Transport and interaction of high current proton beams with dense plasmas.

Application to the fast-ignitor scenario

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Abstract
A theoretical modeling of the interaction of energetic light ion beams with dense plasma targets is presented. The initial energy distribution, the energy loss and the angular dispersion of the beams are taken into account. This modeling is applied to the fast ignition by proton beams of the inertial fusion target as proposed by Roth et al. [1]. We found that the dispersion in angle of the beam imposes severe restriction on the schemes for fast ignitor using proton beams generated by laser irradiation of thin solid targets.

Introduction
We assist in the world, and more particularly in Europe to a rapid increase of the number of sub-picosecond high intensity laser facilities. In the last years it has been demonstrated that these lasers can generate, with a good efficiency, short bunches of energetic (1-100 MeV) light ions with a small emittance [2]. Several applications related to inertial fusion of this new ion-sources are expected to emerge in the near future: Roth et al [1] have proposed to use a laser generated high energy proton bunch to ignite an inertial fusion target, also Borghesi et al [3] have proposed a new diagnostic of inertial fusion targets using these ions sources by proton imaging. Both applications require an accurate description of the beam propagation through complex dense plasma targets. At Orsay we are currently developing a theoretical modeling and numerical simulations devoted to this problem. In this work we present the main characteristics of this model and the results for the fast-ignitor scenario.

Theoretical model
We can distinguish two main interactions in the transport of projectiles through a material: the interaction with the electronic medium of the material and the interaction with the nuclei of the material. The same formalism that was developed for cold targets [4] is now applied to plasmas: we use a dielectric formalism to describe the interactions of the projectile with the electrons through the dielectric function $\epsilon(k, w)$. The energy loss function (ELF) is based on a linear combination of the energy loss function (ELF) obtained by Mermin [5] for the external electrons and a GOS hydrogenlike approach for internal electrons [6], which describes properly the optical properties and the energy loss spectra of real materials:

$$\text{Im} \left[ \frac{-1}{\epsilon(k, w)} \right] = \text{Im} \left[ \frac{-1}{\epsilon(k, w)} \right]_{\text{in}} + \text{Im} \left[ \frac{-1}{\epsilon(k, w)} \right]_{\text{out}},$$

where

$$\text{Im} \left[ \frac{-1}{\epsilon(k = 0, w)} \right]_{\text{out}} = \sum_{i} \alpha_{i} \text{Im} \left[ \frac{-1}{\epsilon(\omega_{i}, \gamma, k = 0, w)} \right] = \text{Im} \left[ \frac{-1}{\epsilon(k = 0, w)} \right]_{\text{exp}}$$
For plasmas where there is no experimental result, \( \varepsilon(k=0,w) \) is derived from sophisticated theoretical models discussed in [7].

The stopping power of the material for a light ion with charge \( Z \) at a high velocity \( v \) is determined within the linear response theory:

\[
S_p = \frac{2Z^2}{\pi v^2} \int_0^\infty \frac{dk}{k} \int_0^{k\nu} dw \ w \ \text{Im} \left[ \frac{-1}{\varepsilon(k, w)} \right],
\]

where \( k \) and \( \omega \) are the module of the momentum \( k \) and the energy transferred to the electronic excitations of the target, respectively. As the electronic stopping is a statistical process, it is also convenient to define the "straggling", which is the variance of the energy loss for unit path length:

\[
\Omega^2 = \frac{2Z^2}{\pi v^2} \int_0^\infty \frac{dk}{k} \int_0^{k\nu} dw \ w^2 \ \text{Im} \left[ \frac{-1}{\varepsilon(k, w)} \right].
\]

The nuclear interactions are due to the elastic collisions between the projectile and the nuclei of the target atoms that form the stopping material, and they cause a change of the projectile direction and a small energy loss, which in our energy range (15 MeV) can be neglected. For these interactions we use the classical dispersion theory.

In the center of mass frame, the angle \( \theta \) with which a projectile with an energy \( E \) a mass \( M \) is scattered from a nucleus of mass \( M_n \), is given by [8]:

\[
\theta = \pi - 2s \int_{R_{\text{min}}}^\infty \frac{dr}{r^3} \sqrt{1 - \frac{V(r)}{E_r} - \frac{s^2}{r^2}},
\]

where \( E_r = 4MM_nE/(M+M_n)^2 \) is the maximum transferable energy, \( s \) is the impact parameter, and \( R_{\text{min}} \) is the distance of minimum approach. The interaction energy \( V(r) \) comes from a Thomas-Fermi Coulomb screened potential:

\[
V(r) = \frac{ZZ_n}{r} \Phi \left( \frac{r}{a} \right),
\]

For cold targets \( a \) is the universal screening length [9]:

\[
a = 0.8854/(Z^{0.23} + Z_n^{0.23}),
\]

while for plasmas \( a \) is temperature dependent. For a fully ionized matter it is given by the dynamical adiabatic screening length:

\[
a = \left( \sqrt{\nu_{th}^2 + \nu^2} \right) / w_p,
\]

where \( \nu_{th} \) and \( w_p \) are the plasma thermal velocity and plasma frequency, respectively.

Stopping and angular dispersion due to multiple scattering small angles are treated as continuum processes, while rare events corresponding to large scattering angles are considered as stochastic processes. Both processes have been introduced in a Monte Carlo simulation code that describes the propagation of a bunch of ions starting with a realistic energy and angular distribution. We consider only dense targets in which screening length is much lower than the average distance between the beam ions so collective electrostatic effects are not included.
Application to the fast-ignitor scenario

Several experiments have been carried out to generate high current beams by lasers [2]. It is thought that in a near future these beams can deposite enough energy to ignite an intertial target. In the standard fast-ignitor scenario an electron beam is generated by an intense laser to create the hot spot. However for electrons beams, plasma instabilities can prevent the transport of energy to the central part of the target.

On the other hand proton beams are much less sensitive to instabilities that can be generated by laser sources with a good emittance. The main technical problem is that the source has to be protected from plasma expansion during inertial drive target main irradiation [1]. So the source has to be put outside the gold capsule which thickness has to be large enough to resist to the strong laser heating of \( \approx 200 \) eV during at least 10 ns. The current accepted value for the minimum gold thickness is around 30 µm. The distance from the capsule walls to the compressed fuel is about 3 mm and filled with the holhraum plasma.

In [1] and in other works [10] the fast-ignitor scenario with protons was investigated without considering angular dispersion of the beam due to the capsule gold walls. Our numerical code (MBC-ITFIP) was used to estimate the influence of angular diffusion in the energy deposition spread in the compressed fuel.

Hohlraum plasma and compressed fuel are supposed to be deuterium, at temperatures 1 keV and 0.1 keV, and with densities \( 10^{17} \) and \( 10^{26} \) cm\(^{-3} \), respectively. The radius of the compressed fuel core is 16 µm. Fig. 1 presents a schematic picture of the experimental device.

First we consider a monoenergetic proton beam of 15 MeV for which there is a maximum energy deposition in the compressed fuel. Fig. 2a represents the proton radial distribution arriving to the core. The energy deposition in the compressed fuel is represented in Fig. 2b. We see that the mean beam radius arriving to the core is much greater than the core radius, so deposited energy is mostly outside the compressed fuel. Lines are drawn to show the core size. Maximum of the distribution is around 110 µm. Less than 1% of the energy of the beam is used to heat the fuel.

**Fig. 1.** Schema of the fast-ignitor scenario.

**Fig. 2.** Proton radial distribution arriving to the core and proton energy deposition in the core.
For a realistic laser source, the initial beam is not monoenergetic, it has an initial energy distribution. This energy distribution is expected to increase even more the beam radial distribution at the core. We have analyzed the influence of the initial spread in energy of the beam to the transverse diffusion using the distribution observed in the experiments [11], which is reported in Fig. 3a. From this figure we observe that the proton radial distribution width at the core is nearly twice than for a monoenergetic beam due to the fact that scattering cross section is larger at low energy. Finally Fig. 3b shows the energy deposition in the core in the longitudinal and perpendicular direction to the initial beam movement. Now, even less energy than before is deposited in the core.

The main conclusion of this work is that realistic applications of energetic proton beams generated by high flux laser irradiation cannot be investigated without taking into account the angular dispersion induced by the interaction with a target. In more conventional accelerator the emittance of the beam is in the range of mm.mrad so that angular diffusion is generally not an important process. However in our case, the source is very small and the emittance several order of magnitude smaller, so that lateral straggling can modify the density of energy deposited in a target.

Concerning the fast ignitor scenario, we confirm the work of [10] in which it was already shown that due to the dispersion in energy, the proton source has to be put more closer to the fuel target. Here we show that this is also the case even with a monoenergetic beam.

References