showing us the regions in which reduced stopping can happen. Then, we have compared our simulation codes with the experimental data, confirming our theoretical studies of stopping power and reduced stopping power range. We can conclude that the reduced stopping depends on lower projectile energies and smaller atomic number, and higher plasma temperatures and mass densities. Our model gives good results, so they can be used to confirm experimental data as the theoretical analysis predicted the experimental results.

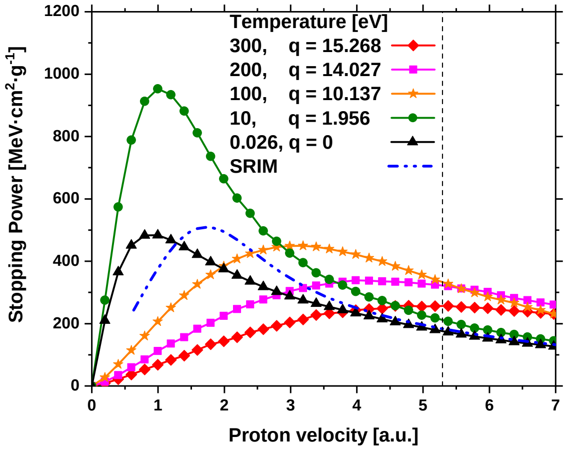

Figure 4: *Stopping power of argon at different temperatures. The argon hot plasma, $\rho = 10$ mg/cm^3, changes its ionization q. SRIM data for the cold gas and Mehlhorn model for the hot plasma are also included. The input proton beam energy is 5.3 a.u.*

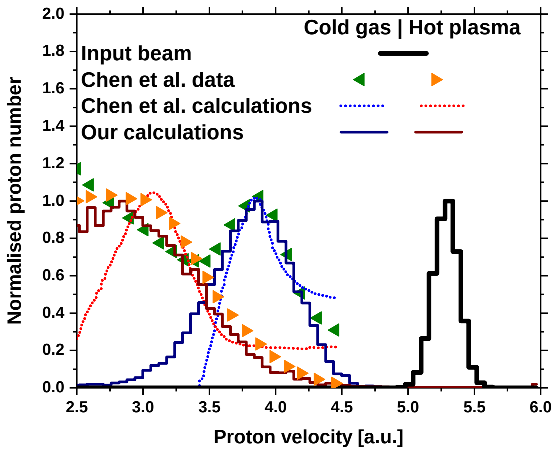

Figure 5: *Data from TITAN experiment, results from the experimentalists and our results for a 5.3 a.u. proton beam traversing the argon gas and plasma.*

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