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Fast model for charged particles transport in ICF targets

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In the Fast Ignition scheme of Inertial Confinement Fusion (ICF) the ignition energy to the core is transported by energetic charged particles, relativistic electrons or fast ions. They are generated by an ultra-high intensity laser in the outer and underdense parts of target or in a cone embedded in the target. They have to deposit their energy in the compressed shell. The particle transport and energy deposition processes are rather complicated and their detailed description requires heavy kinetic multidimensional calculations. The kinetic codes are time consuming and cannot be easily implemented in large-scale radiation hydrodynamic codes that describe the fuel assembly, the resulting energy deposition, and the combustion. Reduced methods are needed that can account for the main features of the kinetic transport process and, at the same time, are sufficiently fast and efficient to be introduced directly the hydrodynamic module.

We present here a two-dimensional model of charged particle transport that accounts for the energy deposition and the slowing down of the particle motion via the stopping power function. The deflection is taken into account through the mean scattering angle. The stopping power describes energy loss per unity length of a relativistic particle propagating through a plasma $\left(\frac{dE}{ds}\right)^c = n_i Z \int_{T_{min}}^{T^{max}} T \frac{d\sigma}{dT} dT$ [1], with $\frac{d\sigma}{dT}$ the cross section for a given energy loss T by the incident particle,n_i is the ion plasma density and Z the atomic number. In the case of a beam of relativistic electrons propagating through a plasma containing partially ionized atoms and cold free electrons the stopping power $(dE/ds)^c$ contains three terms that are describing, respectively, the energy loss of relativistic electrons due to bounded electrons, free electrons and plasma waves [2] [3]:

$$\left(\frac{dE}{ds}\right)^c_b = \frac{2\pi n_i (Z-Z^*) e^4}{mv^2}\left(\ln\left[\frac{(\gamma^2-1)(\gamma-1)}{2(I_p/mc^2)^2}\right] + 1 - \beta^2 - \frac{2\gamma-1}{\gamma^2}\ln 2 + \frac{1}{8}\left(\frac{\gamma+1}{\gamma}\right)^2\right),$$

$$\left(\frac{dE}{ds}\right)^c_f = \frac{2\pi n_i Z^* e^4}{mv^2}\left[\ln\frac{1}{4\varepsilon_{min}} + 1 - \frac{2\gamma-1}{\gamma^2}\ln 2 + \frac{1}{8}\left(\frac{\gamma-1}{\gamma}\right)^2\right],$$

$$\left(\frac{dE}{ds}\right)^c_p = \frac{2\pi n_i Z^* e^4}{mv^2}\ln\left[1 + \left(\frac{v}{w_p D(3/2)^{1/2}}\right)^2\right]$$

Here, Z^* is the ion charge (degree of ionization), e, m, v are the electron charge, mass and velocity, c is the light velocity, $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, $I_p = aZ(1-q)^{-1/2}\exp(1.29q^{0.72-0.18q})$ [4] , $q = Z^*/Z$ and $a = 10$ eV empirical coefficient to fit with quantum calculus. The deflection is taken into account via the mean scattering angle as it was described in Ref. [5]. Calculated without energy losses, the diffusion equation for the fast electron distribution function reads [6]:

$$\frac{\partial f_e}{\partial t} + v\vec{\Omega}\cdot\nabla f_e = v n_i \int [f(x,\vec{\Omega}',v,t) - f(x,\vec{\Omega},v,t)]\sigma(|\vec{\Omega}-\vec{\Omega}'|)d\vec{\Omega}' \tag{1}$$

with the classic Rutherford scattering cross section $\sigma = \frac{1}{4}Z(1+Z)(r_0/\gamma\beta^2)^2\sin^{-4}(\theta/2)$ where $r_0 = e^2/m_e c^2$ is the classical electron radius and n_i is the ion density. Equation (1) is integrated over the directions of the electron velocities $\vec{\Omega}$ and an equation for the angular moment $f_1(v) = \int \vec{\Omega}\, f(v)\, d\vec{\Omega}$ is obtained:

$$\partial f_1/\partial s = -k_1 f_1$$

where $s = vt$, $k_1 = n_i \int \sigma\,(1-\cos\theta)d\vec{\Omega}$ and the second angular moment is neglected. This latter hypothesis is similar to the Legendre polynomial decomposition used in [5] when limiting to the first polynomial P_1. The solution of this equation we present in the form $f_1 = f_1(0)\langle\cos\theta\rangle$ with with the average opening angle of the electron beam defined as

$$\langle\cos\theta\rangle = \exp\left(-\int_0^s k_1(s')ds'\right) = \exp\left(-\int_{E_0}^E k_1(E)\left[\frac{dE}{ds}\right]^{-1} dE\right).$$

Using the stopping power and the mean deflexion, the energy deposition of a mono-energetic beam can be calculated assuming an homogeneous transverse repartition of the beam density. To account for the energy dispersion and spatial distribution in the beam we apply a multi-group approach. The beam at the origin is split in several beamlets in space and in energy. Each beamlet deposits its own energy independently, but the target heating in each point is calculated for each step as a sum of energy depositions of all beamlets crossing this point. This model is called “Trumpet”. It is fast and has been implemented in our large 2D radiation hydrodynamic code. In addition, the effect of plasma heating due to the return current is taken into account assuming the complete current neutralization.

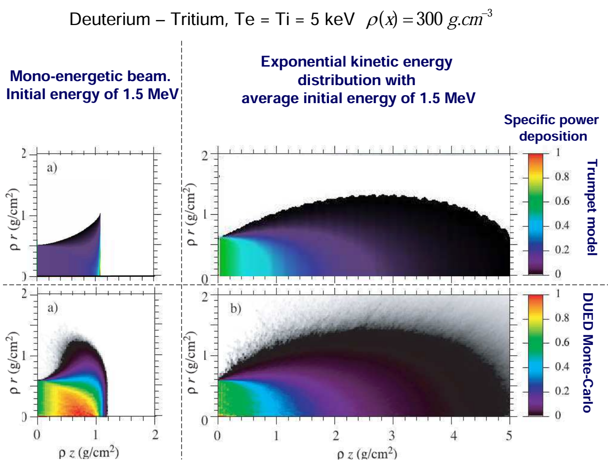

Figure 1: Specific power deposition of trumpet and DUED [8] simulation (upper and lower panels), for a mono- and multi-energetic beam (left and right panels).

The "Trumpet" model approach has been compared with detailed Monte-Carlo simulations [7] of the electron transport in a dense compressed core and with simulations of fuel ignition using a hybrid code combined to a radiation hydrodynamic code. The results are shown in figure 1). Although we calculate the same range, the deposition shape of a mono-energetic beam (left panel) computed by "Trumpet" stops sharply because of all electrons have the same angular divergence. The "Trumpet" simulation of a beam with a broad energy spectrum better reproduces the Monte-Carlo results. Although some differences can be observed, the overall performance is acceptable. Moreover, the "Trumpet" simulations require just a few seconds whereas the DUED simulations require several hours.

The model has also been used for the studies of the ion transport within the frame work of the ICF fast ignition. We use a stopping power which depends on the temperature [12].

The ion fast ignition is considered following the ponderomotive laser acceleration scheme proposed in Ref. [9]. The laser pulse accelerates ions which are a mixture of deuterium and tritium (effective ions with the mass 2.5 of the proton mass) at the bottom of a channel created by an auxiliary laser pulse. The ions are accelerated in a cylinder of a radius of 23 μm in the density range from 0.7 to 3 g/cm^3, the angular divergence of accelerated ions is 6°, the acceleration time of 2.3 ps. The transport and energy deposition of accelerated ions is described by the "trumpet" module coupled to the radiation hydrodynamics code CHIC. The simulations are conducted for the baseline HiPER target [10] and the energy is deposited at the moment of maximum compression. We found that the ion energy needed to ignite that target is 28 kJ. The spatial distribution of the deposited energy and the plasma temperature and density are shown in figure 2.

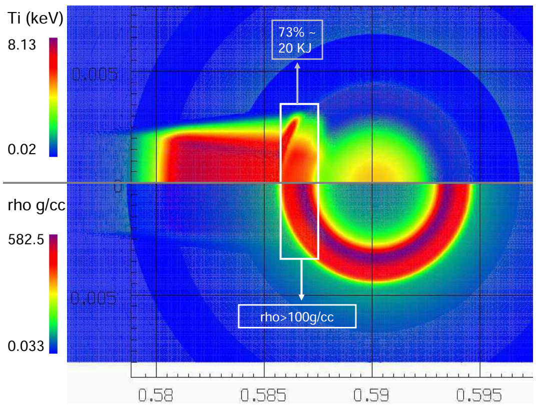

Figure 2: Temperature (upper panel) and density (lower panel) of the HiPER target at stagnation time after the fast ion energy deposition. Color codes show the maximum and minimum values.

Another application of the "Trumpet" model is the proton diagnostic of compressed targets. This diagnostic has been applied in a recent joint experiment on fast electron transport [11]. For a given density profile of the compressed cylinder computed by means of an hydrodynamic code, the "Trumpet" module has calculated the proton energy loss when the angular divergence was neglected (see figure 3). The energy decreases for those protons that pass through high density regions. The experimental results show a larger radius of 65 μm for initial proton energy of 4.8 MeV in difference from the "Trumpet" simulation that provides a radius of 50 μm. This difference can be attributed to the proton scattering that must be accounted for in the model.

In conclusion, the developed module of fast particle transport and energy deposition is an efficient albeit approximate model. It estimates the final plasma temperature within few seconds of calculation time for collisional and collective transport of electrons or ions in a 2D planar and axi-symmetrical geometry. The applications to the ICF fast ignition and proton diagnostic of compressed targets are considered.

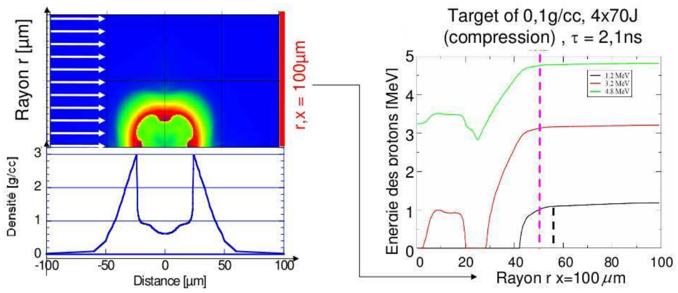

Figure 3: Left panel : density profile provided by hydro simulation, 2.1 ns after the beginning of the laser compression. Right panel : transverse profile of residual protons at 2.1 ns for $x = 100\,\mu$m.

Acknowledgements

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References

[1] J.D. Jackson, Classical Electrodynamics third edition, p625.John Wiley & Sons, New York

[2] H. A. Bethe, Handbuch für Physik, 24/2, p. 273. Julius Springer

[3] Pines & Bohm, Phys. Rev. E **85**, 338 - 353 (1952)

[4] R.M. More ,Plasma processes in non-ideal plasmas,p.157-214. M.B. Hooper

[5] C. K. Li and R. D. Petrasso, Phys. Rev. E **70**, 067401 (2004)

[6] H. W. Lewis, Phys. Rev. **78**, 526 (1950)

[7] S. Atzeni, Plasma Phys. Control. Fus., **51**, 015016 (2009)

[8] S. Atzeni, Comput. Phys. Comm. **43**, 107, (1986)

[9] N. Naumova et al. Phys. Rev. Lett. **102**, 025002 (2009)

[10] X. Ribeyre et al. Plasma Phys. Control. Fus. **50**, 025007 (2008)

[11] J.J. Santos et al., Plasma Phys. Control. Fusion 51, 014005 (2009)

[12] N.A. Krall & A. W. Trivelpiece, Principle of Plasma Physics. McGraw-Hill, N Y, 1973