Dynamical properties of dense plasma in inertial confinement fusion

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Recently, considerable attention of researchers is paid to the study of matter with high energy densities and, as a consequence, with high pressures and temperatures. The research in the field of inertial confinement fusion (ICF) on heavy ion beams takes a special place among the works on various aspects of this problem [1-2].

One of the most important parameters to describe the interaction of ions with matter is the energy of the projectiles. The stopping power is a parameter characterizing the rate of loss of the average energy of fast electrons or ions in plasma [3-4]:

$$\frac{dE}{dx} = 8\pi n\left(\frac{\mu_{\alpha\beta}}{m_\beta}\right)\cdot E_c \cdot b_\perp^2 \cdot \lambda_{\alpha\beta}\ , \tag{1}$$

here $E_c = \frac{1}{2} m_{\alpha\beta}\upsilon^2$ is the energy of the centre of mass, υ is the relative velocity of the scattered test particle, $b_\perp = \frac{Z_\alpha Z_\beta e^2}{2E_c}$, $\lambda_{\alpha\beta}$ is the Coulomb logarithm.

The Coulomb logarithm on the basis of the effective interaction potential of the particles is determined by the scattering angle of the pair Coulomb collisions. Introducing the centre of mass in the collision process the Coulomb logarithm reads [5-6]:

$$\lambda_{\alpha\beta} = \frac{1}{b_\perp^2}\int_0^{b_{\max}} \sin^2\left(\frac{\theta_c}{2}\right) b\, db\ , \tag{2}$$

The center-of-mass scattering angle can be obtained by the formula [5]:

$$\theta_c = \pi - 2b\int_{r_0}^{\infty} \frac{dr}{r^2}\left(1 - \frac{\Phi_{\alpha\beta}(r)}{E_c} - \frac{b^2}{r^2}\right)^{-1/2}, \tag{3}$$

here $m_{\alpha\beta} = m_\alpha m_\beta / (m_\alpha + m_\beta)$ is the reduced mass of the particles of kinds α and β; $b_\perp = Z_\alpha Z_\beta e^2 /(m_{\alpha\beta}\upsilon^2)$, $b_{\min} = \max\{b_\perp, \lambdabar_{\alpha\beta}\}$ describes the minimum impact parameter, where $\lambdabar_{\alpha\beta} = \hbar / \sqrt{2\pi m_{\alpha\beta} k_B T}$ is the thermal de Broglie wave length.

In formula (3) $\Phi_{\alpha\beta}(r)$ is the interaction potential and r_0 is the distance of the closest approach for a given impact parameter b:

$$1-\frac{\Phi_{\alpha\beta}(r_0)}{E_c}-\frac{b^2}{r_0^2}=0. \tag{4}$$

It is known that in order to correctly describe static and dynamic properties of plasmas the collective screening effect is to be taken into account. In this work the dense plasma is considered for which quantum effects must be taken into account at short distances. Further, the effective interaction potential which including both charge screening at large distance and quantum effects at short distance will be used [7]:

$$\Phi_{\alpha\beta}(r)=\frac{Z_\alpha Z_\beta}{r\sqrt{1-\left(2\lambda_{\alpha\beta}/r_D\right)^2}}\left(\exp(-rB)-\exp(-rA)\right), \tag{5}$$

$$B^2=\frac{1}{2\lambda_{\alpha\beta}^2}\left(1-\sqrt{1-\left(\frac{2\lambda_{\alpha\beta}}{r_D}\right)^2}\right),\quad A^2=\frac{1}{2\lambda_{\alpha\beta}^2}\left(1+\sqrt{1-\left(\frac{2\lambda_{\alpha\beta}}{r_D}\right)^2}\right),$$

where r_D is the Debye radius, $\lambda_{\alpha\beta}$ is the thermal wave length of the particles, and $m_{\alpha\beta}=m_\alpha m_\beta/(m_\alpha+m_\beta)$.

The basis of controlled nuclear fusion is to provide a fusion reaction of light nuclei. In this connection reaction involving the hydrogen isotopes deuterium and tritium (DT-cycle) are most important. The energy of the synthesis is arranged in the fuel. In case of DT reaction:

$$D+T\rightarrow\alpha(3{,}5MэB)+n\,(14{,}1MэB).$$

In this reaction, the total energy of 17.6 MeV is distributed between the α-particle (3.5 MeV) and the neutron (14.1 MeV). To absorb the energy α-particle, the size of the fuel has to exceed the range ρr [8]. The range of particles is determined as follows:

$$\rho r=\int_E^{E_0}\left(\frac{dE}{\rho dx}\right)^{-1}dE\,. \tag{6}$$

where the value of the stopping power $\frac{dE}{dx}$ is calculated in accordance with (1), E_0 is the initial energy of the particle. It should be noted the range as a product of mass density times distance, that means the unit of measurement is g/cm^2. For a more accurate description of the thermonuclear fusion also such parameters as mean deflection angle, stopping time, and depth of penetration of the ions have to be introduced. The stopping time of ion in DT plasma is determined by the following equation:

$$t_{dep}=\int_E^{E_0}\left(\frac{dE}{dt}\right)^{-1}dE\,. \tag{7}$$

The penetration depth of the ion with the initial energy E_0 can be calculated using equation:

$$\rho x = \int_{E}^{E_0} \langle \cos\theta \rangle \left(\frac{dE}{\rho dx} \right)^{-1} dE \, . \tag{8}$$

In the present paper the stopping time, the mean deflection angle, the depth of penetration, the effective range of the particles with different energies generated in the DT plasma. The stopping time of ion with initial energy $E_0 = 12\,MeV$ is shown in Fig. 1. The results presented in Fig. 1 show that the stopping time depends on the value of the initial energy as well as on density and temperature of the fuel. But the main problem is the stopping process of ions with energies up to 12 MeV during the initial time $t_{dep} \le 2\,ps$.

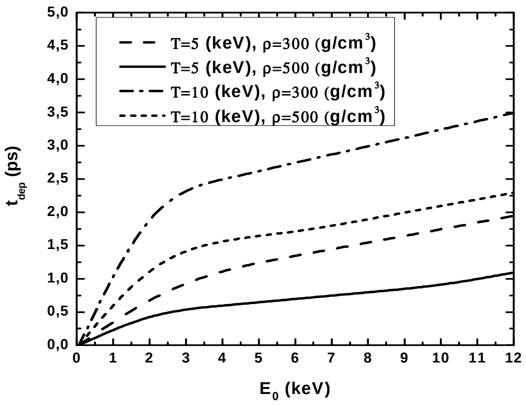

Fig. 1 – The stopping time of ions in DT plasma with initial energy $E_0 = 12\,MeV$.

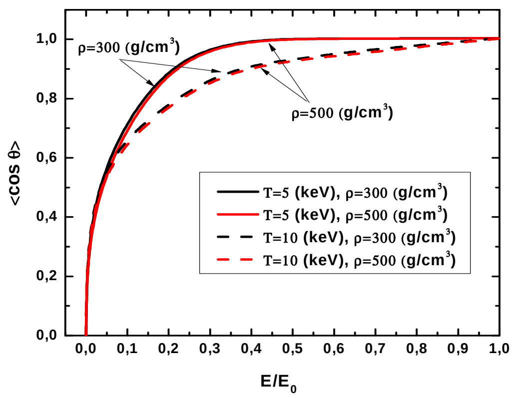

Fig. 2 – The mean deflection angle of ions in DT plasma with initial energy $E_0 = 12\,MeV$.

Figure 2 shows the mean deflection angle of the stopped ions with initial energy $E_0 = 12\,MeV$ in a DT plasma during the stopping process. The angle is presented as function of the residual energy after the collision process, normalized by the initial energy E_0. Fig. 2 shows that the incident ion is constantly changing the direction in the target while losing its energy. Thereat, the change of the mean deflection angle with the particle density is negligible. The influence of the temperature on the mean deflection angle is much more important. The mean angle increases if the temperature grows. The values of the stopping power and slowing down of the initial energy of the α-particles under real conditions in the ICF target are presented in Fig. 3 and 4.

The range of α-particles with an energy of 3.5 MeV in the plasma with a temperature of 30 keV is about $3\,g/cm^2$. Consequently, in order to realize an efficient self-heating due to the absorption of energy of the α-particles by the fuel, the fuel must be brought to such conditions, where $\rho r > 3\,g/cm^2$.

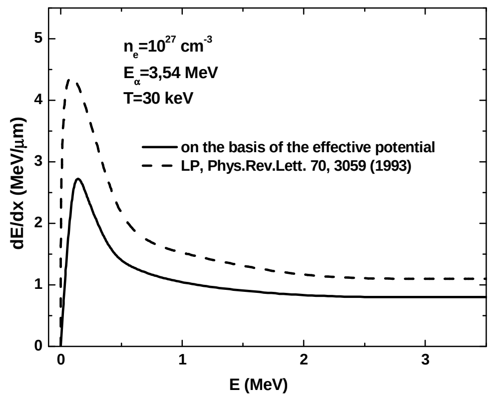

Fig. 3 – The stopping power of the α -particles with an initial energy $E_0 = 3.54\,MeV$.

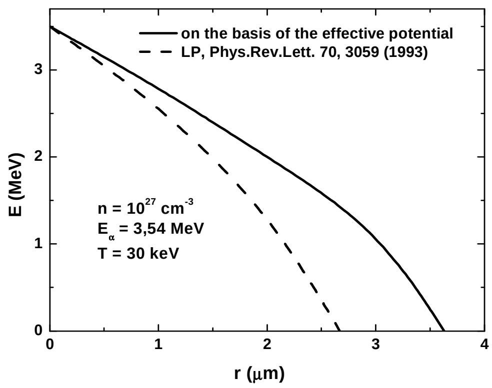

Fig. 4 – The slowing down energy of the α -particles with an initial energy $E_0 = 3.54\,MeV$.

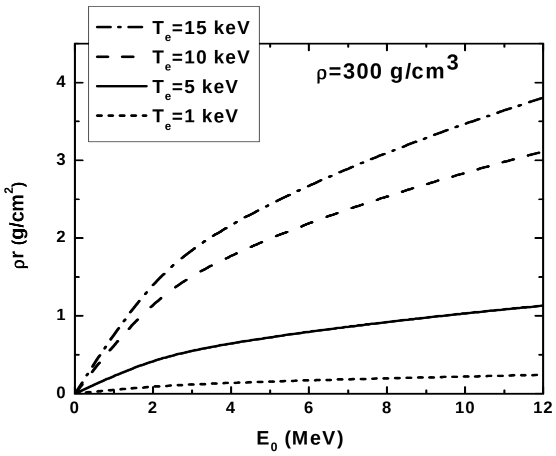

Fig. 5 – The range of protons in DT plasma with a density $\rho = 300\,g/cm^3$.

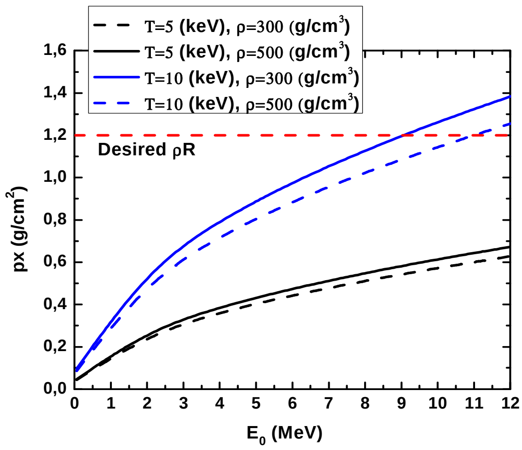

Fig. 6 – The penetration depth of the proton in DT plasma at different values density and temperature.

Figures 5-6 illustrate the dependence of the range and the penetration depth of the protons with different energies on the density and temperature of the target. The results show that at a lower target temperature of $T = 5\,\kappa eV$, the target protons may conserve their energy inside the target if $\rho R < 1.2\,g/cm^2$. However, when the target is hotter $T = 10\,\kappa eV$, the required initial energy of the proton is reduced to $E \le 2\,MeV$, in order to meet the required optimal deposition depth.

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