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Stopping and scattering of relativistic electrons in high density plasmas for fast ignition studies

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Introduction

In the original and most actively investigated scheme [1], fast ignition (FI) is triggered by laser-accelerated relativistic electrons. The ignition requirements (e.g. beam energy, power, intensity) depend on parameters of the compressed fuel and on the transport properties and energy deposition of the fast electron beam [2, 3]. Despite the considerable effort in FI research, perfomance and ignition studies based on hydrodynamic simulations often relied on simplified treatments of electron energy deposition. Even the commonly employed scaling laws for the required beam parameters [2] were obtained by assuming electrons with assigned range, constant stopping power, and straight path.

Recently, we have included in the hydrocode DUED [4] a 3D Monte Carlo scheme for fast electron transport in a dense plasma (see, e.g., Fig. 1). We used this new model to study fast ignition [5, 6] of the targets proposed for the HiPER facility [7]. Here, we outline the above electron transport model, study electron range and energy deposition, and use the model to obtain ignition requirements as a function of electron energy.

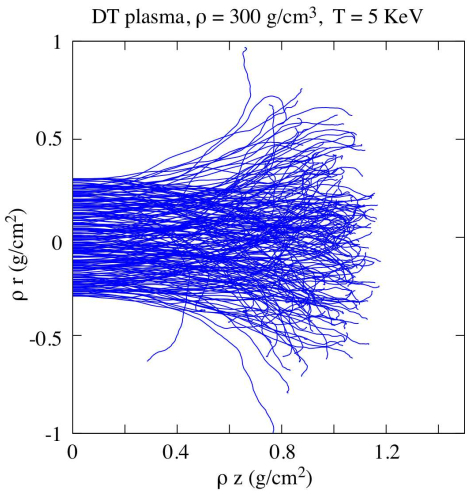

Figure 1: Trajectories of a beam of 1.5 MeV electrons incident on a plasma slab

Stopping power and scattering

In a plasma at high density, electrons are essentially stopped by plasma electrons, and are scattered by both electrons and ions. Self-generated e.m. fields are instead expected to play a minor role, and we neglect them. Our stopping calculation follows that of Ref. [8], and assumes a Moller cross section for e-e collision and also includes collective effects. The scattering calculation employs an expression for the cross-section for e-i collisions in an exponentially shielded potential in the second Born approximation [9], and the Moller cross section (with inclusion of

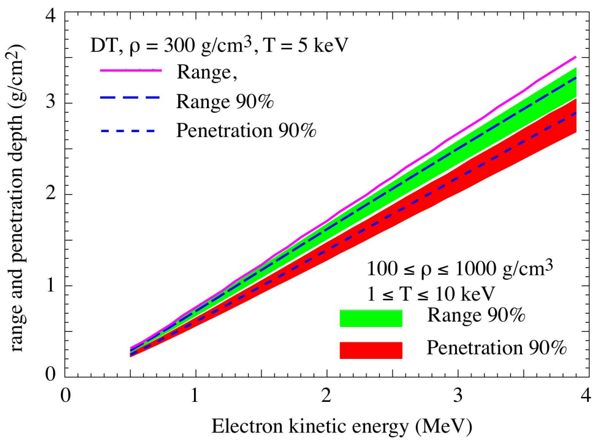

Figure 2: From 3D Monte Carlo simulations: electron range and penetration depth vs initial electron energy.

screening) for e-e collisions. Details will be given in a forthcoming paper. The stopping power for an electron with kinetic energy $\mathscr{E} = (\gamma - 1) m_e c^2$ in a fully ionized plasma, with mass density ρ, atomic number Z and mass number A, is then given by

$$\frac{d\mathscr{E}}{\rho ds} = -\frac{4\pi e^4}{m_p m_e c^2} \frac{Z/A}{\beta^2} \left[\ln \frac{m_e c^2}{\hbar \omega_{pe}} + f(\gamma) \right], \tag{1}$$

where we use Gaussian units, and

$$f(\gamma) = \ln(\beta \sqrt{\gamma - 1}) + \left(\frac{9}{16} - \frac{1}{2} \ln 2 \right) - \frac{(1/8) + \ln 2}{\gamma} + \frac{(1/16) + (1/2) \ln 2}{\gamma^2}, \tag{2}$$

with the usual meaning of m_e, m_p, e, c, $\hbar$, and of $\beta = (1 - \gamma^{-2})^{1/2}$, and with ω_{pe} the electron plasma frequency. (The above result is identical to the one recently presented in Ref. [10], that improves a previous similar treatment [11].) The average square deflection for unit time is

$$\frac{d <\theta^2>}{\rho ds} = \frac{8\pi e^4}{m_p (m_e c^2)^2} \frac{Z/A}{\beta^2 (\gamma^2 - 1)} \left\{ Z \left(ln\Lambda_i - \frac{1 + \beta^2}{2} \right) + \ln \Lambda_e - \frac{\ln[2(\gamma + 3)] + 1}{2} \right\}, \tag{3}$$

with $\ln \Lambda_i$ and $\ln \Lambda_e$ the Coulomb logarithms for collisions between fast electrons and ions, and fast electrons and thermal electrons, respectively. In the quantum limit, applying to hot fusion plasmas, and using the appropriate frame transformations, $\Lambda_i = 2\lambda_D m_e c (\gamma^2 - 1)^{1/2} / \hbar$, and $\Lambda_e = 2\lambda_D m_e c [(\gamma - 1)/(\gamma + 1)]^{1/2} / \hbar$, where λ_D is the Debye length in the laboratory frame.

Electron range and penetration depth

The dependence of the electron range on initial electron energy and plasma parameters has been studied by Monte Carlo simulations. Some results are summarized in Fig. 2, showing the range (i.e. the total electron path), and the penetration depth (path projected along the initial beam direction). The labels *range 90%* and *penetration 90%* refer to the path up to the point where the beam deposits 90% of the initial energy. It turns out that the (undeflected) range of an electron with initial kinetic energy $\mathscr{E}_0$ in a DT mixture is well approximated by [7, 5]

$$\mathscr{R} = \frac{1.52}{1 - 0.0478 \ln \rho} \cdot \frac{\mathscr{E}_0^2}{1.96\mathscr{E}_0 + 1} \ \mathrm{g/cm^2}, \tag{4}$$

with $\mathscr{E}_0$ in MeV, and the fuel density ρ in units of g/cm^3. [Equation (4) is obtained from Eq. (1), by neglecting the velocity dependence of $f(\gamma)$, and setting $f(\gamma) = 0.22$ and is accurate within 10% for electron energies in the interval 1 MeV $\leq \mathscr{E}_0 \leq$ 10 MeV, and for densities up to 1000 g/cm^3]. *Penetration 90%* is about 20% smaller than the (undeflected) range.

Next, we consider energy deposition. Figure 3 compares the specific power deposition of a parallel beam of 1.5 MeV electrons and of a parallel beam of electrons with exponential energy deposition with average particle energy of 1.5 MeV. The figure shows that in the latter case deposition occurs over a much wider region. In both cases, the effect of scattering is apparent.

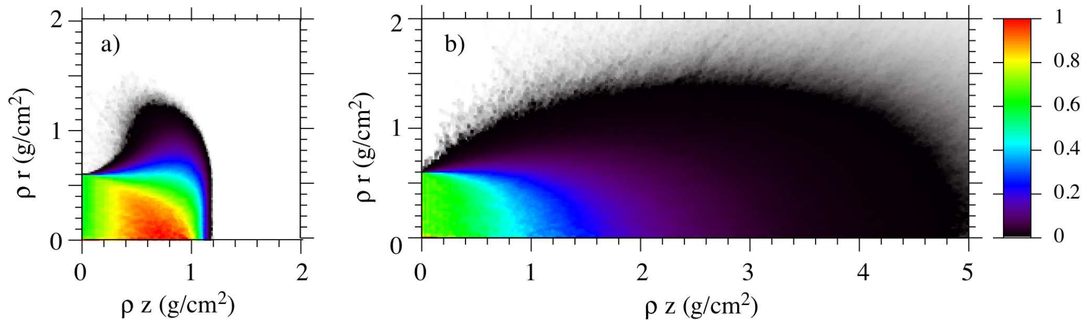

Figure 3: Specific power deposited by a) a beam of 1.5 MeV electrons and b) a beam with exponential energy distribution (with average energy of 1.5 MeV). In both cases a parallel beam impinges from the left h.s. on a DT plasma slab, with $\rho = 300\ \mathrm{g/cm^3}$ and $T = 5$ keV.

Ignition of a uniform plasma by a collimated e-beam

We have used the DUED code, with the new electron Monte Carlo routine to study ignition of a uniform sphere of DT, precompressed to density $\rho = 300\ \mathrm{g/cm^3}$. We consider parallel, cylindrical electron beams with uniform intensity profile, constant power, radius of 20 μm and pulse duration of 20 ps. [These are standard values for fast ignition; according to previous studies [2, 3] ignition is achieved by depositing $E_{\mathrm{ig}} = E_{\mathrm{opt}} = 18$ kJ, if the igniting particles have penetration $R_p \leq R_0 = 1.2$ g/cm^2. For longer penetration, $E_{\mathrm{ig}} = (R_p/R_0)E_{\mathrm{opt}}$]. We have performed series of simulations for monoenergetic beams and for beams with exponential energy distribution.

The results are summarized in Fig. 4. It is apparent that i) scattering slightly increases the ignition beam energy; ii) the optimal electron kinetic energy is about 1 MeV for monoenergetic beams; iii) for exponential electron energy distribution, the total required beam energy grows rapidly with the electron average energy $\mathscr{E}$. We find that in this last case $E_{\rm ig}$ is accurately fitted by the expression

$$E_{\rm ig}({\rm kJ}) = 22[1-\exp(-1.5/\mathscr{E})]^{-1}, \qquad (5)$$

which is also recovered (with a slight different front factor) from a simple analytical model, which will be discussed in a future publication. The results of Fig. 4 exhibit the same trends as those for the HiPER target presented in Ref. [5]. It should however be noted that in both cases we assume an initially parallel beam and we do not tackle the major issue of the generation of the electron beam and its transport to the compressed plasma.

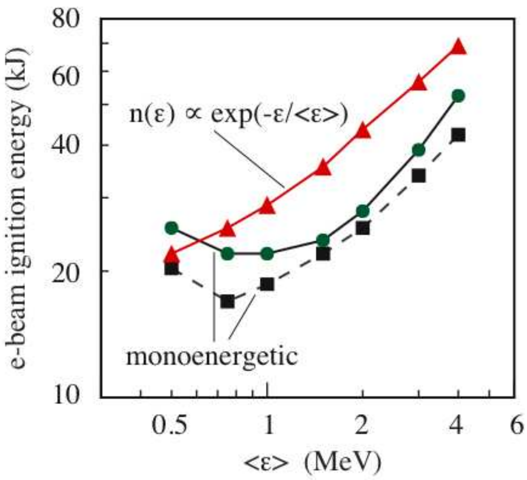

Figure 4: Minimum electron beam energy required for the ignition of a uniform DT sphere, initially at rest, and with mass density ρ = 300 g/cm^3. The dashed curve refers to simulations neglecting scattering.

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