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Research Article

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Investigating the effect of deuterium ignitor beam energy distribution function on the ignition of D/He-3 fuel pellet

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HIGHLIGHTS

- The effect of deuterium beam energy distribution function on the fast ignition of D/He-3 fuel pellet was investigated.
- Deuterium beam energy distribution function from TNSA and RPA mechanisms was considered.
- Penetration depth and stopping power of ignitor beam, Maxwellian and Gaussian distribution of energy are calculated.
- The results show that the energy deposit of the deuterium beam resulting the RPA mechanism is completely localized.

ABSTRACT

In this research, the effect of deuterium beam energy distribution function resulting from TNSA and RPA mechanisms on the fast ignition of D/He3 fuel pellet has been investigated. The fuel is irradiated with a deuterium beam through a conical guide. The energy distribution function will be different in different mechanisms. Penetration depth and stopping power of ignitor beam with mono- energy, Maxwellian and Gaussian distribution of energy are calculated. Calculations show that the Maxwellian beam from TNSA mechanism, penetrates up to about 100 μm in the fuel and the height of deposition peak is still in plasma corona. The height of the peak has also increased about 25 times compared to the case where the Gaussian beam is considered. Also, the obtained results are shown that the energy deposit of the deuterium beam resulting the RPA mechanism will be completely localized and will be more concentrated in the dense fuel core.

KEYWORDS

Fast ignition
Stopping power
Beam penetration depth
Energy deposition

HISTORY

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1 Introduction

Nuclear fusion has long been considered as one of the methods of energy production. Energy is produced from nuclear fusion of two light isotopes of hydrogen. Achieving continuous and economic nuclear energy includes two different methods such as thermonuclear fusion and low temperature nuclear fusion. Temperature and fuel density are two effective parameters in thermonuclear fusion. In this method, the fuel pellet must be confined in such a way that the required temperature for the ignition of the fuel pellet is provided (Tabak et al., 1994; Hegelich et al., 2006). In order to maintain the proper conditions of density and temperature of the fuel pellet, two methods of magnetic confinement and inertial confinement are proposed. To achieve proper energy and efficiency, the fuel plasma must be heated to very high temperatures while being confined. In the inertial confinement method, the fusion fuel nuclei are brought closer together and the probability of fusion increases using laser beam radiation or charged particles produced from the accelerator (Atzeni et al., 2002). In this method, after the beam hits the pellet fuel, the outer layer of the fuel is quickly heated and a plasma corona is created, which is thrown out with great acceleration. The outward ejection exerts a strong inward pressure on the inner layers of the fuel, which compresses and condenses the fuel at high pressure. High density leads to the compression of the center of the fuel pellet. The continuation of this process brings the fuel to maximum compression and the fuel is ready for internal explosion. So that the density of the fuel pellet reaches a thousand times the density of liquid hydrogen and the temperature reaches to 5 to 10 keV (Atzeni, 1999).

Fast ignition is one of the newest approaches of inertial confinement fusion. This method was proposed by

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Tabak, et al in 1994 (Tabak et al., 1994). At first they used lasers for fast ignition and two separate laser beams were irradiated to the fuel. The first beam, called the compression beam, compressed the fuel to maximum compression during a period of high magnitude ns at an intensity of $\sim 10^{15}$ W.cm^{-2} and temperature will raised up to 1keV. But this temperature and compression are not yet suitable for ignition initiation. The ignitor laser beam with intensity $\sim 10^{20}$ W.cm^{-2} in a short time in order of several Ps irradiated after compressing beam, and ignited the compressed fuel (Nassisi et al., 2004; Mima, 2008; Azadifar and Mahdavi, 2017; Tabak, 2016; Zuegel et al., 2006; Fernández et al., 2014; Kawata, 2021; Tabak et al., 2006; Hatchett et al., 2006). Higher target gain with lower driver energy can be achieved in fast ignition compare with conventional methods. Also, the challenge of the symmetric implosion which was a common problem in indirect drive was eliminated. The existence of two separate beams controls the growth of hydrodynamic instabilities (Mima, 2008; Azadifar and Mahdavi, 2017; Tabak, 2016; Zuegel et al., 2006; Fernández et al., 2014; Kawata, 2021; Tabak et al., 2006). The input power required for fast ignition was provided by short pulse laser Basko (1993). Such lasers delivered D/He-3 fuel to a high density (about 1000 times the solid density, $\rho_{DT} > 200$ g.cm^{-2}) required for fast ignition and it was the key to gaining fusion in the future. In high intensities ($\sim 10^{24}$ W.cm^{-2}) laser-electron coupling dominated and the efficiency will yield 25 to 50% (Badziak et al., 2007). Comprehensive study on electrons, even with the use of an explosive capsule including a cone guided and hole boring, showed some flaws in the way of laser fast ignition. In laser fast ignition, electron beams created due to the electron-divergence in fuel cannot get the appropriate gain (Chen et al., 1984; Caruso and Strangio, 2003). On the other hand, other experiments show that fast ignition is a wise and secure investment for the future. Because of the low repetition rate and low efficiency 6 to 10% for laser drivers, the ion accelerator were suggested. The repetition rate and efficiency are higher order in this method. For example, 30% efficiency has been reported for induction accelerators (Mima, 2008). In heavy ions ignition, the ions stopped in fuel layer with the high-Z (same as Lead) and the ions energy deposited in a small fraction of the fuel. The advantage of ion beams compare with laser is high repetition rate and ability to focusing by the magnetic field (Azadifar and Mahdavi, 2017). The main difference between ion beam and laser energy transfer is their penetration depth and their energy deposit in the target. In ignition with an ion beam, a critical density is not created. However, the ions are stopped at a certain distance (Tabak, 2016; Zuegel et al., 2006; Fernández et al., 2014; Kawata, 2021). Ions deposit their maximum energy near the end of the ion range and even before that, which is known as the Bragg peak. Using of light ions will be more economical because the energy required to accelerate is less. But ions beam have disadvantages for igniting, so that the depth of penetration depends on the mass and energy of the ion and type of absorbing material (Basko, 2003). Considering the different methods of ion beam production and the direct effect of the type of beam produced to improve the conditions of energy deposition in the fuel and to achieve optimal ignition conditions, in this study, two main methods of ion beam production are compared.

2 Fast deuterium igniter

The advantages of ion beams to laser radiation have led to the use of ion accelerators in fast ignition has quickly achieved a suitable position. Target Normal Sheath Acceleration (TNSA) mechanism is one of the ion beam production methods (Skupsky, 1977). Successful experiments in the NOVA petawatt laser, with a conversion factor of laser energy to a suitable deuterium beam with TNSA mechanism, could provide a new path in laser-plasma interaction (Davis et al., 2011). The advantages of this method include the localized energy deposition in the hot spot and the higher coupling coefficient of the target-beam in comparison with electron fast ignition (Chen et al., 1984). In this mechanism is used high-intensity laser radiation ($\sim 10^{20}$ W.cm^{-2}) of foil outside of fuel capsules to produce deuterium beams (Esirkepov et al., 2002; Hatchett et al., 2006). The type of foil affects the type of ion beam created. Such as a gold sheath with a thickness of 10 μm or a deuterated polyethylene sheath (C_2D_4), which is called CD foil. The existence of this foil produces a deuterium beam in the TNSA method (Liu et al., 2011). In the TNSA mechanism, due to the laser radiation and the coupling of the laser to the foil, a beam of relativistic electrons is created, which leads to the focusing of the deuterium beam and the ignition of the fuel. The ion beam created by the TNSA method has an energy distribution function, not a mono-energetic (Hu et al., 2014).

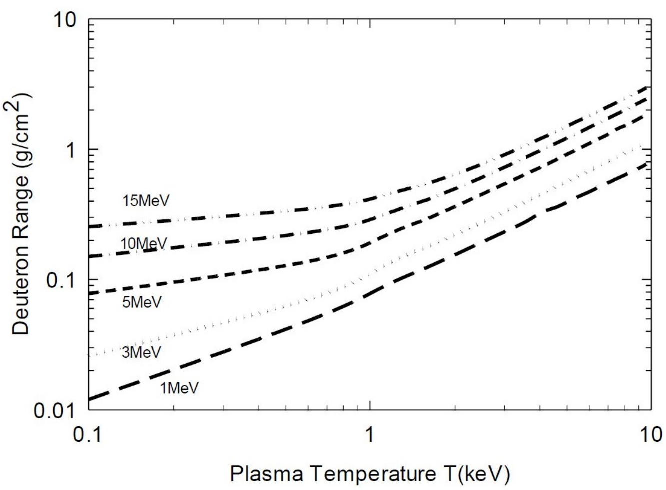

Figure 1: Deuterium beam range changes according to plasma temperature.

The mass range of deuterium beam in terms of plasma temperature with different energies in D/He-3 fuel with a density of 400 g.cm^{-3} is presented in Fig. 1. It is shown that, the mass range of the deuterium with 15 MeV energy is 0.7 g.cm^{-2} in the D/He-3 fuel with plasma temperature 1 keV. While, by increasing the plasma temperature up to 8 keV, a deuterium with an energy of 3 MeV will have a mass range equivalent to the same value. In fact, the faster deuterium, which reach the D/He-3 fuel, have enough range to heat the hot spot in the cold target. But the slower deuterium reach the fuel heated by the faster deuterium and reach enough range to reach the hot spot. This decrease in the effective range of deuterium and increase in the dispersion of effective energies is caused by the function of the quasi-exponential energy spectrum. Calculations are shown that in order for the ion ignition beam to be able to form a hot spot and propagate a thermonuclear wave to the depth of the fuel, the driver energy must be of the order of 10 kJ. According to the Maxwellian function of the accelerated deuterium beam in the TNSA method, this energy is equivalent to the acceleration of approximately 10^{15} particles. Compared to the deuterium beam, the heavy ion beam should be of mono energy because the existence of a broad energy distribution of the beam cannot have a localized deposition like the deuterium. Also, the heavy ion beam needs more energy than the deuterium to penetrate depth of the pre-compressed fuel capsule. It is almost impossible to create such high-energy beams using the TNSA method, so other mechanism such as Radiation Pressure Acceleration (RPA) should be used (Key, 2007; Key et al., 1998).

The range of the deuterium beam with the Maxwellian energy distribution increases with increasing fuel temperature along the path of energy deposition. The energy distribution function of the deuterium ignitor beam is introduced as the following form (Davis et al., 2011):

$$f(E) = \Big(\frac{2N_0}{\pi^{1/2}T_b^{3/2}}\Big)E^{1/2}\exp(-\frac{E}{T_b}) \tag{1}$$

where N_0 is the number of deuterium in the beam and T_b is the temperature of the beam in MeV that is obtained from the following equation:

$$T_b = \frac{2\bar{E}}{3} \tag{2}$$

According to the shape of the energy spectrum of incident particles (Maxwell spectrum), the number of particles at high energies are low, while the number of particles has its maximum value in the energy range of 1 to 7 MeV. Also, the number of particles at low energies is more, so the number of particles decreases with the increase of energy. New simulations have shown that for the acceleration of particles in very thin targets, another acceleration method called Radiation Pressure Acceleration (RPA) is proposed (Li and Petrasso, 1993b). This method requires high intensity lasers $> 10^{21}$ W.cm^{-2} (Li and Petrasso, 1993a). The beams produced in this acceleration have a Gaussian distribution with broadening energy spectra $\Delta E/E = 10 - 20$ %. In fact, about 100 kJ of energy is needed to ignite the D/He-3 fuel, which is not easily accessible. Using two separate beams to compress and ignite the fuel reduces this energy to about 10 kJ (Roth and Schollmeier, 2017). The energy spectrum of the beam generated in the RPA mechanisms follows a Gaussian energy spectrum. Therefore, in this section, we will again examine the conditions of beam energy deposition with Gaussian energy distribution, with the difference that the average energy of the beam with Gaussian distribution is considered to be around 15 MeV, which is introduced as follows (Davis et al., 2011):

$$G(E) = \frac{1}{\pi^{1/2}\Delta E}\exp[-\frac{(E-\bar{E})^2}{\Delta E^2}] \tag{3}$$

where is Gaussian spectrum broadening and is equal to $\Delta E = 0.1\bar{E}$. For different broadening, the curve of deuterium beam range changes for the Maxwellian and Gaussian distribution function with average energy of 3 and 15 MeV are drawn in Figs. 2 and 3.

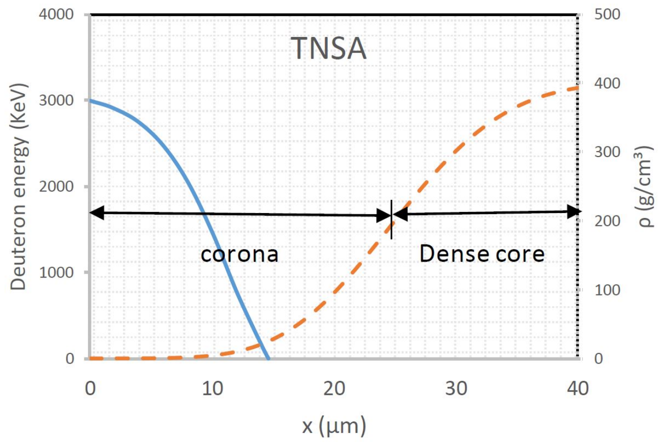

Figure 2: Energy loss of the deuterium beam ignitor accelerated by the TNSA mechanism in the non-uniform D/He-3 fuel with average beam energy of 3 MeV.

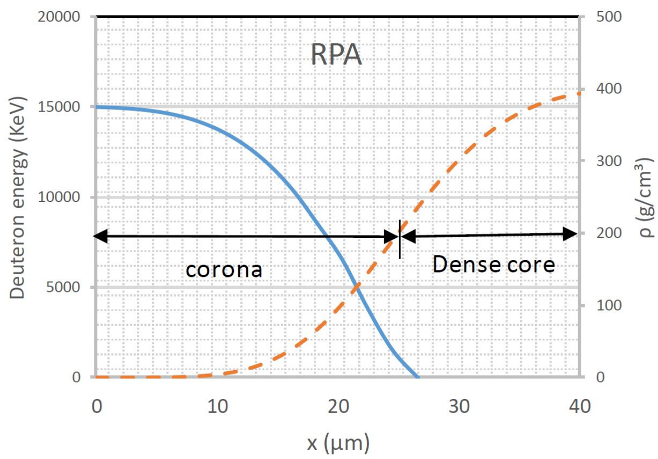

Figure 3: Energy loss of the deuterium beam ignitor accelerated by the RPA mechanism in the non-uniform D/He-3 fuel with average beam energy of 15 MeV

Dense core and the plasma corona are shown in Figs. 2 and 3. The plasma corona extends from the surface of the fuel pellet to a depth of about 25 μm and dense fuel from a depth of 25 μm to the center of the fuel pellet. In Fig 2, it is shown that the deuterium beam with Maxwellian energy distribution with average energy of 3 MeV obtained by TNSA mechanism penetrates the fuel to a depth of

14 μm (in the plasma corona area). But as seen in Fig. 3, the deuterium beam obtained by the RPA mechanism penetrates deeper into the fuel with Gaussian energy distribution and deposits more energy in the dense fuel. To calculate the deuterium energy beam deposition, it is necessary to calculate the number of deuterium needed in the beam. The number of deuterium is needed for calculating the deuterium beam energy deposition. By using the kinetic energy of each ion in the beam, the number of deuterium can be calculated as follows:

$$N_0 = \frac{E_{ig}}{\varepsilon_P} \tag{4}$$

where E_{ig} is the total beam energy for the fast ignition of D/He-3 fuel and ε_P is the initial ignitor beam energy.

3 Beam stopping power in fuel plasma

One of the important factors in improving the efficiency of fast ignition is local deposition energy of ignitor beam in short time in order of ps. Also hot spot temperature evolution must end shorter than the period of its hydrodynamics evolution $t = r_{hs}/c_s \sim 20$ ps, where c_s is the sound speed in compressed fuel and r_{hs} is hot spot radius (Atzeni et al., 2002). According to this, in ICF simulation codes stopping power is calculated by using numerous models that calculated the interaction between alpha particles and matters. The LP model in a low temperature (1 keV) and high density plasma (400 g.cm^{-3}) condition introduce as a suitable model for charged-Particle stopping power in fusion plasma in 1993 (Chen et al., 1984). The accelerated deuterium beam, as a result of the interaction with the ions and electrons of the fuel plasma, deposits its energy in the fuel. Therefore, in order to check the range of the deuterium ignitor beam and the deposit energy concentration in the fuel and plasma corona, the stopping power equations using the LP model are described as follows (Meyer-ter Vehn, 2001; Davis et al., 2011; Mahdavi et al., 2023).

By solving the Fokker-Planck equation and considering the quantum and collective effects of plasma, Lee and Petra expressed the stopping power of charged particles the plasma media as follows (Li and Petrasso, 1993b):

$$\frac{\mathrm{d}E^{t/f}}{\mathrm{d}x} = -\frac{(z_t e)^2}{v_t^2}\omega_{pf}^2 G(x^{t/f}) \ln \Lambda_b \tag{5}$$

In this equation, $\mathrm{d}E^{t/f}/\mathrm{d}x$ is the stopping power of the interaction of the incident charged particle with the charged particles of the plasma media, and also:

$$\begin{aligned} G(x^{t/f}) =& \mu(x^{t/f}) - \frac{m_f}{m_t}\Big\{\frac{\mathrm{d}\mu(x^{t/f})}{\mathrm{d}x^{t/f}} \\ &- \frac{1}{\ln \Lambda_b}\Big[\mu(x^{t/f}) + \frac{\mathrm{d}\mu(x^{t/f})}{\mathrm{d}x^{t/f}}\Big]\Big\} \end{aligned} \tag{6}$$

where $z_t e$ is the electric charge of the incident particle and $x^{t/f} = v_t^2/v_f^2$, $v_t(v_f)$ is the velocity of the incident particle (plasma) and $\omega_{pf} = \sqrt{4\pi n_f e_f^2/m_f}$, $m_t(m_f)$ is the mass of the incident charged particle (plasma) and the frequency of plasma $\mu(x^{t/f}) = 2/\sqrt{\pi}\int_0^{x^{t/f}} \mathrm{e}^{-\xi}\sqrt{\xi}\mathrm{d}\xi$ and Maxwell's integral. Considering the collective effects of plasma, the stopping power is expressed as follows:

$$\begin{aligned} \frac{\mathrm{d}E^{t/f}}{\mathrm{d}x} =& -\frac{(z_t e)^2}{v_t^2}\omega_{pf}^2 G(x^{t/f}) \ln \Lambda_b \\ &+ \theta(x^{t/f}) \ln\Big(1.123\sqrt{x^{t/f}}\Big) \end{aligned} \tag{7}$$

In this equation $\theta(x^{t/f})$ is step function $1 \le x^{t/f}$ or (< 1) has a value of 1 or (0). In the case of an in-degenerated plasma, the Coulomb's logarithm is calculated from the equation $\ln \Lambda_b = \ln(\lambda_D/p_{\min})$, where λ_D is the Debye length, $p_{\min} = \sqrt{p_\perp^2 + (h/4\pi m_r u)^2}$ and $p_\perp = e_t e_f/m_r u$ the classical collision parameter under the scattering angle of 90 degrees, m_r is the reduced mass and u is the relative velocity of the particles. Also, T is the plasma temperature in keV. Nevertheless, in plasmas with high density and low temperature, the effects of the plasma electron degeneracy should be taken into account in the calculations of Debye length and collision parameters.

The fusion plasma has a range of density and temperature ($n_e \le 10^{27}$ cm^{-3} and $0.1 \le T_e(T_i) \le 40$ KeV). According to these conditions, the variation range of Coulomb logarithm will be equal to $1 \le \ln \Lambda_b \le 12$. The quantity of Coulomb's logarithm in investigating the stopping power of charged particles in plasma means impact under small angles compared to scattering under large angles (Roth and Schollmeier, 2017). In other words, the smaller value of Coulomb's logarithm, becomes more important of scattering under large angles (Li and Petrasso, 1993b).

$$\begin{aligned} \frac{\mathrm{d}E^{t/f}}{\mathrm{d}x} =& -\frac{2\pi n_f Z_t^2 Z_f^2 e^4}{E_t}.\frac{m_t}{m_f}.\Big\{\Big[-\Big(1+\frac{m_t}{m_f}\Big) \\ &.\frac{2}{\sqrt{\pi}}\sqrt{x^{t/f}} + \mathrm{erf}(\sqrt{x^{t/f}})\Big] \ln \Lambda_b \\ &+ \frac{m_f}{m_t}\mathrm{erf}(\sqrt{x^{t/f}})\theta(x^{t/f}) \ln\Big(1.123\sqrt{x^{t/f}}\Big)\Big\} \end{aligned} \tag{8}$$

where $Z_t(Z_f)$ is the charge of the incident particle (target), e is the electron charge, E_t is the kinetic energy of the incident particles, n_f is the density of the target particles. In this research, we consider the incident particle as a deuterium and investigate the process of stopping power in D/He-3 plasma. Regarding the formation of the plasma corona, in the numerical simulations, instead of considering the homogeneous fuel sphere with constant density, the radial distribution function of the fuel is used. For this purpose, the super- Gaussian radial density distribution function with the following characteristics is used (Roth and Schollmeier, 2017):

$$\rho(r) = \rho_p \mathrm{e}^{\frac{-(r-r_0)^4}{R^4}} \tag{9}$$

where $\rho_p = 400$ g.cm^{-3} is the peak density, $R = 28$ μm, $r_0 = 100$ μm is the peak place, and r is the distance from peak. In addition the equmolar D/He-3 fuel temperature considered 1 keV (Stephens et al., 2005). The thickness of the fuel layers, for deuterium with energy 3 to 10 MeV, in plasma temperature 1 to 10 keV and plasma density 300 to 500 g.cm^{-3}, can be estimated by following equation;

$$\lambda_D = \left(\frac{T_e}{4\pi\rho e^2}\right)^{1/2} \quad (10)$$

Thus, the average deuteriums scattering value is $\lambda_D = 2$ to 3 μm. Accordingly, the thickness of the layers is about this value. In the following, the fuel plasma is divided into layers with 2 μm thickness so we can observe the energy deposition in different layers

4 Ignitor beam energy deposition in fuel

In order to study the effect of the beam energy distribution function on energy deposition process in the D/He-3 fuel, the initial temperature of the fuel is considered to 1 keV, which is irradiated by a mono-energy deuterium beam. At first, a mono-energy deuterium incident beam is considered and the contribution of deposited energy in the fuel by dividing D/He-3 fuel layer into layers with a thickness of 2 μm is calculated according to the radial distribution function of the introduced fuel pellet. The obtained results are presented in Fig. 4.

As seen in Fig. 4, the deuterium beam penetrates to a small depth of the fuel and has a peak in the plasma corona, which leads to the energy loss of the beam. The results of experimental calculations with ions accelerated by short pulse lasers show that ion beams have energy distribution not mono-energy. The distribution in the energy of the ion beam leads to the spread of energy in D/He-3 fuel, which changes the efficiency of energy deposition in D/He-3 fuel compared to the mono-energy beams. Because ions with high or low energy may be deposit only a part of their energy by changing the target or beam parameters.

In the following, deuterium beam energy deposition has been investigated with Maxwellian energy distribution. D/He-3 fuel pellet with supper-Gaussian mass density distribution with a peak mass density 400 g.cm^{-3} and initial temperature 1 keV is radiated with a deuterium beam obtained from TNSA mechanism with Maxwellian energy spectrum. In Fig. 5, the process of the ignitor beam energy deposition in fuel is drawn. It is shown that, the deuterium beam penetrates the fuel and energy deposition occurs in the fuel plasma and the plasma corona. The mass range of the deuterium beam with the Maxwellian energy distribution increases with increasing the fuel temperature along the path of energy deposition.

As can be seen in Fig. 5, deuterium beams has penetrated to about 100 μm of the fuel, but the peak of the deposit is still located in the plasma corona. Compared to the results obtained from Fig. 4, (for a monoenergy deuterium beam) under the same energy conditions, the peak of energy deposition of the beam for the Maxwell energy distribution has increased about 25 times.

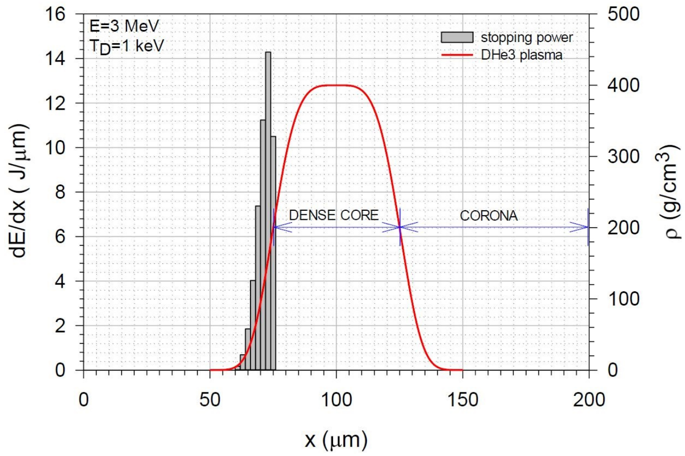

Figure 4: The stopping power of mono-energy ignitor deuterium beam beams in D/He-3 fuel with a super-Gaussian radial density distribution function.

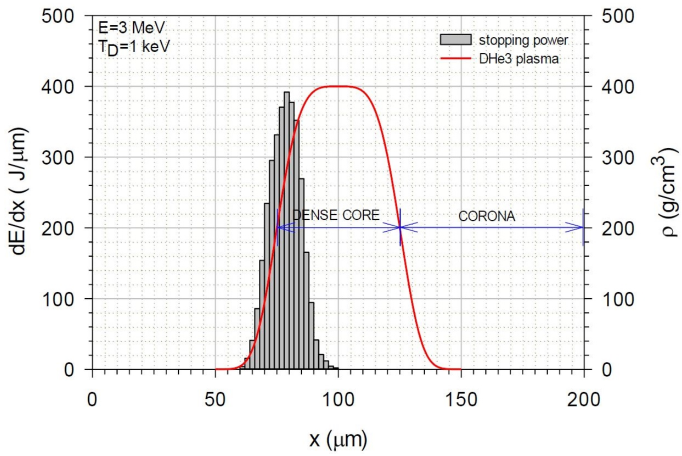

Figure 5: The stopping power of Maxwellian ignitor deuterium beam beams in D/He-3 fuel with a super-Gaussian radial density distribution function.

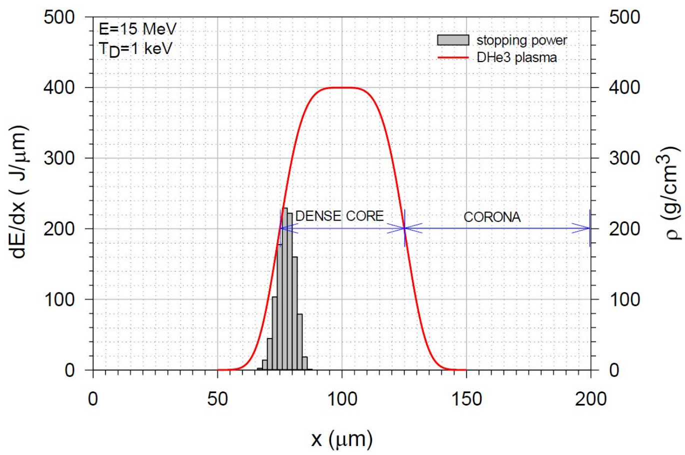

Figure 6: The stopping power of Gaussian ignitor deuterium beam beams in D/He-3 fuel with a super-Gaussian radial density distribution function.

In the next step, the energy deposition conditions in D/He-3 fuel pellet for the ignitor beam with the energy Gaussian distribution produced by the RPA mechanism is investigated. The obtained results in Fig. 6 are shown that, the Gaussian beam, have the energy deposition more localized and the ignitor deuterium beam deposits its energy in the fuel dense core. This process provides the suitable conditions for the formation of a hot spot. But the deuterium beam with the Maxwellian energy distribution is deposited its energy in the fuel plasma corona with the larger peak.

5 Conclusions

In this research, the effect of deuterium beam energy distribution function on the fast ignition of D/He-3 fuel pellets has been discussed. The fuel is irradiated with a deuterium beam through a conical guide. In the condition that the ignition beam has mono-energy, the energy deposition proceeds to a small depth of the fuel and has a peak in the plasma corona, which causes the energy of the beam to be loosed. The deuterium beam resulting from TNSA and RPA have different distribution of energy. Calculations show that in the TNSA mechanism, the resulting Maxwellian beam penetrates the fuel and ignites the fuel, but in addition to the fuel dense core, it also heats the fuel corona, which helps the fuel deposition. In the RPA mechanism, the created beam is Gaussian, which has a lower penetration depth in the fuel compared to the TNSA method, but it causes local deposition in the fuel pellet. In the investigation of the Maxwellian beam from TNSA mechanism, it can be seen that the penetration depth of the beam in the fuel has improved and it penetrates up to about 100 μm in the fuel. The height of deposition peak is still in corona. The height of the peak has also increased about 25 times compared to the case where the Gaussian beam is considered. Also, according to the calculations, it was observed that using the RPA mechanism to produce a deuterium beam with Gaussian distribution, the energy deposit of the deuterium beam will be completely localized and will be more concentrated in the dense fuel core.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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