Transport of proton beams in fast ignition in proton-boron-11 degenerate plasma

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Abstract

In this study, the ignition conditions of proton-boron-11 fuel pellets by proton driver have been investigated under degenerate conditions. For this purpose, it used a proton driver beam was accelerated by the TNSA method. First, the stopping power is calculated using the Li-Petrasso stopping-power then the fraction energy deposited proton beam in the proton-boron-11 fuel pellet was calculated. The optimum energy of proton beam is calculated about 1MeV by considering the confinement parameter ρR=20 g/cm^2 and the numerical density ratio of boron-11 to proton equal ε=0.3. The obtained results show that at an electron temperature of about 450eV, the proton-beam driver with energy 1MeV deposits about 85% of its energy in the hot spot area in depth of 0.27µm from the surface of the fuel pellet to ignite the proton-boron-11 fuel pellet.

Keywords: Inertial confinement fusion, Fast ignition, Stopping power, Degenerate plasma.

Ignition condition in hot spot

Fusion plasma behavier in the degenerate state is different from classical plasmas due to high density, low temperature of plasma electrons and the reduction the loss power. In this study, first the ignition condition for proton-boron-11 fuel is calculated, then the energy fraction of the deposited energy with plasma electrons and proton beam range are calculated by using the stopping power equations. In the proton-boron-11 fusion reaction, three alpha particles with 8.7MeV energy are produced. Permissible areas in the degenerate state can be calculated from the following equation [2].

$$W_{dep} - W_b - W_m - W_{he} \geq 0 \qquad (1)$$

W$_{dep}$, W$_B$, W$_m$ and W$_{he}$, represents the deposited fusion power density, Bremsstrahlung emission, mechanical work and thermal conduction of plasma electrons respectively[2].

$$W_{dep}\left[\frac{erg}{cm^3\,s}\right] = 4.99 \times 10^{42}\,\frac{\epsilon\rho^2 f_\alpha < \sigma v >_{p11B}}{(1+11\epsilon)^2} \qquad (2)$$

$$W_B\left[\frac{W}{m^3}\right] = \frac{KT_e^2}{h}\left[F_1(\eta) - \frac{1}{2}\ln^2(e^\eta + 1)\right] \qquad (3)$$

$$K = \left(\frac{256\pi^3}{3\sqrt{3}}\right)\left(\frac{1}{4\pi\varepsilon_0}\right)^3 \frac{e^6 Z^2 n_i}{h^3 c^3}\ ;\eta = \frac{\varepsilon_f}{T_e}$$

$$W_m\left(\frac{erg}{cm^3\,s}\right) = \frac{4\pi C_s R^2 (n_e k_B T_e + n_i k_B T_i)}{V} \qquad (4)$$

$$W_{he}\left(\frac{erg}{cm^3\,s}\right) = 1.67 \times 10^{29}\,\frac{Te^{7/2}}{R^2 \log\Lambda\, Zi(1+3.3Zi)} \qquad (5)$$

ϵ represents the boron-11 to proton number density ratio. η and f$_\alpha$ it represents the degenerate parameter and the energy fraction of alpha particles deposited in the ignition area, respectively. ε_f, is Fermi energy reagent and C$_s$ represents the speed of sound. By replacing equations ((2) - (5)) in equation (1), the ignition condition can be calculated for the proton-boron-11 fuel degenerate.

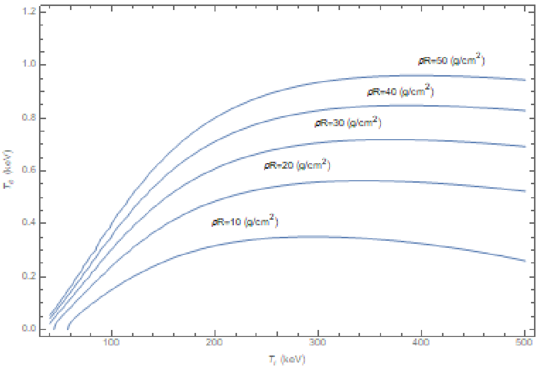

Fig. 1. The chart Ignition condition for proton-boron-11 deganerate fuel per ε=0.3

As shown in Figure (1), for a surface density of ρR =10g/cm^2 and a maximum electron temperature of about 300eV, the ion temperature will reach about 260keV. However, with an increase in surface density of more than ρR =20g/cm^2, the ionic temperature does not increase for an electron temperature of more than 450eV. Hence the required surface density value is considered as ρR =20g/cm^2.

Transport of proton beam in hot spot

The stopping power equations of the proton beam in the collision with ions and electrons of the degenerate plasma can be calculated as follows[2].

$$\left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_i = \frac{-4\pi}{m_i}\frac{\alpha^2}{v_p^2}\ln(\Lambda)$$

$$\left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_e = \frac{-4}{3\pi}\frac{m_e^2\alpha^2 v_p}{\hbar^3}\ln(\Lambda_{\mathrm{RPA}}^D)\left(\frac{1}{1+\exp(-\eta)}\right) \quad (6)$$

where in v_p represent the velocity of the proton beam, $\ln(\Lambda)$ and $\ln(\Lambda_{\mathrm{RPA}}^D)$ are the Coulomb logarithm[2].

The fraction of the energy of the proton driver beam, η_p , is deposited with electrons, can be calculated as follows [2].

$$\eta_p = \int_{E_p}^{3k_BT/2}\left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_e \Big/ \left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_{tot} dE \quad (7)$$

$(dE/dx)_{tot}$ indicates the total stopping power.

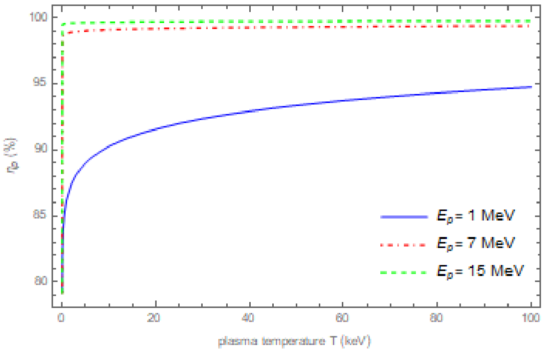

Fig. 2. The chart changes η_p in the proton-boron-11 degenerate plasma.

Figure (2) shows that in the temperature range less than 1keV, the proton-beam driver with energy 1MeV compared to the proton driver beam with energies greater than 1Mev, It deposited about 85% of its energy with plasma electrons.

Proton driver beam range proton-boron-11 degenerate plasma can be calculated as follows[2].

$$R = \int_{E_p}^{3k_BT/2}\left[\left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_e + \left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_i\right]^{-1} dE \quad (8)$$

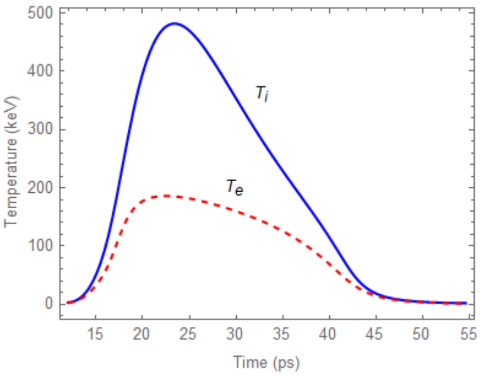

Fig. 3. The time-dependence of ion and electron temperature in the hot spot with ρR=20 g/cm^2 and ε = 0.3

In this study, the TNSA-accelerated proton-driver beam was used. The energy distribution between the particles of this beam is expressed as follows [4].

$$\frac{\mathrm{dN_p}}{\mathrm{dt}} = \frac{2\mathrm{N_0}\sqrt{\mathrm{E_p}}}{\sqrt{\pi}\mathrm{T_p}^{3/2}}\exp\left[-\frac{\mathrm{E_p}}{\mathrm{T_p}}\right] \quad (9)$$

where N_0 is the total number of protons in the beam. T_p is the temperature of the beam protons and, the energy of the beam protons, E_p , are equal to:

$$\mathrm{E_p} = \frac{\mathrm{m_p d^2}}{2\mathrm{t}^2} \quad (10)$$

For the proton beam driver power we will have:

$$\mathrm{P_p(t)} = \left(\frac{8\mathrm{E_{tot}}}{3\tau\sqrt{\pi}}\right)\left(\frac{\tau}{\mathrm{t}}\right)^6 \exp\left[-\left(\frac{\tau}{\mathrm{t}}\right)^2\right] \quad (11)$$

where $\tau = \sqrt{(m_p d^2)/2\,T_p}$ is characteristic time, while d and E_{tot} are the distance from the target to the hot spot and the total energy, respectively. By simultaneously solving the temperature evolutions of ions and electrons equations for the confinement parameter with ρR=20 g/cm^2 and the numerical density ratio of boron-11 to proton at ε = 0.3, the ionic and electron temperature changes in the hot spot will be obtained as in Figure (3). As shown in Figure (3), for heating the target to a temperature of about 450 keV, a driving pulse with a total energy of 238 MJ must be emitted over a period of 45 ps. This energy is equivalent to a population of $N_0 \approx 10\times10^{20}$ protons, each of which has an average energy of 1 MeV. As the energy of the proton driver beam decreases, the range of the beam decreases. For a temperature of about 450eV, the proton-beam driver with energy 1MeV penetrates to a depth of 0.27μm into the fuel pellet.

Conclusions

In this paper, by calculating the Production density and dissipation power for proton-boron-11, the optimal conditions of surface density and electron temperature are estimated to be ρR =20g/cm^2 and 450eV, respectively. The results of the calculations show that the the proton-beam driver with energy 1MeV at the electrons temperature of 550eV deposited about 85% of its energy to provide ignition conditions at a depth of 0.27μm of the fuel pellet.

References

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