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ENERGY LOSS OF PROTONS AND He^{2+} BEAMS IN PLASMAS

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ABSTRACT

In this work, the stopping power due to free and bound electrons in a plasma target is analyzed for two different kinds of projectile, protons and alpha particles. The stopping of free electrons is calculated using the dielectric formalism, well described in previous literature. In the case of bound electrons, Hartree-Fock methods and oscillator strength functions are used. The ionization degree of the plasma target is calculated using the Saha equation. Differences between the two methods of calculations for bound electrons are shown in noble gases. The influence of ionization is also estimated for argon plasma. Finally, we compare our calculations with two experiments. In the first one the stopping is calculated for protons in polyethylene plasma, and the second one the stopping is obtained for alpha particles in hydrogen plasma. In both cases, a good agreement with the experimental data is found.

Keywords: Nuclear fusion, plasma physics, stopping power, energy loss, ion beams.

1. Introduction

Nuclear fusion is a promising way to obtain endless energy using a clean resource, like deuterium, that it is obtained from water. However, there are many challenges in the requirements of this kind of energy source. The main ones are the high temperature and density needed in order to obtain the fusion of deuterium nuclei. In these conditions the matter in a state known as plasma, a fluid made of positive ions, electrons, neutral atoms and photons. Understand how to create and maintain this fusion plasma is nowadays an important field of research. In the case of inertial confinement fusion (Atzeni and Meyer-Ter-Vehn, 2009), plasma is created using energetic beams, like laser or ion beams (Snavely *et al.*, 2000), such as the proton the simplest ion and the alpha particle a completely stripped light ion.

Ion beams are used to create and to analyze inertial confinement fusion plasmas (Tabak *et al.*, 1994). For both cases, electronic stopping is the main process that causes energy deposition on the target, and also it could be used to measure temperature and plasma density (Bortfeld, 1997). This stopping is divided into two contributions: free electrons and bound electrons (Casas *et al.*, 2013).

In section Methods we will describe the theoretical calculations that estimated both stoppings. Afterwards, we will compare our calculations with experimental results in section Results and finally we will summarize all in section Conclusions.

2. Methods

The stopping of free electrons is analyzed using a dielectric function known as the Random Phase Approximation (RPA) which calculates the effect of the incident charged particle as a perturbation that loses energy on target proportionally to the square of its charge.

RPA dielectric function (DF) is developed in terms of the wave number k and of the frequency ω provided by a consistent quantum mechanical analysis. The RPA analysis yield the expression (Lindhard, 1954)

$$\varepsilon_{RPA}(k,\omega) = 1 + \frac{1}{\pi^2 k^2}\int d^3k' \frac{f(\vec{k}+\vec{k}') - f(\vec{k}')}{\omega + i\upsilon - (E_{\vec{k}+\vec{k}'} - E_{\vec{k}'})} \quad (1)$$

where $E_{\vec{k}} = k^2/2$. The temperature dependence is included through the Fermi-Dirac function

$$f(\vec{k}) = \frac{1}{1 + \exp[\beta(E_k - \mu)]} \quad (2)$$

being $\beta = 1/k_B T$ and μ the chemical potential of the plasma with electron density n_e and temperature T. In this part of the analysis we assume the absence of collisions so that the collision frequency tends to zero, $\upsilon \to 0$.

Analytic RPA DF for plasmas at any degeneracy can be obtained directly from Eq. (1) (Gouedard and Deutsch, 1978; Arista and Brandt, 1984).

$$\varepsilon_{RPA}(k,\omega) = 1 + \frac{1}{4z^3 \pi k_F}[g(u+z) - g(u-z)] \quad (3)$$

where *g*(*x*) corresponds to

$$g(x) = \int_0^\infty \frac{y\,dy}{\exp(Dy^2 - \beta\mu) + 1} \ln\left(\frac{x+y}{x-y}\right),$$

$u = \omega / k v_F$ and $z = k / 2k_F$ are the common dimensionless variables (Lindhard, 1954). $D=E_F\beta$ is the degeneracy parameter and $v_F = k_F = \sqrt{2E_F}$ is Fermi velocity in a.u.

Finally, electronic stopping of free plasma electrons will be calculated in the dielectric formalism as

$$Sp_f(v) = \frac{2Z^2}{\pi v^2}\int_0^\infty \frac{dk}{k}\int_0^{kv} d\omega\, \omega\, \mathrm{Im}\left[\frac{-1}{\varepsilon_{RPA}(k,\omega)}\right] \text{ (a.u.)},$$

where *Z* is the charge and *v* is the velocity of the projectile.

The electronic stopping due to bound electrons is determined using analytical formulas in the limit of low and high projectile velocities and, an interpolating expression is derived for intermediate velocities. For a plasma target with atomic density n_{at}, bound electron density for each populated atomic shell is $n_i = P_i n_{at}$, where P_i is the average electron population in the shell of a target atom (Barriga-Carrasco and Maynard, 2005). We can estimate electronic stopping for a proton beam in the form

$$S_p = \frac{4\pi n_{at}}{v^2} L_b \quad (4)$$

the stopping number L_b being defined as

$$L_b = \sum_i P_i L_i \quad (5)$$

where L_b is the stopping number for the whole bound electrons of atom or ion, and L_i is the stopping number for bound electrons of each shell.

We reckoned L_b by interpolating between the asymptotic formulas valid either for low or for high projectile velocities (Maynard and Deutsch, 1985)

$$L_b(v) = \begin{cases} L_H(v) = \ln\frac{2v^2}{I} - \frac{2K}{v^2} & \text{for } v > v_{int} \\ L_B(v) = \frac{\alpha v^3}{1+Gv^2} & \text{for } v \le v_{int} \end{cases} \quad (6)$$

$$v_{int} = \sqrt{3K + 1.5I} \quad (7)$$

where *G* is given by $L_H(v_{int}) = L_B(v_{int})$, K is the electron kinetic energy, I is the excitation mean energy and α is the friction coefficient for low velocities. Eq. (8), is used to determine the mean excitation energy of each shell (Garbet *et al.*, 1987)

$$I = \sqrt{2K / \langle r^2 \rangle} \quad (8)$$

where $\langle r^2 \rangle$ is the average of the square of the radius, for the electron in the *i* shell. Within the hydrogenic approximation, the friction coefficient of each shell is given by $\alpha = 1.067\sqrt{K}/I$ (Garbet *et al.*, 1987).

Using this approximation we can easily estimate I from the atomic parameters K and $\langle r^2 \rangle$ (Barriga-Carrasco and Casas, 2013). These late quantities are been determined by two methods: (1) Hartree-Fock calculations (Fischer, 1987) and (2) oscillator strength sums (Bell *et al.*, 1972).

We can see in Fig. (1) an estimation of the stopping for plasmas of noble gases with the same ionization using both methods, Hartree-Fock and oscillator strength. In this case the projectiles are protons.

In order to calculate the ionization degree, a very useful expression, known as Saha equation is used in this work.

$$\frac{N_{i+1}}{N_i} = \frac{(2\pi m_e kT)^{3/2}}{N_e h^3} \frac{2u_{i+1}}{u_i} e^{-\chi_{i+1}/kT} \quad (9)$$

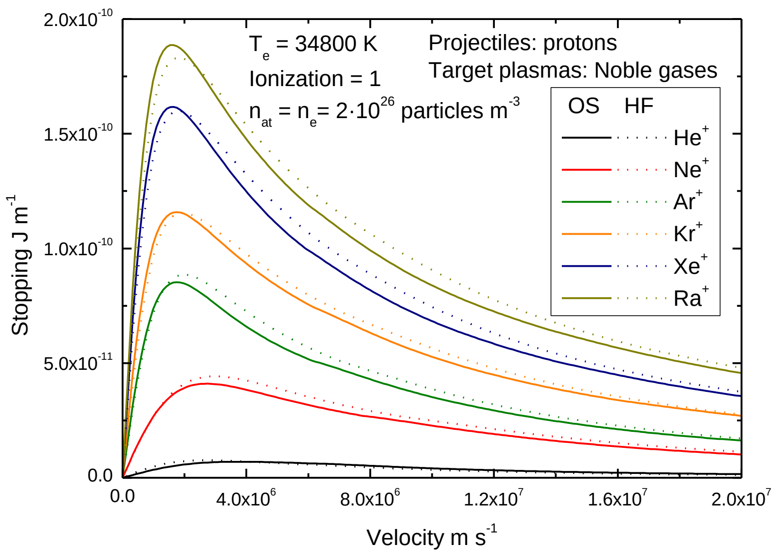

Figure 1. Stopping calculated using Hartree-Fock and oscillator strength methods for plasmas of noble gases as a function of proton beam velocity

3. Results

The CH_2 plasma was created from a polyethylene plastic, $[CH_2]_n$, using an electric discharge at GSI facility (Golubev *et al.*, 2001) Energy loss of proton beams with different velocities were measured after passing through a plasma column of 50 mm long. In this experiment the free electron density, n_{fe}, was measured, but not the ionic density or the ionization degree. We have calculated the ionization for hydrogen using the Saha equation. In the case of carbon, the authors estimated that there are five electrons bound to the nucleus in the plasma target. We represent our calculations and compare with the experimental result in Fig. (2).

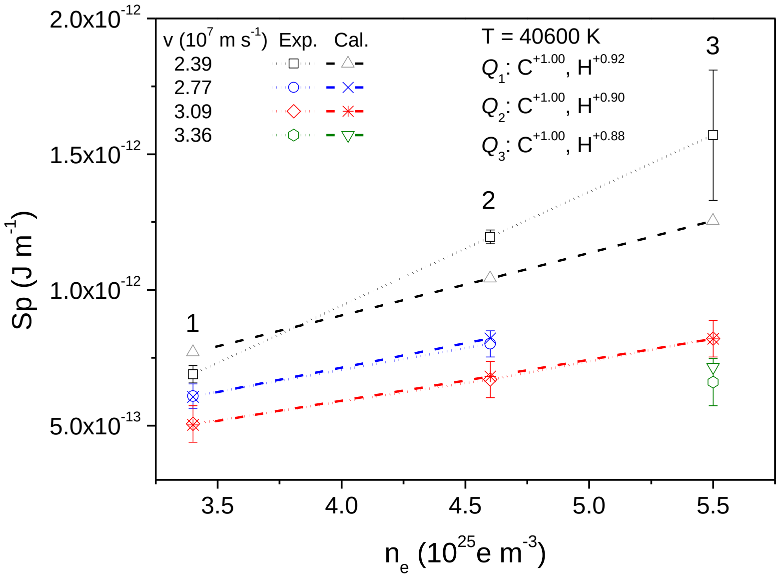

Figure 2. Stopping of proton beam with different velocities in CH_2 plasma

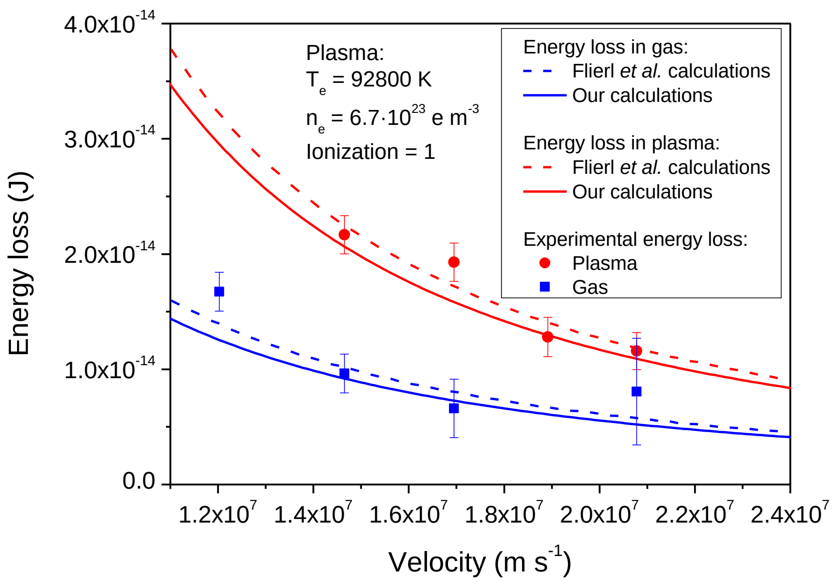

Figure 3. Stopping of alpha particles in hydrogen, plasma and cold gas.

The hydrogen plasma was obtained at the Physics Department of University of Erlangen (Flierl *et al.*, 1998). A discharge from z-pinch device created a fully ionized hydrogen plasma with a length of 20 cm. The projectile probes were alpha particles (He^{+2}) with energies between 4.5 and 9 MeV. We compare our calculations for two cases: cold gas with all electrons bound, and hot plasma with all electrons free, and we represent this comparison in Fig. (3).

Finally, to understand the influence of ionization degree in plasma stopping power, we have performed a simulation, where protons travel inside an argon plasma target. We can see this stopping in Fig (4).

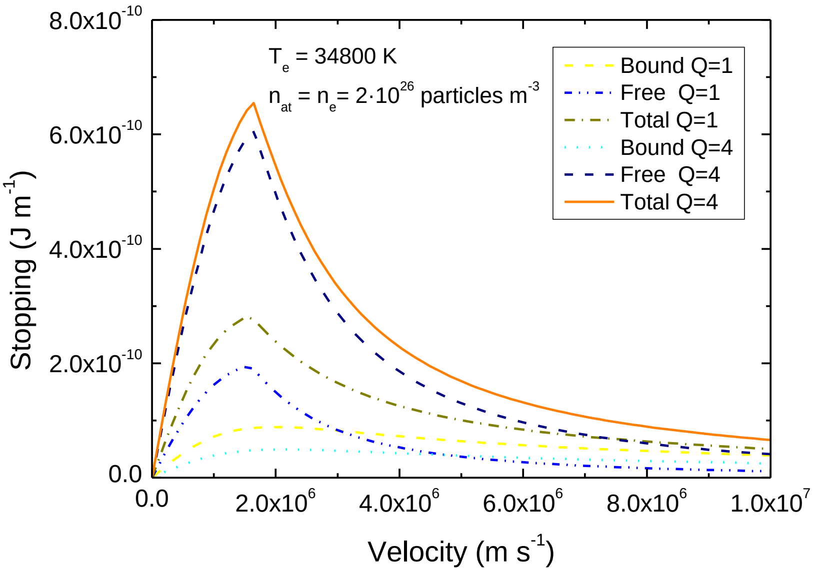

Figure 4. Stopping of proton beams in argon plasmas

4. Conclusions

Proton stopping was measured in CH_2 plasmas resulting that free electrons were responsible part of stopping power and the remaining part was due to bound electrons. Using the Saha equation, we calculated the mean ionization, and we have estimated total stopping. We have found that it increases when the electron density rises. Our calculated stopping was very close to experimental measures that showed the same dependence with electron density.

For hydrogen plasma we have calculated the stopping in the case of cold gas, where there are mainly bound electrons, and the case of fully ionized plasma, where the stopping is due to free electrons of plasma. Our calculated stopping showed a fair agreement with the experimental data, and their theoretical estimations.

We have estimated the stopping power of noble gases using both methods, Hartree-Fock and oscillator strength, and we have obtained similar results for the two methods. For this reason, we can choose the most simple, i.e. Hartree-Fock, in order to calculate other kinds of plasmas. We have calculated also the stopping power of argon plasmas with two different ionizations and we have found that for the highest ionization the stopping power is also the highest. It is known as enhanced plasma stopping and it is due to there are more free electrons in plasma target.

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