Plasma target density profile effects on proton energy loss

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1. Introduction

Laser-accelerated proton beams are used to analyze laser irradiated thin foils. The low longitudinal emittance of the beam together with a continuous distribution of proton kinetic energies of a few MeV allow to trace the temporal evolution of strong electric and magnetic fields in plasma foils [1]. A diagram of this process is shown in Figure 1.

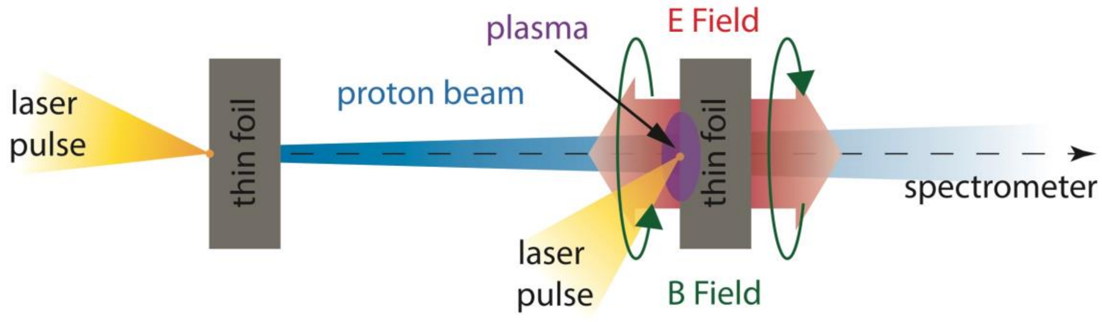

Fig. 1. Sketch of the experiment.

The temporal evolution of energy loss can be evaluated using the proton streak deflectometry, where the proton energy, which encodes the time, is resolved using a magnetic spectrometer.

2. Calculation methods

In the classical work of Peter and Meyer-ter-Vehn [2], an analytic approximation of stopping power of free electrons for arbitrary projectile velocities is introduced. Combining this expression with the stopping power of bound electrons by means of Bethe formula, analytical formulas for plasmas of any ionization are obtained [3]. In these, units are given in MeV for proton beam energy E_p, g/cc for density of the material, and eV for the temperature of the plasma. The general expression for stopping power is the following:

$$Sp\left(E_p\right) = K_U \frac{\rho}{A \cdot E_p}\left[q_i L_f + \left(Z - q_i\right) L_b\right] \tag{1}$$

where Z and A are the atomic and mass numbers of the material, q_i is the ionization, L_f and L_b are the free and bound electron terms, and K_U is a numerical factor to express the stopping power in the desired units. Volpe et al. use the numerical factor 1.23×10^{-9}. The expressions for the stopping power number; L_b for bound and L_f for free electrons and its related functions are shown in next equations:

$$L_b = \ln\left(2149\frac{E_p}{I}\right),\ \ I = 8Z\left(1+\frac{1.8}{\sqrt{Z}}\right) \tag{2}$$

$$L_f = G(x)\ln(\lambda_d k) + H(x)\ln(x), \tag{3}$$

$$G(x) = erf\left(\frac{x}{\sqrt{2}}\right) - \sqrt{\frac{2}{\pi}}x\exp\left(-x^2/2\right) \tag{4}$$

$$H(x) = \frac{x^3}{3\sqrt{2}\pi\ln(x)}\exp\left(-x^2/2\right) + \frac{x^4}{x^4+12} \tag{5}$$

$$x = 33\sqrt{\frac{E_p}{K_B T}}\ ; \qquad \lambda_d = 7.6\times10^{-12}\sqrt{\frac{AK_BTE_p}{q_i\rho_p}} \tag{6}$$

$$k = Min\left[7.46\times10^{11}\left(E_p + 1.8\times10^{-3}K_BT\right), 2.4\times10^{11}\sqrt{E_p}\right] \tag{7}$$

We must to remark that the density is a variable not only in Ec. (1) but also in Ec. (6) through the plasma density ρ_p. The consequence is that the density is an almost linear variable, but no strictly linear. Ec. (1) show some disadvantages: first, it calculates a negative stopping power when the proton energy is near to zero, due to logarithms. Second, it does not take into account the ionization of the plasma ion in the calculation of I: when the ionization increases I also rises and this implies that the stopping power decreases. Third, the stopping for free electrons is different that the calculate using others dielectric functions as the random phase approximation. To avoid these limitations, we modify the equations from (1) to (3) using next fits:

a) The stopping power function is fitted between the point (0, 0) and the maximum using a parabolic function:

$$parabola(x) = \left(\frac{-y_1}{x_1^2}\right)(x-x_1)^2 + y_1, \tag{8}$$

where x_1 and y_1 are the coordinates of the stopping power maximum.

b) A more realistic value of I for any ionization is obtained using a short approximation [4]:

$$I(Z,q) = \left(\frac{Z}{Z-q} \right)^2 I(Z-q,0) \tag{9}$$

c) The free electron stopping function is multiplied by a coefficient to obtain values close to the calculated using the random phase approximation, previously checked with experiments in a recent work [5]:

$$Sp_f \propto L_f \cdot Coef\,(T, n_e) \tag{10}$$

The comparison between the results using the original formula of Volpe et al. and the one modified by us is showed in Figure 2. The stopping power calculated by our method [5] is also plotted.

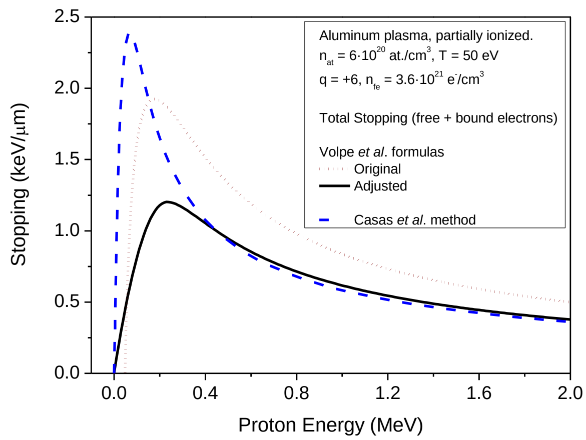

Fig. 2. Stopping as a function of proton energy.

The energy loss of a proton beam in a material, like plasma, is a dynamical process. When it impacts with an initial energy, E_{p0}, it starts losing energy with a rate that is given by the stopping power function. 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:

$$E_{L_i} = \frac{Sp_i}{\Delta x}, \tag{11}$$

where Sp_i is the stopping power in the ith segment and Δx its length.

3. Results

Using the equations from (1) to (11) it is possible to evaluate the target density profile effects for different density distributions: Rectangular shape with a constant density and the piecewise approximation of a trapezium shape with a density profile given by [6]:

$$n_i(z) = \frac{2n_{i\,\max}}{1+\exp\left[\frac{2\varsigma\theta(\varsigma)}{l_r} - \frac{2\varsigma\theta(-\varsigma)}{l_{fr}}\right]} \tag{12}$$

Both cases conserve the particle quantity. The density profiles and energy losses are given in the two graphs of Figure 3.

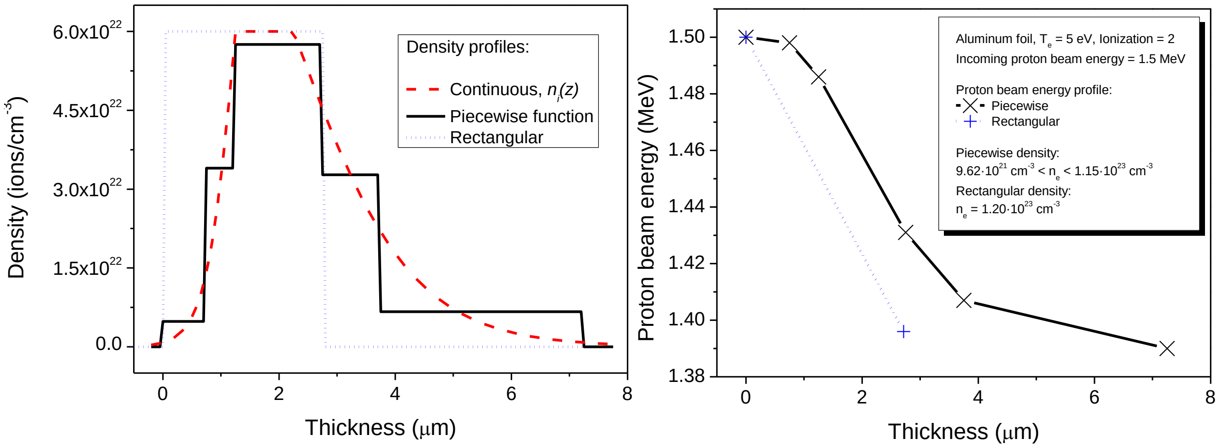

Fig. 3. The target density profiles (left) and its corresponding energy loss functions (right).

4. Conclusions

The combination of improved analytical formulas for the stopping power with an iterative scheme of energy loss calculation has been a useful tool to analyze the proton beam interactions with plasma. The influence of the target density profile in the shape of energy loss function has been showed and we have found a slight difference in the final energy of the proton beam due to the quasi-linearity of density in the stopping power expressions.

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