Slowing-down of proton beams in plasmas and gas-jet targets with non-uniform features

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1. Introduction

Laser-accelerated proton beams are used to analyse plasmas and gas-jet targets. These beams have a continuous of proton kinetic energies of a few MeV that allow tracing the temporal evolution of the target using the Thomson parabola technique [1]. The proton energy can be selected by means of magnetic fields and slits when the time of flight method is used to resolve the energy loss [2].

The estimation of the energy loss of a proton bunch that traverses a plasma target is made by means of electron stopping power, which is divided into two contributions: free electron stopping power and bound electron stopping power. The first one, due to plasma electrons, is calculated using a kind of Random Phase Approximation (RPA) dielectric function. The latter one, estimated for electrons bound to plasma ions, is calculated by means of an interpolation between low and high projectile velocities [3].

2. Calculation methods

The stopping power of a free electron gas can be calculated by means of RPA dielectric function using this expression:

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

However, this calculation could be computationally hard in some cases. An alternative way to obtain free electron stopping power using RPA calculations consists to interpolate from a complete database [4]. The stopping power depends mostly on temperature and density, for this reason a bilinear interpolation of these two variables is used in a 2D grid.

Bound electron stopping power is calculated by means of this expression:

$$Sp_b(v) = \frac{4\pi Z^2 n_{at}}{v^2} L_b(v), \tag{2}$$

where $L_b(v)$ is interpolated between a high and low projectile velocities:

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

$$v_{int} = \sqrt{3K + 1.5I} \tag{4}$$

and G is given by $L_H(v_{\text{int}}) = L_B(v_{\text{int}})$, K is the electron kinetic energy, I is the mean excitation energy and α is the friction coefficient for low velocities [5].

Mean excitation energy can be estimated using oscillator strengths method [2, 5] where the sum rules referred to energy momenta are defined as [6]:

$$S(\mu) = \sum_n f_{0n} E_{0n}^{\mu} + \int_{IP}^{\infty} \left(\frac{\mathrm{d}f}{\mathrm{d}E}\right) E^{\mu} \mathrm{d}E \tag{5}$$

Where $S(-1)$ is related to quadratic mean radius, and $S(1)$ is proportional to electron kinetic energy:

$$\begin{aligned} \langle r^2 \rangle &= \frac{3}{2} S(-1) \\ K &= \frac{3}{4} S(1) \end{aligned} \tag{6}$$

Then, the mean excitation energy, I, is obtained,

$$I = \sqrt{\frac{2K}{\langle r^2 \rangle}} = \sqrt{\frac{S(1)}{S(-1)}} \tag{7}$$

The quantities $S(1)$ and $S(-1)$ are calculated using the Flexible Atomic Code (FAC) and tabulated data [7-9].

The energy loss of a proton beam in a material, like plasma or gas-jet target, is a dynamic process. When it impacts with an initial energy, E_{p0}, it starts losing energy with a rate that is given by the free and bound electron stopping power estimated before. Using an iterative scheme, this energy loss could be calculated. The method is to divide the plasma length in segments and to evaluate the energy loss in the ith step by means of:

$$E_{L_i} = \frac{Sp_i}{\Delta x} \tag{8}$$

where Sp_i is the stopping power in the ith segment and Δx its length. The target is divided in many thin layers where temperature, density, and ionization are chosen constants. The layer thickness is calculated so that gradients of plasma features inside are small and, they can be supposed uniforms along the layer length.

3. Results

Using the previous equations, it is possible to evaluate the target density profile effects for different density distributions. For instance, a rectangular shape with a constant density and a piecewise approximation of a trapezium shape with a density profile given by [10]:

$$n_i(z) = \frac{2n_{i\,\max}}{1+\exp\left[\frac{2\varsigma\theta(\varsigma)}{l_r} - \frac{2\varsigma\theta(-\varsigma)}{l_{fr}}\right]} \tag{9}$$

Both cases conserve the particle quantity. The density profiles and energy losses are given in the two graphs of Figure 1.

Stopping power of helium gas-jet was also analysed [2]. The density of this jet was modelled using a Gaussian profile and a mean atomic density of $2.675\times10^{20}\ at/cm^3$ was obtained. At this density, our theoretical calculations, using the excitation energy calculated by means of Eqs. (5), (6), and (7) (see Table 1), are close to experimental data, see Figure 2.

I	2.292
S(1)	2.612
S(-1)	0.497

Table 1. Mean excitation energy and energy momenta obtained using oscillator strength method for atomic helium in atomic units.

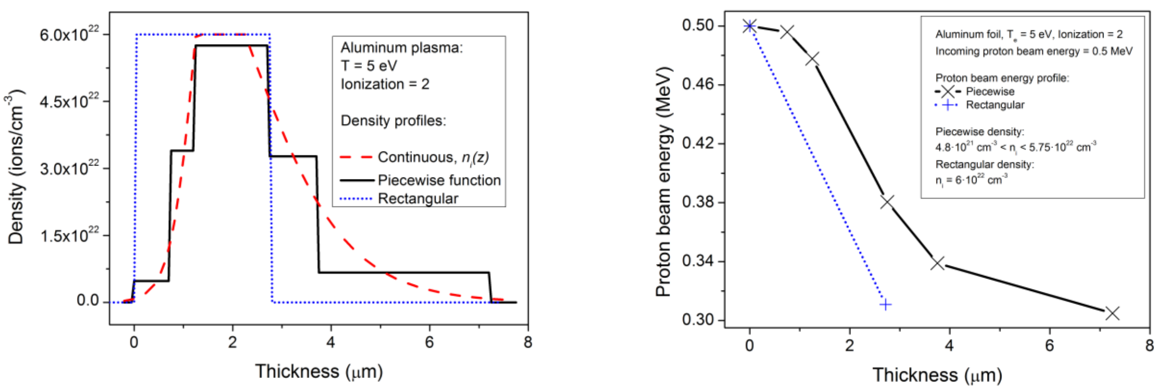

Fig. 1. The target density profiles (left) and its corresponding energy loss functions (right).

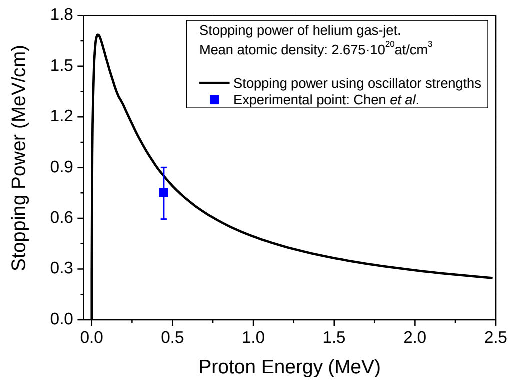

Fig. 2. Stopping power of a helium gas-jet as function of proton beam energy.

4. Conclusions

The combination of interpolation formulas with an iterative scheme for the stopping power calculation has been a useful tool to analyse the proton beam energy loss in laser-created plasma and gas-jet target. The influence of the target density profile in the shape of energy loss function has been shown. It supposes a slight difference in the final energy of the proton beam due to the quasi-linearity dependence on density in the stopping power expressions. The stopping power of helium gas-jet has been calculated from its average atomic density, obtained from its Gaussian profile, and its mean excitation energy, estimated by means of oscillator strength method. This theoretical estimation has been close to the experimental result.

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