A simple model for propagation of fast electron in matter taking into account refluxing and electric stopping power: "preliminary results"

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1. Introduction

Generation of fast electrons, via laser-matter interaction, and their propagation in matter are an important problems related to the Fast Ignition (FI) approach to Inertial Confinement Fusion (ICF). The study of the main proprieties of the fast electron beam , such as penetration range and angular spread is essential for the success of scheme [1,2]. Fast electron transport in matter is described by two effects: collisional, described by stopping power and collective which depend by the self generated electric and magnetic fields. In 1997 Bell et al have shown how electric field effects may become dominant in fast electron propagation. They also derive a simple formula for the effective penetration of fast electrons in matter valid in the limiting case in which collision effects are negligible with respect to electric effects. In these conditions, the electron penetration range is proportional to the conductivity of the bulk. In this paper we derive a general formula for the electric stopping power which account both collision and electric field at the same time showing how this approach is mandatory for many cases in which both the effects are in competition.

2. A model for electron refluxing

A model accounting for refluxing must take into account the evolution of the main beam proprieties such as beam divergence and beam flux as a function of collisional and electromagnetic effects (see section 3). Moreover the model must depend on target geometry and laser beam proprieties. The model can be applied at different target configurations: i) simple target, ii) composed targets (made inserting a tracer layer in the propagation layer). Moreover there are different regimes as a function of the relation between the target thickness L_z and the electron penetration range R_z (for simplicity we neglect the photons re-absorption): i) $R_z<L_z$ electron beam is stopped before to arrive at the rear face of the atrget , ii) $R_z>L_z$ electron beam is reflected many times into the target refluxing regime. The fast electron beam is described by the following distribution:

$$(1)\quad \Sigma(E,r,z) = f(E)\,G(r,z)\,e^{-z/R_z}e^{-z/r_z}$$

where f(E) represent the energy spectrum, R_z and r_z are respectively the electrons and photons penetration range. G represent the traversal distribution and can be described by using a Gaussian shape [3]:

$$(2)\quad G(r,z) = \frac{1}{\sqrt{2\pi}\,\Gamma(z)}e^{-r^2/2\Gamma(z)^2};\quad \Gamma(z) = \Gamma_0\sqrt{1+(z/z_0)^2};\quad z_0 = r_0\tan^{-1}(\Delta\theta_0);\quad \Gamma_0 = 2r_0$$

Starting from these assumptions and by using our model [4] we can calculate some important physical quantities such us electron number and FWHM of the beam. These quantity are directly related to the properties of the collected photon distribution on the detector [4]. Fig.1 shows preliminary results concerning the the above mentioned quantity as a function of the refluxing number (i.e how the collected signal change varying the geometrical conditions)

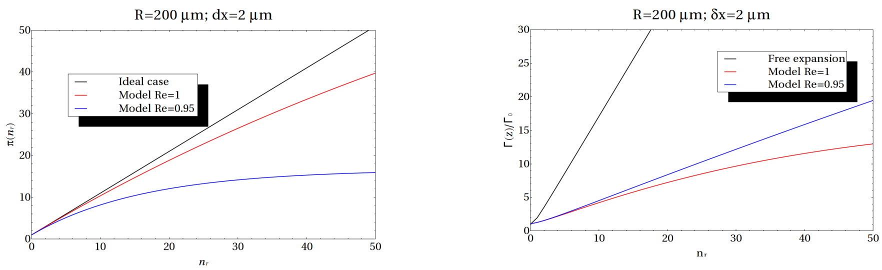

Fig.1) (left)The total photons number increase due to the refluxing mechanism, the enhancement of the signal is not linear as suggested by the ideal case (Black line). Electron beam lose energy and diverge during the propagation, both these effects reduce the final signal in comparison with ideal case. In fig are shown two cases: R_e=1 Red line and R_e=0.95 Blue line. (right) Free expansion (Black line) R<L_z the "real" electron beam size increase as factor G(z)/G_0 (G_0 =1). In fig are shown two cases: R_e=1 Red line and R_e=0.95 Blue line

3. Total electron stopping power

The total energy loss by electron traveling in matter can be written as the sum of two terms :

$$(3)\quad S(E) = \left[\frac{dE}{dz}\right]_{collisional} + \left[\frac{dE}{dz}\right]_{collective}$$

The Collisional stopping term is well known and can be written as follows [1,2]:

$$(4)\quad \left[\frac{dE}{dz}\right]_{collisional} = (Z-\bar{Z})\,\mathbf{B} + \bar{Z}(\mathbf{F}+\mathbf{W}) + (Z-\bar{Z})(Z-\bar{Z}-1)\,\mathbf{Br}$$

where **B** and **F** are respectively bound and free electrons term, **W** account for plasma wave and **Br** is the radiative term which becomes important for energies larger than 1 MeV. This formula can account for electron stopping power in cold matter (Z*=0 or Z*<<Z) , in plasma (Z*=Z) and in the intermediate plasma states. The collective term in eq. 3 is the Electrostatic Stopping Power (ESP) which come from the electric field generated by the separation charge inside the target, the return current represent the response of the medium to the the electric field and it is generated by the plasma free electron population which is present in the target. Bell. et al. [5], show how electric field effect may become dominant in fast electron propagation. They also derive a formula for for the effective penetration of fast electron in the limit in which collisional effects are negligible. We start from this work in calculating ESP. Let's assume a bunch of laser-driven hot electrons traveling into a finite size L target of material X. The electric field generated by the charge separation into the target has been calculated in ref [5] assuming that the hot-electron population is in thermal equilibrium and that the hot-current is completelyneutralized by the return current in such a way that $J_{hot} \sim j_{cold}$. Using continuity equation and with standard calculations Bell obtained the following expression for electric field, penetration range and resistive (collisional) stopping power.

$$(5)\quad \epsilon = 2\frac{T}{z+z_0};\quad z_0 = \frac{T_h^2 \sigma}{\eta I_{18}};\quad \left[\frac{dE}{dz}\right]_{collective} = e\epsilon = \frac{2T_h}{z+z_0} \rightarrow \left[\frac{dE}{dz}\right]_{collective} = \frac{2T_h}{z_0} e^{-E/2T_h}$$

where z is the electron beam direction, T_h is the fast electron temperature, s is the conductivity in unit of $(W\ m)^{-1}$ of the plasma, I_{18} is the laser intensity on target in unit of 10^{18} W/cm^2 and h represent the laser-electrons conversion efficiency. To describe target conductivity we have used semi classical model by Huller and Eidman [6].

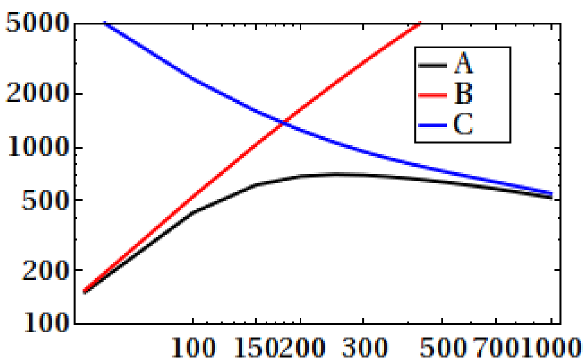

Fig2. Average electron penetration range calculated by using **TSP (A)** Compared with that calculated by using CSP (B) and ESP (C) as function of electron beam temperature T_h (KeV)).

The collective stopping power can be defined as the force acting on the electrons and produced by the the electric field ε where E is the electron beam kinetic energy and R is the electric stopping range. Finally we can estimate the total electron stopping range not only in the cases in which collisional or collective effects are dominant one with respect to the other (which can be described by the well know terms eq. 4 and eq.5) but also the regions between these two limits which is not still well understood.

3.Conclusions

We developed a simple model that gives a simple and clear description of the refluxing processes model prediction are in agreement with experimental evidences showing that in the refluxing regime the final yield on the detector is given mainly by the first few refluxing [ref 6] The model predicts that electron divergence cannot be inferred by direct measurement in the refluxing case because the final recorder beam size is the results of n_r contributions. However the model can be used to estimate the real beam divergence. Electron penetration range has been calculated considering both collisional and collective effects, this approach gives the possibility to calculate the electron range with more precision especially in the ragion of the target-plasma parameters in which collisional and collective effects are concomitant 10^{17} < I(W/cm2)<10^{19} The model predictions are in agreement with recent experimental results [7]

References

[1] A. Morace, D. Batani, NIMA 623(2010)797–800
J.A, Koch, et al., Review of Scientific Instruments 74 3 (2003)
Volpe, et al., Proceeding of 38th EPS conference Strasbourg 2011
[2] D. Batani Laser and Particle Beams ~2002, 20, 321–336
[3] Debayle et al., Physical Review E 82, 036405 2010
[4] L. Volpe et al., Submitted to physics of Plasmas
J. Myatt, et al., Physics of Plasmas 14, 056301 2007
[5] R.A. Bell et al., ppcf 39 (1997) 653–659]
[6] A. Benuzzi et al., Physics of Plasmas 5, 2827 (1998)
[7] J. J. Santos, et al, O4.209 in this conference