Study the Influence of Temperature and Density of (DT) Plasma on Stopping Power in the ICF by Using (BPS) Model

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Abstract

The computation rate of energy deposition of alpha particles as they go through the plasma is a remarkable case in the experiments of inertial confinement fusion (ICF) implosion. There are many models of energy deposition or stopping power with different physics background. In this research we investigate the effect of temperature, density, and alpha particle energy for deuterium-tritium (DT) plasma due to Brown-Preston-Singleton (BPS) model. First the evaluation of Coulomb logarithm for various electron density and temperature is worked and graphically shown. The results are in good agreement with other referred researchers. Then the ion, electronic, and total stopping power dependence on energy of alpha particles is studied and graphically explained for different electron temperature, and electron density. While the electronic stopping power is increased exponentially as alpha particle energy increases, the ion stopping power decreased exponentially, and therefore the total stopping power results from the two effects. However, one can distinguish two regions where the two effects appear in the total stopping power due to alpha energy; the ion stopping power is governed at lower alpha energy and the electronic at higher energy. The influence of temperature on stopping power is that the higher temperature produced lower electronic stopping power and higher ion stopping power. The influence of lower electron density on electronic stopping power explicitly appears at high energy compared to higher density such that it gives higher electronic stopping power. For the ion stopping power, lower density yields higher stopping power at lower energy. The presented results here can be used to assess the performance of ICF experiments.

Key Words: Brown-Preston-Singleton (BPS) Model, Stopping Power, Deuterium-tritium (DT) Plasma, Quantum Effects.

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Introduction

A long time ago as yet there was a great interest in the theory of the ion stopping power in D-T plasmas [1-5]. The dynamic of pellet implosion involved phases of ablation and compression, and then the ignition. The latter is carried out through the shock waves convergence in the centre of the pellet target of the compressed fuel. Although, the ignition phase is very hard due to the non-equilibrium situation, attention is directed toward it because the charged particles deposited the energy over this phase [6]. Basically the inertial confinement fusion pellet with D-T fuel is a spherical target encompassed by radiation shield with high density and high Z to maintain a long time for burn and to confine radiation to the fuel [7]. As soon as the burn front extent, the energy of alpha particles deposes and then heated up in the temper when it reaches to it. As a result, an emitted radiation moves inwards due to the radiation conduction that moves outwards. The formation of hot spot affected by some processes such as radiation and electron conduction, hydrodynamic expansion and radiation losses.

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These processes are enhanced rapidly as the temperature raises by the neutron that induced fast ions which generated during nuclear reactions and the heating by alpha particles [8]. Then the burn propagates outwards through the fuel sphere and alpha particles escaped causing the temperature to fall down. However, more energy remains in the burning sphere that leads the temperature to rias once more. The range of alpha particles streaming out the sphere is very short [9]. There are two main types of interaction between plasma and charged particle that usually often attributed the stopping power which is assigned by electron and ion. The first interaction is electronic stopping power which is due to inelastic collisions between the ions moving through the bound electrons of plasma. The other interaction is ion stopping power which is due to elastic collisions between projected ion and plasmas ions [3]. The latter interaction is indicted as flexible collisions between plasma ions and travel ion, thus the interaction process is actually complex due to difficulty of description of the entire interactions for the states of ion charge. Under certain assumptions, there are several analytical models suggesting these major interactions [10,11]. For instant, the unitless fundamental parameter Coulomb logarithm supports to determine stopping power of charged particle in plasma is utilized in most of the models of stopping power in plasma. Many of these models assumptions are somewhat differ in some degree although they are related to the condition of the plasma. For example, different assumptions of physics used in those models affect the parameters used in Coulomb logarithm.

(BPS) presented a model for stopping power in the last decade [12]. The model uses dimensional continuation technique. It identified with the quantum mechanical figure of dense plasma and calculate the rate of energy loss of non-relativistic particles moving through completely ionized plasma. The model had developed an equation for the ion-electron energy transfer rate in an extensive variety of plasma conditions including quantum and coupling impacts. The BPS model does not place any restrictions on mass, charge, or particle velocity. It is supposed that the coupling of the plasma is not strong that the plasma coupling parameter is small.

In this research we investigate the stopping power based on BPS model by examine various parameters that interfere with the stopping power of alpha particles. This study is pertinent to fundamental plasma physics and to the likely realization of laboratory-scale thermonuclear fusion.

Mathematical Model

Basically the energy deposited in this matter or the rate of energy loss by charged particles is characterized by stopping power $SP(\epsilon)$. The general equation that identify the stopping power of the matter is [12, 13].

$$SP(\epsilon) = -\frac{d\epsilon}{dz} \qquad (1)$$

where the $d\epsilon/dz$ represents the energy loss ϵ per unit length z. The mean range of the particle, Δz, is calculated by equation

$$\Delta z = \int_0^{\epsilon_0} \frac{1}{SP(\epsilon)} d\epsilon \qquad (2)$$

in which the ϵ_0 denoted initial kinetic energy of the particle. However, in plasma physics the retarding force acting on charged particles by the matter because of the mutual interaction leads to loss of energy.

In the BPS model the Coulomb algorithm consists of three terms, the main term that incorporates quantum mechanics effects and the other two terms are correction factors. The first corrective term is taken due to the plasma coupling parameter that is no more near the quantum limit. The third corrective term takes into account the effect of electron degeneracy on many objects when Fermi-Dirac statistics become pertinent [12].

$$\ln\Lambda = \ln\Lambda_{QM} + \ln\Lambda_{\Delta C} + \ln\Lambda_{FD} \qquad (3)$$

In which the $\ln\Lambda$ is the Coulomb logarithm. Disregarding the small electron-ion mass ratio effects the working three terms are given [12].

$$\ln\Lambda_{QM} = \frac{1}{2}\left[\ln\left(\frac{8k_B^2 T_e^2}{\hbar^2 \omega_e^2}\right) - \gamma - 1\right] \qquad (4)$$

where k_B is the Boltzmann constant, T_e is electron temperature, $\hbar = h/2\pi$ is the plank constant , $\omega_e = \sqrt{4\pi n_e e^2/m_e}$ is electron plasma frequency, n_e is the electron density, m_e is the electron mass, e is the electron charge, and $\gamma = 0.57721$ is the Euler constant [12].

$$\ln\Lambda_{\Delta C} = \frac{e_H}{k_B T_e} \sum_i \frac{\omega_i^2 Z_i^2}{\omega_i^2} \left\{1.202205\left[\ln\left(\frac{k_B T_e}{Z_i^2 e_H}\right) - \gamma\right] + 0.39624\right\} \qquad (5)$$

where e_H is the binding energy of hydrogen, ω_i ion plasma frequency, n_i is the ion density, m_i is the ion mass, $\omega_I = \sum_i \omega_i$ is the average ion frequency, and Z_i is the effective charge number [12].

$$\ln \Lambda_{FD} = \frac{n_e \lambda_e^3}{2}\left\{-\frac{1}{2}\left(1-\frac{1}{\sqrt{3}}\right)\times\left[\ln\left(\frac{8k_B^2 T_e^2}{\hbar^2 \omega_e^2}\right)-\gamma-1\right]+\left(\frac{\ln 2}{2}+\frac{1}{\sqrt{2^5}}\right)\right\} \qquad (6)$$

where $\lambda_e = \hbar\sqrt{2\pi/mk_BT_e}$ the electron thermal wavelength.

Fundamentally the total stopping power involves a combination of two terms: the ions stopping power and the electrons stopping power.

$$\text{Total stopping Power} = \frac{e_p^2}{4\pi}\frac{\omega_b^2}{v_p^2}(\ln \Lambda) + \frac{e_p^2}{4\pi}\kappa_e^2(\ln \Lambda)\frac{2}{3}\left(\frac{\beta m_e v_p^2}{2\pi}\right)^{1/2} \qquad (7)$$

The subscript b is used to describe the background plasma ions and the subscript p is used when describing the projectile particle. The ionic plasma frequency is given by $\omega_b^2 = 4\pi e_b^2 n_b/m_b$, where m_b is the ion mass, n_b is the ion density, e_b is the background ion charge, , e_b and v_p are the charge and velocity of the projectile particle, β is $1/k_BT$, and κ_e is the electron Debye wave number.

Results and Discussion

As stated above the Coulomb logarithm includes three correction terms that depend on temperature and density of plasma. For the used range of electron temperature and density, **Fig. 1** shows BPS Coulomb logarithm as a function of density and temperature of electron, the Coulomb logarithm decreases linearly as electron temperature increased, and it is increased linearly with increasing electron density through increased plasm frequency. This behaviour is a good agreement with literatures as in Ref. [14].

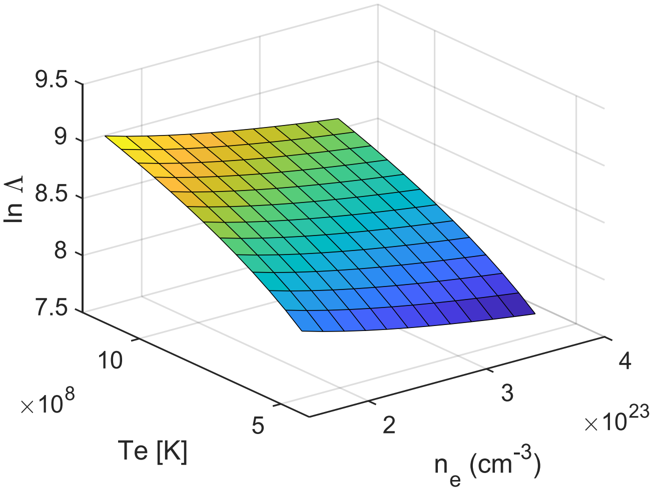

Figure 1. Coulomb logarithm due BPS model as a function of density and temperature of electron

Fig. 2 expresses the effect of alpha particles energy on electronic stopping power (ESP) at different plasma temperatures and at fixed other parameters. The ESP increases exponentially as alpha particles energy increased. Higher plasma temperature yields lower values of ESP. While the effect at lower energy for different plasma temperatures is slightly small, the effect at the high energies of alpha particles is obviously significant.

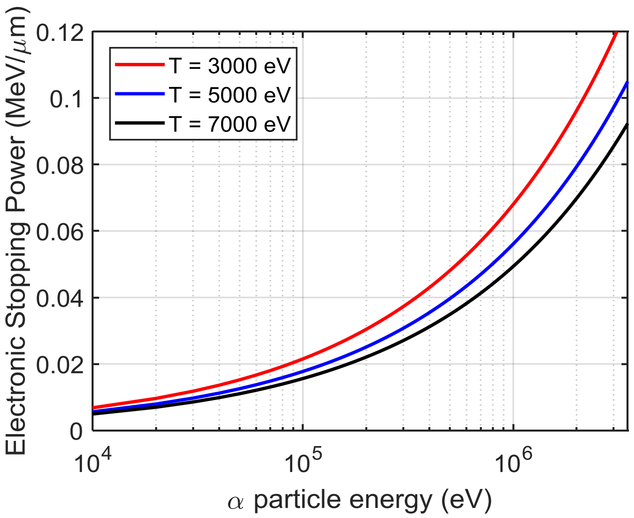

Figure 2. The dependence of electronic stopping power on alpha particles energy at different plasma temperatures

Fig. 3 explains the dependence of ion stopping power (ISP) on alpha particle energy for different temperatures. The ion stopping power is decreasing exponentially with the increase of alpha particle energy. The effect of plasma temperature is evident at the low energies of alpha particles where the curve of ISP is higher for the higher the temperature of the plasma. The curves tend to overlap on each other as alpha particles increase. Plasma temperature has no appreciable effect at the high energies of alpha particles.

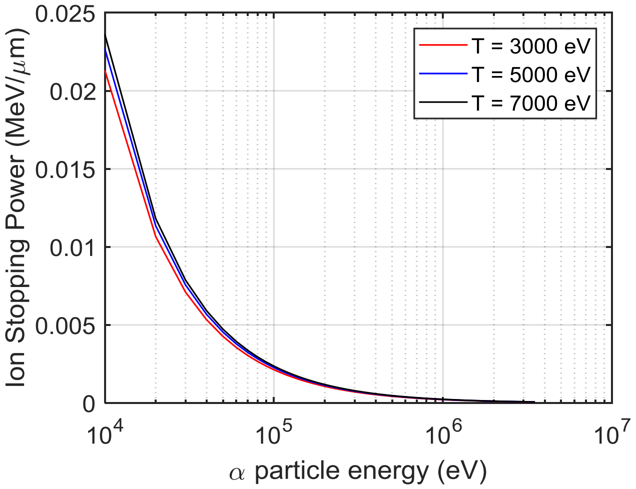

Figure 3. The ion stopping power verses the energy of alpha particle at different plasma temperatures.

Fig. 4 shows total stopping power (TSP) dependence on alpha particle for different plasma temperatures and fixed other parameters. The TSP is the sum of the effect of both ESP and ISP in whole range of energy. The TSPs decrease exponentially at the lower energies and overlap on each other for different plasma temperatures. The contribution of higher ISP to the TSP is to rise the TSP curves compared to ISP in **Fig. 2** at lower alpha energies. However, at high energy the effect of ESP is dominated because ISP is no longer contributes to TSP as described in **Fig. 3**.

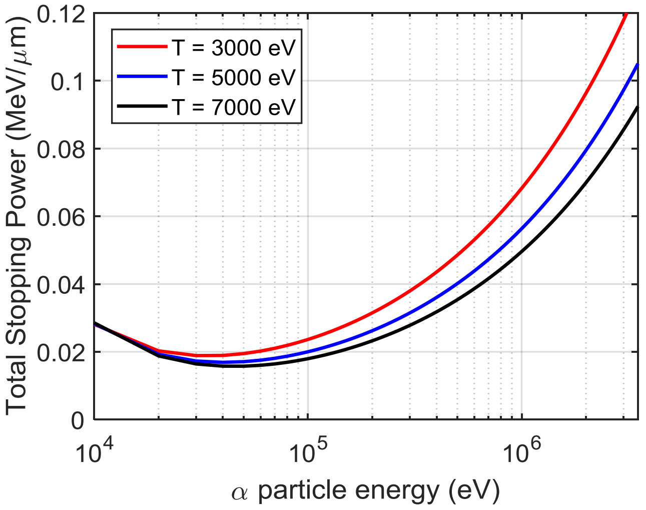

Figure 4. The dependence of total stopping power on alpha particle for different plasma temperatures.

Fig. 5 shows ESP as function of the alpha particle energy for various plasma densities. Clearly the curves are exponentially increased and the higher the plasma density yields to the lower the ESP curve. At lower energies of the alpha particles, the three curves share roughly the same values, but as the alpha energy increases the curves dissipated. This is obvious in higher values of alpha energies where the curves are clearly differentiated.

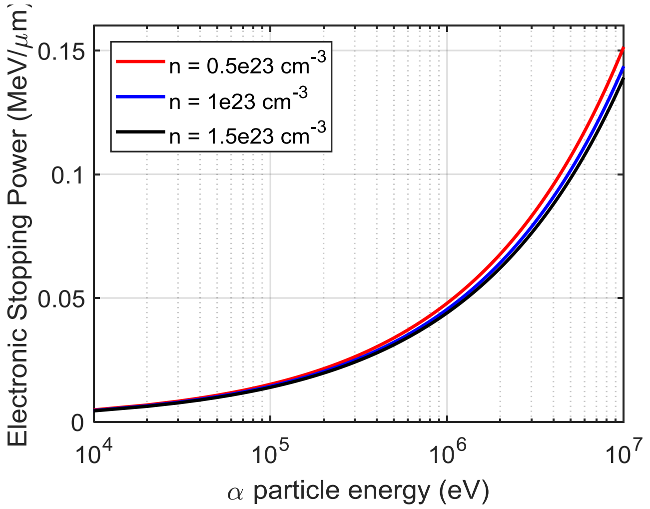

Figure 5. The electronic stopping power verses the energy of alpha particle at different plasma densities

Fig. 6 expresses the effect of different plasma density on ISP that depends on alpha energy. The effect of increasing plasma density is to give higher curve at lower alpha energy, whereas the curves share approximately similar values at higher alpha energies. The ISP decreases exponentially as alpha particle increased.

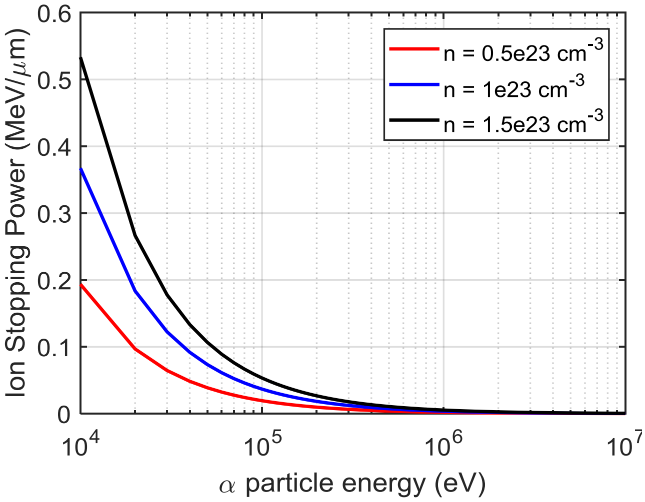

Figure 6. The ion stopping power verses the energy of alpha particle at different plasma densities

Fig. 7 shows the TSP dependence on the alpha particle energy for different plasma density which is similar to that used for ESP and ISP. Because the TSP depends on both the ESP and the ISP, the behaviour here is to combine the two effects. In the low energies the ISP is demented while at higher energies the ISP is governed. The curves in the intermediated region are raised due to the effect of ESP.

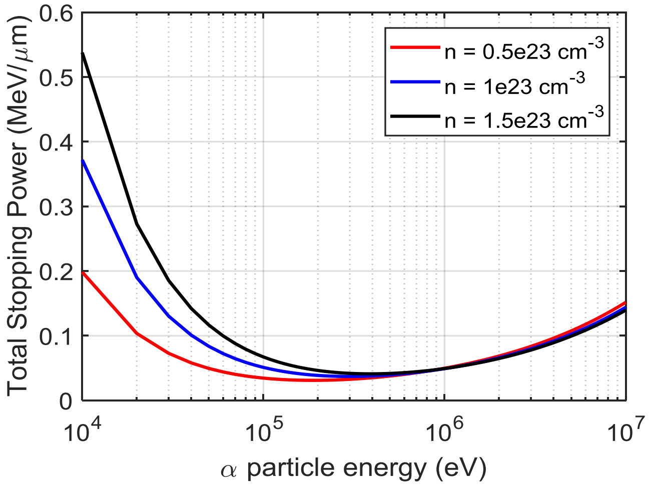

Figure 7. The dependence of total stopping power on alpha particle for different plasma densities

Conclusion

Stopping power of charged particle in plasma is one of the most objective field of research, that has a wide application in inertial confinement fusion but still has some uncompleted issues. Many theories on hands are developed to solve the problem as the research is going on. Among the stopping power theories, BPS's theory emerges as one of the advanced and reliable theory in describing stopping power because it relies on the Coulomb term that comes with quantum mechanics corrections compared to the Spitzer term that gives higher values. Understanding how the stopping power changes with the density, temperature of the plasma with the energy of the alpha particles gives a clear picture of what will happen in the experiment. Therefore, this research results have a positive effect in the required knowledge for selecting the most appropriate parameters in the inertial confinement fusion experiments.

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