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Research Paper

Effect of External Magnetic Field on Fuel Pellet Plasma Ignition Conditions in Magneto- Inertial Fusion

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Abstract. Deuterium-helium-3 fuel is a suitable option for investigation in the magneto-inertial fusion cycle due to its non-neutron-producing nature and suitable reactivity rate at low temperatures. Due to the application of appropriate degenerate and temperature anisotropy conditions for the fuel pellet plasma environment, optimal fuel pellet ignition conditions will be provided. In this research, by calculating the production and loss powers for the plasma environment of the deuterium-helium-3 fuel pellet under the conditions of the degenerate environment and temperature anisotropy, the surface density optimal of the fuel pellet and the applied magnetic field have been estimated as $\rho R = 100 g.cm^{-2}$ and $B = 3.5 \times 10^5 T$ respectively. The obtained results show that in the estimated optimal surface density conditions, applying a magnetic field reduces the temperature of electrons in the degenerate plasma by fifty percent of classical plasma state. This decrease in temperature and the creation of degenerate conditions leads to a decrease in the dissipated bremsstrahlung power of the plasma environment. Also, it is shown that the plasma temperature anisotropy in partial degenerate plasma conditions causes decreases 65 percent in the electron's temperature of plasma. Furthermore, it is shown that under completely degeneracy conditions, temperature anisotropy will not play an effective role in the ignition conditions of the deuterium-helium-3 fuel pellet due to plasma degeneracy.

Keywords: Magneto-Inertial Fusion, Degenerate Plasma, Temperature Anisotropy, Deuterium-Helium-3 Fuel, Surface density Fuel.

1 Introduction

In order to population growth rate, one of the fundamental problems todays, is the need for new energy sources. Nuclear fission and fusion processes can be considered as new sources of energy. Compared to developed fission reactors, nuclear fusion energy in order to particular importance as a preferred method indeed of economic, environment and safety features [1].

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In most study Deuterium-Tritium fuel (D-T) is used as main fuel reaction for fusion reactors. Among of all usable fuels in fusion reactors, $(D-^{3}He)$ fuel has the most reactivity at lowest temperature. Reasons that have made researchers interested in studying advanced fusion fuels include: Deuterium-Helium-3, $(D-^{3}He)$, Proton-Boron-11, $(P-^{11}B)$, instead of D-T fuel is duo to the absence of tritium as a radioactive fuel, not any requirement to tritium production and its problems caused by 14.1MeV neutrons. Also, the neutrons produced from this reaction carry 80% of the fusion energy, which causes radioactivity and neutron damage to the reactor structural materials [2]. The $(D-^{3}He)$ aneutronic reaction is usually considered as a solution to overcome these problems. Also, in $(D-^{3}He)$ reaction, neutrons are not released directly, rather they arise in the side channels. $(D-^{3}He)$ fuel compared to D-T fuel has less reactivity rate and also, according to the reactivity diagram, it ignites in the temperature range of 100keV that in this temperature, energy loss through thermal conduction and bremsstrahlung power processes is very significant [2,3].

The Magnetic Target Fusion (MTF), which is also known as Magnetic-Inertial Fusion (MIF) [4], that's as Inertial Confinement Fusion (ICF) reagent using an additional external magnetic field. It can also be said that MIF is a better approach to fusion that combines the compressive heating of Inertial Confinement Fusion (ICF) with the reduced heat transfer of Magnetic Confinement Fusion (MCF) [5,6]. MIF in comparison with MCF has higher ionic density and shorter confinement time, and compressive heating as the dominant heating mechanism, which effectively reduces the impact of magnetic field-induced instabilities. Compared to ICF, magnetic thermal transfer, density reduced and alpha particle deposition in MIF increased so leads to a multi-order reduction of required surface density and causes significant reduction in internal detonation velocity required and radial convergence which Potentially reduces the harmful effects of internal hydrodynamic instabilities of explosion. As expected, MIF is a two-step process: the first stage, the formation of magnetic plasma or within an impervious shell with higher density (it means a kind of liner or presser) or outside the shell, in which case the preformed magnetic plasma must be injected into the shell; the second stage, is shell explosion. The first stage is similar to the MCF process, with important differences, including the preformed plasma does not need to reach fusion temperature and it doesn't have to be magnetically enclosed. The second stage is more similar to the ICF process, but important differences, including higher energy drivers are available [7].

Lidemuth and Siemon investigated controlled thermonuclear fusion parameter space from fundamental view and demonstrated that fuel density in MCF in first level by MCF target is determined by steady state, while that fuel density in ICF is primarily determined by the driver constraints and usage of non-magnetic fuel [8]. They also showed that by reducing these constraints, the potential of fusion operating space can be greatly expanded and the lower energy requirements of magnetic targets compared to MCF and the lower heating power of magnetic targets compared to ICF potentially result in lowing the construction costs. The potential to achieve significant fusion efficiencies with relatively inexpensive short-duration internal detonation drivers remains the primary motivation for pursuing MIF [7]. Lidemuth and Siemon provided a starting point for researchers and those interested in the topic of MIF and also in Reference 7 refers to some articles that have examined this issue.

In this paper, first, in section 2 the degeneracy and temperature anisotropy parameters are introduced in $(D-^{3}He)$ fuel pellet plasma, then in section 3 by introducing the production and loss powers density in a degenerate plasma in the MIF mode, the ignition criterion for $(D-^{3}He)$ fuel is calculated. And also, in Section 4, the effect of the magnetic field, the degeneracy parameter and the temperature anisotropy on the surface density are discussed, and in Section 5, the results obtained from the calculations are presented.

2 Investigation of Degeneracy and Temperature Anisotropy Conditions in Fuel Pellet Plasma

2.1 Degeneracy Conditions of Fuel Pellet Plasma

In quantum mechanics, when conditions of relatively low temperature and high density dominated on the environment, the study of the gaseous behavior of electrons is introduced as an important problem. In this case, because the electrons are compressed much more than a de Broglie wavelength, the number of accessible quantum states is limited. As a result, electrons behave similarly to a degenerate electron gas by following Fermi-Dirac distribution function. This means that when the energy states are full, not anymore electrons be added to this state and must be added on higher states [9].

$$n(\varepsilon) \sim \frac{1}{\exp\left[{(\varepsilon-\mu)}/{KT}\right]+1}$$

ε_f represents the Fermi energy and is called the energy of the highest filled state, which can be calculated from the following [9]

$$\varepsilon_f = \frac{1}{8}\frac{h^2}{m_e}\left(\frac{3n_e}{\pi}\right)^{\frac{2}{3}} = 2.19\times 10^{-15} {n_e}^{\frac{2}{3}}\,[eV],$$

n_e and m_e represent the number and mass density of electrons. The Fermi degeneracy condition is expressed by comparison of the thermal energy with the Fermi energy and the electron degeneracy parameter also is introduced as follows

$$\eta = \frac{\varepsilon_f}{K_B T_B}. \tag{1}$$

Which k_B and T_e represents the Boltzmann constant and the electron temperature, respectively. If $\eta \succ 1$, the plasma is said to be in a partially degenerate state, and when $\eta \gg 1$, the plasma is considered to be completely degenerate [9].

2.2 Temperature Anisotropy Conditions of Fuel Pellet Plasma

As mentioned in the previous section, the second stage of MIF is much similar to ICF. Fast ignition is recognized as a diverse and high-yield method for advancing ICF concepts. In the fast ignition method, hot electrons produced by the laser-fuel interaction provided the power density required to ignite the fuel pellet. Electron beams are produced at critical density levels by the Ponderomotive force. The Ponderomotive force creates a shock wave as an igniter for the pre-compressed fuel in the context of fast ignition. The fuel plasma exerts a high pressure on the surrounding material, leading formation of an intense shock wave and temperature anisotropy that travels into the fuel pellet. The Ponderomotive force is associated with the intense electromagnetic laser beam fields that emitted from the fusion fuel. Then, a large magnetic field as order of 10^8G is generated. The attendance of temperature anisotropy or momentum space anisotropy, anisotropic distribution functions in velocity region may give rise electromagnetic instabilities, including Weibel instability in the fuel pellet plasma environment [9–14].

Weibel instability in most environments in Astrophysical and space plasmas and also laboratory plasmas are widespread [14–18]. For the asymmetric angular distribution function around the z-axis, which is considered to be the temperature parallel axis to the electrons

$(T_{ez} = T_{e\|})$. The vertical temperature of the electrons is also chosen to be proportional to the $x - y$ plane. When the vertical temperature of the electrons is greater than the parallel temperature of the electrons, $(T_\perp \rangle T_\|$ or $T_{e\perp} \rangle T_{e\|})$ causes electromagnetic instability. These instabilities propagate electromagnetic waves along the magnetic field [19]. These conditions also lead to 'mirror' instability in the fuel plasma [21]. In condition that take place the fire hose instability $(T_\| \rangle T_\perp)$ and produces waves along the parallel temperature of the electrons, which pushes the distribution to a more isotropic temperature [22]. The ignition conditions of the fuel plasma and the deposition of radiation energy in fuel plasma can be influenced by these instabilities and anisotropic temperature. In this study, $D -^3 He$ fuel combustion conditions will be investigated despite of temperature anisotropy and the state that electron and ion temperatures are not equal. By interaction of laser pulse and the fuel pellet, the fuel plasma is heated only in the velocity dimension along the direction of wave propagation which causes temperature anisotropy of electron distribution. A shock wave is created by the laser beam in the fuel with different ion and electron temperatures. Electron temperature Anisotropic parameter is demonstrated by $(\beta = \frac{T_\perp}{T_\|})$ that in this case $(T_e = T_\perp^{\frac{2}{3}} T_\|^{\frac{1}{3}})$ can be written as follow [24]

$$T_e = \beta^{\frac{2}{3}} T_\|. \tag{2}$$

Therefore, in all calculations, Eq. (2) will be used for the electron temperature.

3 $D -^3 He$ Fuel Pellet Hot Spot Ignition Criterion in the MIF Method

The main reaction the ignition of $D -^3 He$ fuel pellet is

$$\mathrm{D} + {}^3\mathrm{He} \rightarrow \alpha(3.6\mathrm{MeV}) + \mathrm{P}(14.7\mathrm{MeV}).$$

Duo to high reactivity of D-T and D-D in comparison with reactivity of $D -^3 He$, all three reactions are considered as side reaction

$$\begin{aligned} &\mathrm{D} + \mathrm{T} \rightarrow \alpha(3.5\mathrm{MeV}) + \mathrm{n}(14.1\mathrm{MeV}), \\ &\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}(1.01\mathrm{MeV}) + \mathrm{P}(3.02\mathrm{MeV}), \\ &\mathrm{D} + \mathrm{D} \rightarrow \mathrm{n}(2.45\mathrm{MeV}) + {}^3\mathrm{He}.(0.82\mathrm{MeV}) \end{aligned}$$

Of course, there are other side reactions that are neglected because they have very small fusion cross sections. By calculating the production and loss powers density, the ignition condition for $(D -^3 He)$ fuel pellet can be calculated under MIF conditions as follows [25]

$$W_f - W_{loss} \geq 0, \tag{3}$$

where W_f represent the fusion power density. loss powers density consisting of bremsstrahlung power density, mechanical work, thermal conduction of electrons and cyclotron radiation. The fusion power density for a $D -^3 He$ fuel pellet is given by [25]

$$W_f[\mathrm{erg\,cm^{-3}\,s^{-1}}] = n_D n_{^3\mathrm{He}} \langle\sigma\nu\rangle_{D^3\mathrm{He}} E, \tag{4}$$

where (n_D) and $(n_{3_{He}})$ represent the number densities of Deuterium and $Helium - 3$, E, Fusion energy indicator, respectively. $\langle\sigma v\rangle_{D^3He}$ represents the reactivity of the $D -^3 He$

reaction that in temperature range $(0.5keV \leq T_i \leq 190keV)$ is defined by below [26]

$$\langle \sigma v \rangle_{D^3He}\left(\frac{cm^3}{s}\right) = 151.16 \times 10^{-16} \varsigma^{-\frac{5}{6}} \xi^2 \exp\left(-3\varsigma^{\frac{1}{3}}\xi\right),$$
$$\varsigma = -\frac{6.4192\times10^{-3}T_i - 0.019108\times10^{-3}T_i^2}{1-2.0290\times10^{-3}T_i + 0.13578\times10^{-3}T_i^2}, \quad (5)$$
$$\xi = \frac{10.572}{T_i^{\frac{1}{3}}}.$$

The bremsstrahlung process is one of the most important energy loss mechanisms. In this process, when an electron passes near by a heavy nucleus, it is deflected from path and then accelerated by the electromagnetic force generated by the heavy nucleus. According to quantum mechanical theory, accelerated electrons lose some of their kinetic energy by emitting photons, thereby reducing the plasma temperature. The bremsstrahlung power density can be expressed as follows [9]

$$W_B[\mathrm{erg\,cm^{-3}\,s^{-1}}] = K(\beta^{2/3}T_\parallel)^{1/2} n_e^2 \bar{Z} F_1(\eta), \quad (6)$$

in which

$$K = \left(\frac{256\pi^3}{3\sqrt{3}}\right)\left(\frac{1}{4\pi\varepsilon_0}\right)^3 \frac{Z^2 e^6 n_i}{h^3 c^3}. \quad (7)$$

The pressure generated by fusion reactions during the pellet burning causes the expansion of pellet. It can be concluded that part of this energy is lost due to mechanical expansion. The mechanical work density of ion and electron in the degenerate state can be presented as follows [9]

$$W_{me}\left(\frac{erg}{cm^3 s}\right) = \frac{4\pi c_s R^2 n_e K_B \beta^{\frac{2}{3}} T_\parallel}{V},$$
$$W_{mi}\left(\frac{erg}{cm^3 s}\right) = \frac{4\pi c_s R^2 n_i K_B T_i}{V}, \quad (8)$$

in which $\gamma = 5/3$, C_s denotes the speed of sound and P represent the pressure indicators are introduced as follows [9]

$$C_s = \sqrt{\frac{\gamma p}{\rho}},$$
$$p = \frac{n_e K_B \beta^{\frac{2}{3}} T_\parallel + \sum_i n_i K_B T_i}{V}. \quad (9)$$

In (Eq. (9)), ρ and V are the density and volume of the fuel pellet, respectively. The thermal conductivity power density of electrons is introduced as follows [9]

$$W_{he}(\mathrm{erg\,cm^{-3}\,s^{-1}}) = 3A_e \frac{(\beta^{2/3}T_\parallel)^{7/2}}{R^2 \log\Lambda Z_i(1+3.3Z_i)}. \quad (10)$$

That $A_e = 5.529 \times 10^{28}\left(keV^{-\frac{5}{2}} cm^{-1} s^{-1}\right)$, $\log\Lambda$ is the representative of the Coulomb logarithm in the degeneracy plasma.

$$\log\Lambda = \log\left[0.1718 n_e^{-\frac{1}{3}} \rho_c\right],$$
$$\rho_c = \frac{Z_i Z_j e^2}{2E_\alpha}. \quad (11)$$

The subscripts i and j indicate the type of ions. By applying an external magnetic field, plasma electrons and ions are limited to a specific frequency range called the cyclotron frequency, which means that the plasma is confined to very high temperatures. For electrons with a Maxwellian velocity distribution, the cyclotron radiation power can be obtained by the following [27]

$$W_{cy}[\mathrm{erg\,cm^{-3}\,s^{-1}}] = \frac{4e^4 k_B}{3m_e^3 c^5} B^2 n_e \beta^{2/3} T_{\parallel}. \tag{12}$$

B represents the intensity of the magnetic field in which electrons are spinning. In this case assumed that the kinetic pressure of the plasma is equal to the applied magnetics pressure. Therefore [16]

$$\frac{B^2}{8\pi} = n_i K_B T_i + n_e K_B \beta^{\frac{2}{3}} T_{\parallel}. \tag{13}$$

4 Analysis and Discussions of the Obtained Results

In order to investigate the parameters affecting the ignition conditions, it is necessary, the relation of ignition conditions (Eq. (3)) should be solved by introducing the production and loss powers in the previous section. To investigate the electrons temperature changes in terms of the environment ions temperature for different surface densities, first, the magnetic field intensity has been estimated to be about $3.5\times10^5 T$ for optimal ignition of the $D-^3He$ fuel core as result of Eq. (13) under fuel degenerate conditions.

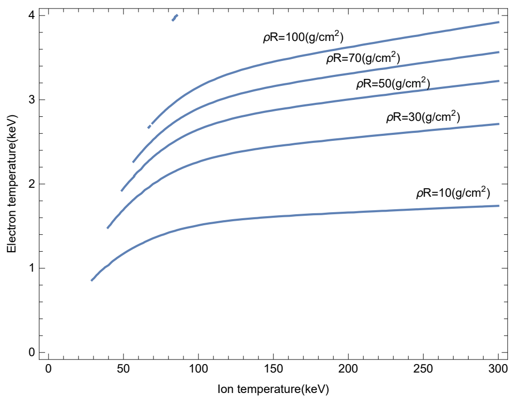

Figure 1: Variation of the confinement parameter, ρR, with respect to ions and electrons temperature for $(D-^3He)$ fuel in MIF.

As shown in the Figure (1) with increasing surface density of $\rho R = 10\,\mathrm{g\,cm^{-2}}$ to $\rho R = 100\,\mathrm{g\,cm^{-2}}$ for ionic temperature $100keV$ fuel pellet environment electrons temperature changes in the range $(1.3-3.4)keV$. However, by increasing the surface density to $\rho R = 100\,\mathrm{g\,cm^{-2}}$, the electrons temperature will not change much in the range of $100keV$ ions temperature. Therefore, by determining the surface density of the fuel pellet, $\rho R = 100\,\mathrm{g\,cm^{-2}}$, can be estimated the values for density and radius of the hot spot.

Figure (2) shows the variation of electrons temperature as function of ions temperature at surface density, $\rho R = 100\,\mathrm{g\,cm^{-2}}$, of $D-^3He$ fuel pellet for different strength of magnetic field. It is observed that for magnetic field strengths in the range of $10^4 T$ and below, the electronic temperature varies in the range of $6keV$. By increasing of magnetic fields intensity to $3.5\times10^5 T$, electrons temperature in ionic temperature range of $100keV$ reaches to $3.4keV$

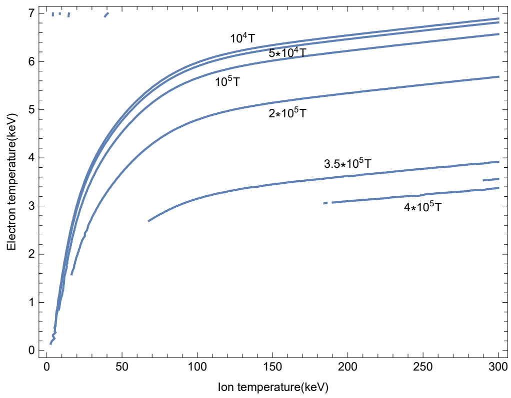

Figure 2: Variation of electrons temperature based on ions temperature with surface density $\rho R = 100\frac{g}{cm^2}$ of $(D -^3 He)$ fuel in MIF mode for different magnetic field.

as shown in Figure (1). By increasing the magnetic field intensity to $4 \times 10^5 T$ provides ignition condition for $D -^3 He$ fuel at ion temperatures greater than 180keV. Therefore, more energy must be spent for fuel ignition. So, the appropriate magnetic field intensity for fuel pellet ignition is estimated about $3.5 \times 10^5 T$.

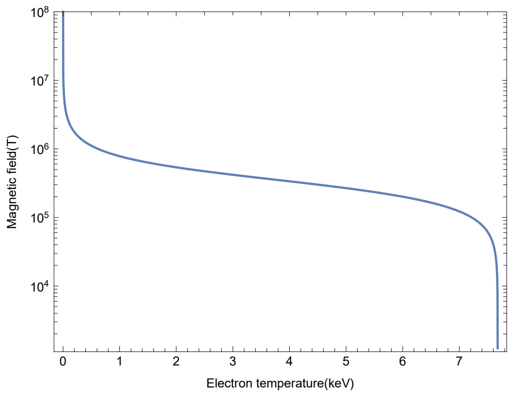

Figure 3: Variation of electrons temperature as a function of magnetic field.

In the following, by choosing the surface density value, $\rho R = 100\,\mathrm{g\,cm^{-2}}$, and the ionic temperature, $100keV$, the variation of electron temperature verse to magnetic field intensity can be obtained by using Eq. (3). It can be seen in Figure (3) that when the magnetic field intensity increases from $10^3 T$ to $10^5 T$, the electron temperature has not significantly changed. It is also observed that with increasing magnetic field intensity up to $10^6 T$ the electron temperature decreases sharply, so that with increasing magnetic field intensity from $10^6 T$ to $10^8 T$ the electronic temperature has not considerably changes and reaches a minimum value.

By introducing the electron degeneracy parameter (Eq. (1)), the variation of electrons temperature in terms of degenerate parameter are shown in Figure (4). As can be seen, the Fermi energy obtained from this relationship is $3.4keV$. Therefore, as shown in Figs. ((1) and (2)), the electrons temperature is in the Fermi energy range and also the plasma is in a partially degenerate state. It is observed that with increasing the degeneracy param-

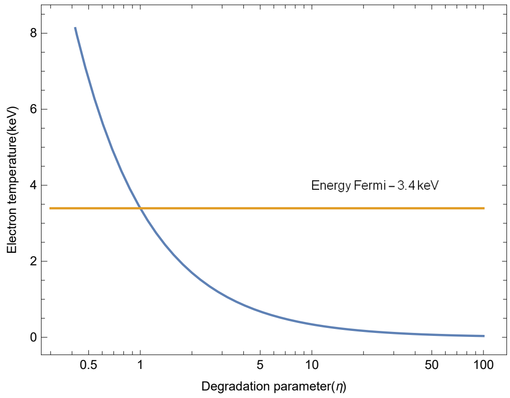

Figure 4: Changes in electrons temperature based on the degenerate parameter.

eter, the electrons temperature decreases, and when this parameter increases to more than 10 times, the electrons temperature does not significantly change, as result increasing in degeneracy parameter, involves decrease in electrons temperature and creates conditions of plasma environment degeneration. As the degeneracy parameter decreases and the electrons temperature increases, the properties of the degeneracy plasma tend to the classical state.

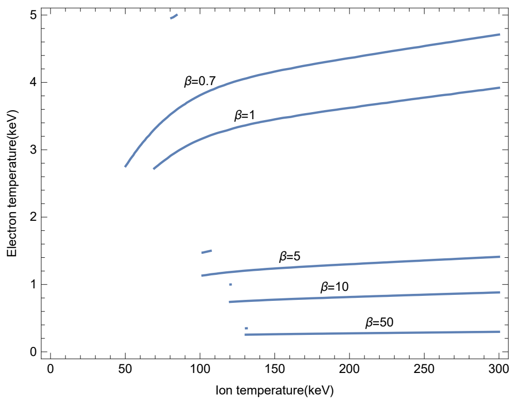

Figure 5: Variation of electrons temperature based on ions temperature with surface density $\rho R = 100\frac{g}{cm^2}$ of $(D -^3 He)$ fuel in MIF mode in the partially degenerate state $(\eta \approx 1)$ for different of the temperature anisotropy parameter.

In order to investigate of thermal anisotropy parameter effect on the ignition conditions of the $D -^3 He$ fuel pellet, the electron-ion temperature changes are presented in Figure (5) in the partial degenerate plasma conditions. It has been demonstrated in Figure (5) that partially degenerate plasma state $(\eta \approx 1)$ while value of the temperature anisotropy parameter is less than 1, the electrons temperature has increased and this increasing leads to plasma generation. So, by increasing of temperature anisotropy, electrons temperature extremely decreases in order to for $\beta = 50$ electronic temperature decrease to 1.2keV.

Figure (6) shows the electrons temperature changes for the degenerate and fully degenerate plasma. It is observed that in the case of plasma degenerate $(\eta \approx 10)$ by increasing temperature anisotropic parameter from 0.7 to 5, electrons temperature has not significantly change and electrons temperature can be considered constant in this range. But

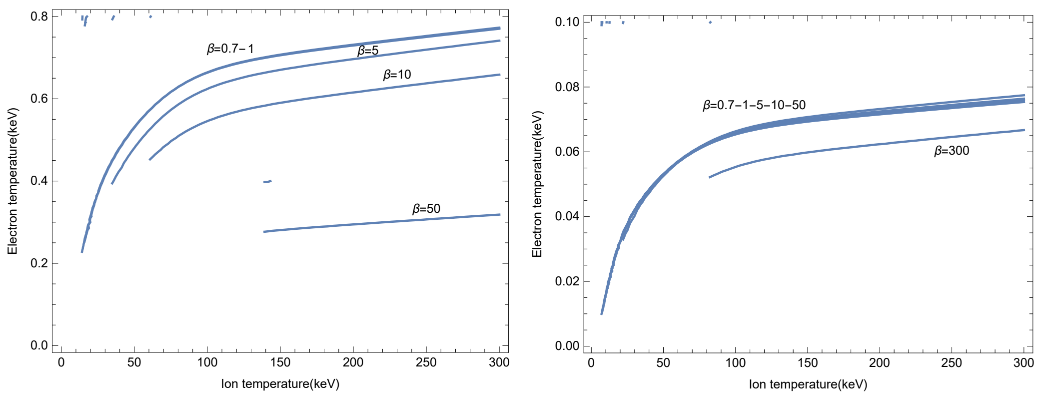

Figure 6: *Variation of electrons temperature based on ions temperature with surface density* $\rho R = 100\frac{g}{cm^2}$ *of* $(D -^3 He)$ *fuel in MIF mode in the partially degenerate state (a)* $(\eta \approx 10)$ *and completely degenerate (b)* $(\eta \approx 100)$ *for different of the temperature anisotropy parameters.*

gradually, as the temperature anisotropy parameter increases, it is observed that the electrons temperature decreases and for $\beta = 50$ decrease to its lowest, that is reaches 0.3keV. It is further observed that in the case of a completely degenerate plasma $(\eta \approx 100)$ variations of electrons temperature per temperature anisotropy parameter from 0.7 to 50 have not significantly change, in other words, in a completely degenerate plasma, the temperature anisotropy will not play an effective role in the ignition conditions of the $D -^3 He$ fuel pellet.

5 Conclusion

Today, effective methods are used to improve fuel plasma ignition conditions. One of these methods, which was discussed in detail in this paper, is the MIF process. It has been shown that degenerate and temperature anisotropy parameters can improve the performance in obtaining ignition conditions. It has been shown that by applying a magnetic field as order of $10^5 T$ to$D -^3 He$ fuel pellet reduces the electrons temperature up to 50% . However, by increasing in the magnetic field beyond $3.5 \times 10^5 T$, the plasma ignition conditions are not accessible and ignition conditions require higher ionic temperatures, as a result, higher costs for design and construction. Obtained results are concordance with reference (25), hence it can be concluded that by applying a magnetic field to the fuel pellet, the ignition temperature is reduced compared to the ICF state. When the plasma be in partially degenerate state $(\eta \approx 1)$, by applying and increasing the temperature anisotropy parameter, we will see a 65% decrease in electrons temperature (1.2keV range). For a temperature anisotropy parameter less than 1 for example, $\beta = 0.7$, the electron temperature increases by 20% to about $4KeV$ and the plasma behavior approaches the classical state. It has been shown that by increasing the degenerate parameter, the effects of the temperature anisotropy parameter for$(\eta \approx 10)$ in $\beta \langle 50$ and for $(\eta \approx 100)$ $\beta \langle 300$ values can be ignored and the electrons temperature will not change significantly, so that in completely degenerate plasma conditions, the temperature anisotropy values will not play an effective role in the ignition conditions of the $D -^3 He$ pellet. Also, comparing to reference (4 and 24), its perception that the degeneracy and temperature anisotropy parameters can have significant effects on reducing the electrons temperature.

Authors' Contributions

All authors have the same contribution.

Data Availability

No data available.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Ethical Considerations

The authors have diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

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