Proton-boron-11 fusion under Effect of the Temperature Turbulence

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Abstract

The temperature turbulence generated by the ponderomotive force of the high-power laser can significantly modify P-11B fusion reactivity. The results of this study have shown that higher temperature turbulence leads to an increased requirement for the confinement parameter in P-11B fuel. As a result, achieving ignition necessitates greater driver energy and a longer development time. Additionally, a 50% reduction in the temperature turbulence parameter yields a substantial 71% decrease in the confinement parameter, accompanied by a 21% increase in the maximum fusion energy fraction. When the temperature turbulence exceeds a value of 10, the bremsstrahlung surpasses the fusion power, making ignition unattainable. The findings underscore the importance of maintaining temperature turbulence below 1 to approach the ignition conditions required for P-11B fuel.

Keywords: Confinement parameter; Ignition condition; P-11B fuel; Temperature turbulence.

1. Introduction

In fusion energy research, mixtures of hydrogen isotopes (such as deuterium and tritium) with other elements like helium, lithium, and boron are indeed referred to as advanced fusion fuels. These alternative fuel combinations are being explored as potential options for achieving controlled nuclear fusion, which holds the promise of providing abundant and clean energy [1,2].

The Gamow energy represents the energy at which nuclear reactions are most likely to occur, determined by the Coulomb barrier that charged nuclei must overcome to fuse [3]. The reaction cross section measures the probability of a specific interaction occurring between particles, often expressed in units of area (e.g., barns). This measure reflects how effectively particles can collide and react. The reaction cross section is influenced by the tunneling probability, which is related to the Gamow factor.

The D-T fusion reaction has a relatively low Gamow energy, around 17.6 MeV. This low Gamow makes it more favorable for achieving fusion at lower temperatures (around 100 million Kelvin). The D-T reaction is often considered the most promising for current fusion research due to its high reaction rate and energy yield. Advanced fusion fuels, such as deuterium-helium-3 (D-3He) and proton-boron (p-B), typically have higher Gamow energies compared to the deuterium-tritium (D-T) fuel combination [4]. The D-3He reaction has Gamow energy of about 20 MeV, while p-B fusion can have even higher Gamow energies (around 60 MeV).

Higher Gamow energies indicate that particles must overcome a greater Coulomb barrier, which necessitates higher temperatures and pressures for successful fusion. This makes achieving the necessary conditions for fusion more challenging, as higher temperatures are required to reach the threshold energy for effective reactions. As a result, fewer reactions will occur unless the kinetic energy of the particles is significantly increased. Conversely, a lower Gamow energy allows nuclei to fuse at lower energies, leading to a higher reaction cross-section at those energy levels. This makes fusion more likely under achievable conditions. Attaining a significant fusion reaction rate with advanced fuels requires higher temperatures compared to deuterium-tritium (D-T) fuel. Higher Gamow energies necessitate operating at much higher temperatures, which poses additional engineering and material challenges. Understanding the dynamics of Gamow energy and reaction cross sections is crucial for the development of future fusion reactors. While requiring higher conditions, advanced fusion fuels can offer benefits such as cleaner fusion products (like helium from D-He3) and reduced neutron activation (as in p-B fusion), which can lead to less radioactivity in reactor materials.

Among these advanced fuels, the fusion reaction between protons (hydrogen nuclei) and boron-11 (11B) nuclei is particularly promising for controlled fusion energy generation. One of the key advantages of the proton-boron fusion reaction is that it produces no neutrons as direct by-products, which mitigates issues related to neutron activation of materials and radioactive waste. This reaction releases energy in the form of kinetic energy of the reaction products, with a total energy release of approximately 8.9 MeV (million electron volts) per reaction. The reaction channel can be represented as: $p+^{11}B \rightarrow 3\alpha+8.9$ MeV. The production of charged particles, such as helium nuclei, instead of neutrons offers several benefits. Charged particles can be more easily controlled, and their energy can be directly converted into electricity through mechanisms like direct energy conversion or traditional thermal cycles. This method allows for the direct transformation of the kinetic energy of charged particles into electricity, eliminating the traditionally costly process of generating heat to produce steam for driving turbines and generators. By directly harnessing this kinetic energy, we can enhance efficiency and reduce costs associated with energy conversion in fusion systems.

Ultimately, this approach has the potential to streamline energy production and make fusion a more viable option for sustainable electricity generation. Thus, the proton-boron fusion reaction stands out as a compelling candidate for future fusion energy applications, contributing to the development of cleaner and more efficient energy solutions.

To initiate and sustain p-B fusion, high temperatures of ions exceeding 200 keV (or 2.2 billion Kelvin) are required [5, 6]. These high temperatures of the protons and boron nuclei, allow them to approach closely enough for fusion to occur. The need for high ion temperatures in p-B fusion poses challenges in terms of plasma heating, confinement, and overall system design. Researchers are actively exploring different approaches and technologies to achieve and maintain the required ion temperatures in order to harness the potential of p-B fusion as a viable energy source. Achieving self-burning conditions in p-B fusion is indeed challenging due to the high temperatures required and the potential power losses from bremsstrahlung [7]. In cases where the ion temperature is greater than the electron temperature, there is potential to achieve ignition using aneutronic fuel. For the possibility of self-sustaining fusion, the electron temperature needs to be around 100 keV [8]. However, the optimal regimes for Proton-Boron reactions are characterized by an electron temperature that is much lower than the 80 keV suggested by Eliezer and Martinez-Val [9].

P-B fusion requires extremely high temperatures to create the necessary conditions for reaction. Developing materials and technologies that can withstand and operate efficiently at these temperatures is critical. Boron, being abundant and less radioactive than other fusion fuels, enhances its appeal. However, the extraction and preparation of boron fuel in a cost-effective manner need further exploration. While p-B fusion has the potential for a high energy yield, practical implementations must ensure that the energy generated exceeds the energy input. Achieving breakeven or ignition is essential for practical use.

One significant challenge is that p-B fusion is not self-sustaining like other fusion processes (e.g., deuterium-tritium), necessitating continuous energy input to maintain the reaction. Research into hybrid systems or advanced magnetic confinement methods could help address this issue. Advancements in plasma confinement, heating methods (such as laser or electromagnetic heating), and reactor design are vital for achieving practical p-B fusion. Innovative engineering approaches could pave the way for more efficient systems. Additionally, the cost of constructing and operating p-B fusion reactors must be competitive with other energy sources. Economic assessments and pilot projects could clarify feasibility.

While the challenges of using advanced p-B fusion fuel are significant, targeted engineering solutions, ongoing research, and a focus on economic viability can enhance its practical usability in future fusion reactors. Several theoretical attempts have been made to use P-11B fuel for inertial confinement fusion (ICF) and explore its potential for clean and sustainable energy generation. In a study by S. Eliezer and J.M. Martinez-Val [10], they proposed inducing P-11B fusion reactions by a heat-detonation wave expanding across a compressed target. The study concludes that the burning wave can propagate only if a significant portion of radiation losses from the already burning fuel is reabsorbed in the colder fuel. The paper by P. Lalousis et al. published in 2015[11], discusses the utilization of kilo-tesla magnetic fields and ultrahigh laser acceleration for achieving high gain boron-11 fusion with protons, offering improved performance for ICF.

The paper by H. Hora et al., published in 2017, outlines a roadmap based on recent experiments and simulations for utilizing P-11B fusion as an alternative to the traditional DT fusion option [12].The study presented by B. Chen et al.at the APS Division of Plasma Physics Meeting in 2019 explored the necessary conditions and parameters for operating a P-11B fusion reactor. It highlights that the substantial radiation loss caused by electron bremsstrahlung presents a significant challenge in achieving net power generation in thermalized P-11B plasmas [13]. In a paper by S. Eliezer and J.M. Martinez-Val, published in 2020, a novel concept of a nuclear reactor with chain reactions for proton boron-11 is proposed [14]. The proposed reactor design utilizes a combination of plasma generation and laser-driven shock waves to facilitate nuclear fusion reactions. The process involves creating background plasma composed of boron-11 and hydrogen ions with free electrons. A high-power laser is then used to initiate a plasma channel within a solid target, generating an intense shock wave that propels protons towards the boron-11 ions. This results in the production of alpha particles through collisions. The system is designed to sustain a chain reaction process by employing an induction current and a magnetic confinement system.

In a separate publication by S. Eliezer et al., the research entails a proton beam traveling at a velocity of approximately 109 cm/s interacting with a charge-neutral hydrogen-boron medium such as 11B[15]. The charged particles resulting from this process are confined by magnetic fields. The fusion process commences with protons, initiating a chain reaction in a neutral medium with a density around 10^{19}cm^{-3}, where the alpha particles generated by P-11B fusion heat the system to about one electron volt. Radiation losses due to bremsstrahlung are minimal in this system, and the thermal pressure of the plasma remains low. The paper introduces a novel concept that emphasizes fundamental physical processes rather than providing a detailed engineering design. The innovative configuration for mitigating stopping power and the presented numerical solutions show potential for various applications involving feasible P-11B fusion reactions. On the other hand, the paper by H. Hora et al. in 2021 emphasizes the significance of low carbon energy generation and the mitigation of secondary neutrons in laser proton-boron fusion processes [16]. The paper presents a method that involves the use of tin to mitigate the production of secondary neutrons. In this method, tin is employed to undergo nuclear reactions with the neutrons present in the system.

Fast ignition is indeed recognized as a high-gain approach that can enhance conventional Inertial Confinement Fusion (ICF) concepts. In the Fast Ignition scheme, the process of achieving ignition is divided into two key steps: compression and ignition [17]. In Fast Ignition schemes, the ponderomotive force plays a crucial role in producing electron beams at the critical density surface. When an intense laser pulse interacts with the plasma, it generates an electromagnetic field that exerts a ponderomotive force on the electrons. This force drives the electrons away from the regions of high field amplitude, resulting in the formation of electron beams. These electron beams can then propagate through the fuel plasma, carrying energy and depositing it in the interior of the target. This energy deposition is essential for initiating the fusion reactions and achieving ignition. The ponderomotive force provides a means to efficiently transport energy to the fuel core. Additionally, the ponderomotive force can create a shock wave in the pre-compressed fuel, acting as an igniter. The intense laser pulse can produce a high-pressure plasma region, which generates a shock wave that propagates into the compressed fuel. This shock wave helps to further compress and heat the fuel, aiding in the ignition process. This shock wave enhances the compression and heating of the fuel, contributing to the overall ignition process. Furthermore, the ponderomotive force can induce temperature turbulence within the fuel pellet. The interaction between the intense laser pulse and the fuel plasma can result in a preferential heating of electrons in certain directions, leading to a temperature difference within the plasma.

The electron's perpendicular temperature refers to the temperature dispersion in the direction perpendicular to the propagation direction in plasma. This parameter is crucial in fusion research, particularly in the context of plasma stability and confinement. When the perpendicular temperature is higher than the parallel temperature, it can create turbulence, affecting the overall stability of the plasma. A significant difference between the parallel and perpendicular temperatures can lead to instabilities within the plasma. Turbulence can facilitate energy transfer within the plasma, impacting heating efficiency and overall performance. This turbulence can affect the dynamics and behavior of the plasma, influencing the ignition process and leading to induced instabilities [18, 19]. An electromagnetic instability known as the Weibel instability occurs when the electron's temperature perpendicular to the magnetic field exceeds its temperature parallel to the field. This instability leads to the generation of electromagnetic waves that travel along the magnetic field, helping to restore isotropy in phase space [20-22].

If the perpendicular electron temperature is not well-controlled, it may lead to increased energy losses, hindering the conditions necessary for sustainable fusion reactions. To effectively control temperature turbulence in plasma, the density of the plasma must be controlled within optimal ranges. High-density plasmas can lead to increased collisional interactions, which may stabilize the plasma, while low-density conditions can result in greater turbulence. Non-uniform heating can lead to temperature gradients, exacerbating turbulence. Controlled heating profiles are essential to maintain a balanced temperature distribution. Understanding and defining stability thresholds for various plasma parameters (such as temperature, density, and pressure) is critical. These thresholds help identify conditions under which turbulence can be effectively controlled. The materials used in the reactor must withstand high temperatures and pressures without degrading. Assumptions include the availability of advanced materials that can maintain structural integrity under extreme conditions. By establishing these assumptions and conditions, researchers can better control temperature turbulence in plasma, enhancing the stability and efficiency of fusion reactions.

The presence of instabilities and temperature turbulence can indeed impact the energy deposition beams and the ignition conditions [23, 24]. Hydrodynamic and electromagnetic instabilities play significant roles in inertial confinement fusion (ICF), affecting the efficiency and stability of fusion reactions. Hydrodynamic instabilities, such as Rayleigh-Taylor and Kelvin-Helmholtz instabilities, can lead to the growth of perturbations during the implosion process, adversely affecting the symmetry of compression. This can result in inefficient energy deposition, thereby reducing the chances of achieving ignition. Electromagnetic instabilities can alter the energy transfer mechanisms within the plasma, impacting temperature gradients and pressure distributions, which are critical for achieving fusion conditions [25, 26]. These phenomena occur during the implosion, where a target is compressed to extreme densities and temperatures to initiate fusion reactions. Additionally, hydrodynamic and electromagnetic instabilities can interact, leading to complex behaviors in the plasma. For instance, the growth of hydrodynamic instabilities might enhance or dampen electromagnetic effects, further complicating the dynamics of the implosion. Temperature turbulence exacerbates these issues, impacting the efficiency of energy transfer and the overall performance of the fusion reaction.

Identifying and controlling these turbulence is essential for improving the efficiency and effectiveness of inertial fusion as a potential energy source. The specific effects of temperature turbulence on the confinement parameter value and fusion energy fraction of P-11B fuel have not been investigated. In this study, examining the role of temperature turbulence in the ignition process, we aim to gain insights that can contribute to advancing our understanding of fusion reactions involving P-11B fuel.

The ignition criterion of P-11B fuel

When a high-power laser pulse greater than 10^{21} W/cm^2 interacts with the P-11B fuel, the plasma of the fuel will be heated predominantly in the velocity dimension along the wave propagation direction, resulting in temperature turbulence of the electron distribution. The temperature of the electron, T_e, can be defined as a function of the temperature turbulence as $T_e = \beta^{2/3}T_{\parallel}$. When the internal heating produced by fusion products (alpha particle) exceeds all energy losses and no further external heating is necessary to keep the plasma in the burning state, thermonuclear ignition occurs. The fusion power density of P-11B reaction is [27]

$$W_f = n_p n_B \langle\sigma v\rangle_{P-11B} Q_a \sim 4.99\times10^{42}\frac{\varepsilon\rho^2\langle\sigma v\rangle_{P-11B}}{(1+11\varepsilon)^2}, \quad (1)$$

where ε is the ratio of boron to proton, the reactivity of the proton-Boron 11 reaction, $\langle\sigma v\rangle_{P-11B}$, is given by,

$$\langle\sigma v\rangle_{P-11B} = 5.41\times10^{-15}T_i^{-3/2}e^{-\frac{148}{T_i}} + \zeta^{-5/6}(44.735T_i^{-\frac{1}{3}})^2\, e^{-53.124\zeta^{1/3}T_i^{-\frac{1}{3}}}\, cm^3/s. \quad (2)$$

Here $\zeta = 1 - \frac{-0.0594T_i+0.0010T_i^2-9.1653\times10^{-6}T_i^3}{1+0.2017T_i+0.0028T_i^2+9.8305\times10^{-7}T_i^3}$.

The alpha energy is not entirely deposited into the igniter zone [28]. The fraction of energy deposited by alpha particles in the presence of temperature turbulence within the specified hot-spot can be estimated as

$$f_\alpha = \begin{cases} \frac{3}{2}\frac{R}{R_\alpha} - \frac{1}{5}\left(\frac{2R}{R_\alpha}\right)^2 & if \quad \frac{R}{R_\alpha} < \frac{1}{2} \\ 1 - \frac{1}{4\frac{R}{R_\alpha}} + \frac{1}{160\left(\frac{R}{R_\alpha}\right)^3} & if \quad \frac{R}{R_\alpha} \geq \frac{1}{2} \end{cases}. \quad (3)$$

The igniter dimension R is defined as as $R = (\frac{u_s}{c} - \frac{u_p}{c})c\tau_l$, where τ_l is the laser pulse duration, c is the speed of light, u_s is the shock velocity, and u_p is the particle velocity and from the Hugoniot-Rankine equations is obtained [29]. Also, the alpha range for P-11B in the presence of temperature turbulence is

$$R_\alpha(cm) = \begin{cases} \frac{0.25}{\rho}\left(\frac{1000\beta^{\frac{2}{3}}T_{\parallel}}{c}\right)^{0.79} & if \quad T_e < 50\, KeV \\ \frac{1.1}{\rho}\left(10\beta^{\frac{2}{3}}T_{\parallel}\right)^{0.31} & if \quad T_e \geq 50\, KeV \end{cases} \quad (4)$$

where ρ is the fuel density. The condition for achieving ignition can be expressed as the net energy gain being greater than or equal to zero. Mathematically, this can be written as:

$$W_f - \sum W_{losses} \geq 0. \quad (5)$$

Where $\sum W_{losses}$ is the total energy lost through various mechanisms. A quadratic inequality in the confinement parameter ρR is obtained as in the following

$$f_\alpha W_f - W_B - W_{he} - W_m \geq 0, \quad (6)$$

This equation represents the ignition criterion for the general case of inertial confinement fusion. The ignition criterion for P-11B fuel in inertial confinement fusion leads to a quadratic inequality in the areal density (ρR), which can be expressed as:

$$Y_{P-11B} \equiv A(\rho R)^2 + B(\rho R) + C \geq 0, \quad (7)$$

Where,

$$A = f_\alpha 4.99\times10^{42}\frac{\varepsilon\langle\sigma v\rangle_{P-11B}}{(1+11\varepsilon)^2} - 4.74\times10^{-24}n_e(n_p + 25n_B)(\beta^{2/3}T_{\parallel})^{\frac{1}{2}}\frac{1+2\beta^{2/3}T_{\parallel}}{0.511\times10^6},$$

$$B = -1.86\times10^{18}[(1+\varepsilon)T_i + (1+5\varepsilon)\beta^{\frac{2}{3}}T_{\parallel} + 1 + 11\varepsilon]^{3/2},$$

$$C = \frac{3.11\times10^9\left(\beta^{2/3}T_{\parallel}\right)^{7/2}}{ln\Lambda}.$$

This criterion defines a surface in 3D space using areal density (ρR), electron temperature (T_e), and ion temperature (T_i) for P-11B fuel. The equations for the time rate of change of specific quantities are provided as follows:

$$\frac{3}{2}\frac{d}{dt}(n_e k_B \beta^{\frac{2}{3}}T_{\parallel}) = \eta_d W_d + W_{ie} - W_B + f_\alpha \eta_f W_f, \quad (8)$$

and,

$$\frac{3}{2}\frac{d}{dt}(n_e k_B T_i) = (1-\eta_d)W_d - W_{ie} - W_B + f_\alpha(1-\eta_f)W_f, \quad (9)$$

These equations describe the energy balance and evolution of the system in terms of the ion and electron temperatures. Here, ne represents the electron density, k_B denotes Boltzmann's constant, W_d signifies the power density deposited by the driver (induced by the laser-plasma), η_d is fraction of the driver energy, W_{ie} is the ion-electron exchange power density, W_B corresponds to the bremsstrahlung power density, and W_f represents the fusion power density created in the shocking volume. The energy fraction deposited in the in the presence of temperature turbulence is given by

$$\eta_f = \frac{0.15}{0.15+\beta^{2/3}T_{\parallel}}. \quad (10)$$

The bremsstrahlung power density loss in the presence of temperature turbulence is given by

$$W_B = 4.74\times10^{-24}n_e(n_p + 25n_B)(\beta^{2/3}T_{\parallel})^{\frac{1}{2}}(\frac{1+2\beta^{2/3}T_{\parallel}}{0.511\times10^6}). \quad (11)$$

The mechanical expansion power loss in the presence of temperature turbulence is estimated by

$$W_m = 1.86\times10^{18}[\frac{(1+5\varepsilon)\beta^{2/3}T_{\parallel}+(1+\varepsilon)T_i}{(1+11\varepsilon)}]^{\frac{3}{2}}(\frac{\rho}{R}). \quad (12)$$

The ambient temperature is significantly lower than that of the fuel plasma. The thermal conduction loss in the presence of temperature turbulence from the igniter domain for P-11B fuel is given by,

$$W_{he} = \frac{3.11\times10^9\beta^{2/3}T_{\parallel}}{R^2 ln\Lambda}. \quad (13)$$

The NRL Plasma Formulary [30] suggests the following expressions for the coulomb logarithm,

$$ln\Lambda = \begin{cases} 30 - ln\sqrt{\frac{n_e}{T_e^3}} & if \quad T_e < 10eV \\ 31 - ln\left[\frac{\sqrt{n_e}}{T_e}\right] & if \quad T_e > 10eV \end{cases}. \quad (14)$$

The Coulomb logarithm for the temperature turbulence $T_\perp \neq T_\parallel$ can be given by

$$ln\Lambda = 31 - ln[\frac{n_e^{\frac{1}{2}}}{\beta^{2/3}T_\parallel}]. \quad (15)$$

The ion-electron exchange power density can be defined as:

$$W_{ei} = 2.70 \times 10^{-19} n_e \frac{T_i - \beta^{2/3}T_\parallel}{(1000\beta^{2/3}T_\parallel)^{\frac{3}{2}}} \sum_k \frac{Z_k^2 n_k}{m_k} ln\Lambda. \quad (16)$$

This expression describes the energy transfer dynamics between ions and electrons due to Coulomb collisions in fusion plasma. The deposition power density loss in the presence of temperature turbulence can be defined as:

$$W_d = \frac{I_L \kappa}{4\times10^3 \tau_L}. \quad (17)$$

Where I_L is the laser intensity, and $\kappa=\rho/\rho_0$ is the shock compression. This expression describes the relationship between the laser intensity, shock compression, temperature turbulence, and laser pulse duration in determining the deposition power density loss. Therefore, η_d can be estimated as follows:

$$\eta_d = \frac{\frac{3\times10^{23} m_p}{n_i m_i} E_i}{\frac{3\times10^{23} m_p}{n_i m_i} E_i + \frac{5\times10^{22}}{n_e ln\Lambda}(1000\beta^{2/3}T_\parallel)^{\frac{3}{2}}}, \quad (18)$$

where $E_i(MeV) = 1250\left(u_p/c\right)^2$. The confinement factor is influenced by various factors such as laser intensity, fuel density, and geometry. The rate of change of the number density of protons (n_p) and boron (n_B) with respect to time is given by

$$\frac{dn_p}{dt} = \frac{dn_B}{dt} = -n_p n_B \langle\sigma\, v\rangle_{P-11B}. \quad (19)$$

This equation indicates that the decrease in the number densities of protons and boron is proportional to the product of their densities ($n_p n_B$) and the reaction rate $\langle\sigma v\rangle_{P\text{-}11B}$ for the fusion of P-11B fuel. The temporal behavior of the alpha particle number density (n_α) throughout the fusion reaction process is described as follows:

$$\frac{dn_\alpha}{dt} = 3 n_p n_B \langle\sigma\, v\rangle_{P-11B}. \quad (20)$$

The equation indicates that the rate of change of the number density of alpha particles is proportional to three times the product of the number densities of protons and boron, as well as the reaction rate $\langle\sigma v\rangle_{P\text{-}11B}$. The confinement parameter, determined by the laser and fuel parameters, plays a crucial role in the overall efficiency and success of the fusion reaction in the shock fast ignition scheme. The solution of Eq. (7) with $f_\alpha=1$, $\ln\Lambda=3.5$, and $\varepsilon=0.33$ shows that the temperatures T_i and T_e fall within the range of 100-700 keV and 1-100 keV, respectively, for both $\beta<1$ and $\beta>1$, and for $\rho R<20$ g/cm^2.

Results and Discussions

The confinement factor is shown as a function of the ion and electron temperatures in Fig. 1. The temperature ranges where the confinement parameter is less than 20 are 100-700 keV for the ions and 10-90 keV for the electrons. It is noteworthy that without temperature turbulence ($\beta=1$) and for temperatures within the range of 1 keV < T_i < 360 keV and T_e < 10 keV, the confinement parameter is less than 1.5.

As shown in Fig. 2, by increasing β, the confinement parameter of less than 20 occurs in a lower range of the electron temperature and a higher range of the ion temperature. It is found that the confinement parameter significantly depends on the temperature turbulence of the P-11B fuel. As the temperature turbulence increases, a significant gap will be observed between T_e and T_i. It is clear that as β approaches infinity, the small ρR required for ignition tends to diminish. For a higher value of the temperature turbulence parameter ($\beta=100$), the values of ρR are around two orders of magnitude greater compared to a lower value ($\beta=10$). This necessitates a larger pre-compression and igniter size, as well as a larger energy laser, in order to achieve the required conditions for ignition. For different values of T_i, the ρR parameter of the P-11B fuel increases as the temperature turbulence, β, increases. The suitable T_i is typically above 150 keV. This value by increasing the temperature turbulence will increase which makes ignition more difficult.

By reducing the temperature turbulence parameter by a factor of 2, the confinement parameter is reduced by 71% (Fig. 3). The ignition criterion in terms of time has been investigated for different values of temperature turbulence in P-11B fuel. In Figure 4, it is observed that the product required for ignition will increase with increasing temperature turbulence. Increasing the temperature turbulence by a factor of 4 results in a roughly 30% increase in the confinement parameter. For $\beta=0.5$, this value is 5.3 g/cm2, while for $\beta=10$, it is 40 g/cm^2. As the pulse duration elapses, a greater proportion of the generated alpha particles escape the ignition region, transferring heat to the surrounding area. The variations of the fraction of absorbed α-particles in the hot spot over time for different values of the temperature turbulence are depicted in Fig. 5. As the temperature turbulence parameter increases, the energy fraction of alpha particles ($f\alpha$) decreases. For a turbulence value of $\beta=0.25$, the deposited energy fraction of alpha particles is 0.95. In contrast, for $\beta=1000$, f_α is 0.12. In the absence of thermal turbulence, f_α will reach 0.89. At the duration of the laser pulse, f_α decreases with time, reaching a minimum value of approximately 0.087. For $\beta<1$, the minimum value of the deposited energy fraction will be less than 0.047. As shown in Fig. 6, the maximum value of f_α decreases as β increases. Reducing β by a factor of 2 results in a 14% increase in the minimum fusion energy fraction and a 21% increase in the maximum fusion energy fraction. Fig. 7 presents the fusion power density (W_f), electron-ion exchange power density (W_{ei}), deposition power density (W_d), and radiation losses (W_b) as a function of time for different values of β.

During the time of one picosecond of the laser pulse duration, the fusion power density increases and reaches its maximum value of about 3.68×10^{32}erg/cm^{3}s in 2.7×10^{-13}s. It then decreases to less than 3.28×1032erg/cm^{3}s at 5×10^{-13}s. The fusion power density and deposition power density are independent of the temperature turbulence changes. At the duration of the laser pulse, deposition power density is constant and equal to 1.2457×10^{30}erg/cm^{3}s. It is found that the bremsstrahlung radiation losses are strongly influenced by temperature turbulence. As temperature turbulence increases, electron-ion exchange power density decreases, and radiation losses increase. The bremsstrahlung radiation losses will increase with increases β. For $\beta<1$, radiation losses are less than the fusion power density. For $\beta>10$, radiation losses are much larger than the fusion power density which makes ignition impossible. It is seen that for $\beta<1$, the relationship between densities is as $W_{ei}>W_f>W_b>W_d$ while for $\beta>1$, the relationship between densities is as $W_b>W_f>W_{ei}>W_d$. In the absence of the turbulence, $\beta=1$, maximum fusion power density is 21% larger than the value maximum of bremsstrahlung radiation losses and 90% less than maximum electron ion exchange power density. At 5×10^{-13}s, the fusion power density is 7% larger than maximum bremsstrahlung radiation losses and 71% less than maximum electron ion exchange power density. By decreasing the temperature turbulence by a factor of 2, the fusion power density becomes 91% less than the maximum electron ion exchange power density. At the end of the laser pulse duration, for $\beta=0.5$ the fusion power density is 15.28 times bremsstrahlung radiation losses. For $\beta=10$, the fusion power density at $1.6191\times10^{-13}\text{s}<t<1.8691\times10^{-13}$s is greater than the other energy densities. On the other hand, the fusion energy fraction, f_α, in this time interval is less than 0.2 which makes ignition of P-11B fuel more difficult. By increasing the temperature turbulence 100 times, the fusion power density is 95% less than maximum bremsstrahlung radiation losses.

Conclusions

This paper examines the influence of temperature turbulence on the ignition of P-11B fuel through analytical methods. The ignition criterion is derived from energy considerations, highlighting the role of picosecond laser-fuel interactions, shock wave-induced temperature turbulence, and electron oscillatory velocity coupling in enhancing fusion energy fraction. The ignition heating power density required is 1.245×10^{30} erg/cm^{3}s, with ignition achieved when temperature turbulence is below one.

Temperature turbulence significantly affects electron-ion exchange power density and bremsstrahlung radiation losses. For a β-value of 100, the product of plasma density and hot spot dimension must be at least twice that of a β-value of 10, necessitating greater pre-compression, larger igniter sizes, and higher energy lasers. A fourfold increase in temperature turbulence results in a 30% increase in the confinement parameter.

Controlling temperature turbulence is critical for optimizing fusion plasma performance and minimizing energy losses. For $\beta > 1$, the relationship between densities complicates ignition, requiring higher temperatures to compensate for increased radiation losses. Thus, larger and denser igniters are necessary to achieve ignition conditions. In contrast, maintaining temperature turbulence below one can facilitate ignition at lower temperatures, potentially allowing for smaller igniters. As temperature turbulence increases, the peak fusion energy fraction decreases, with significant declines observed during the laser pulse duration. Reducing temperature turbulence by half can enhance the minimum fusion energy fraction by 14%. Therefore, to achieve ignition conditions for P-11B fuel, temperature turbulence must be maintained below unity.

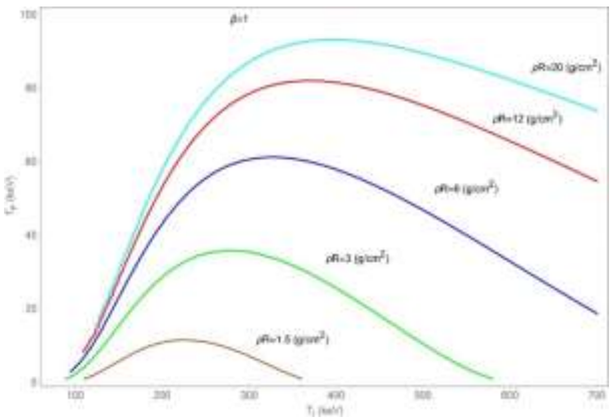

Fig.1. Variation of the confinement parameter, ρR, with respect to ion and electron temperatures

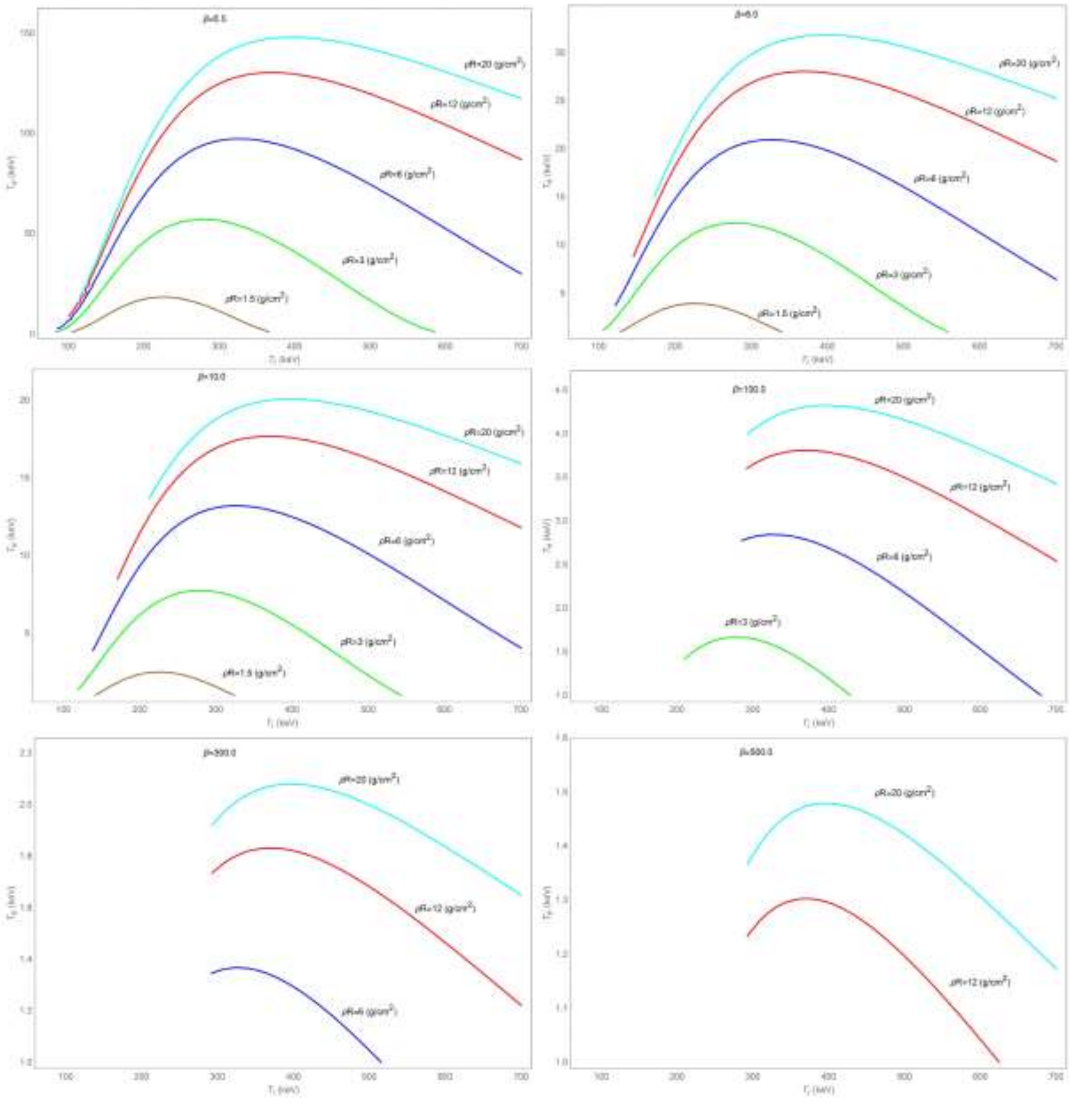

Fig.2. Plots of the confinement parameter ρR against ion and electron temperatures for temperature turbulence values of β=0.5, 5, 10, 100, 300, and 500.

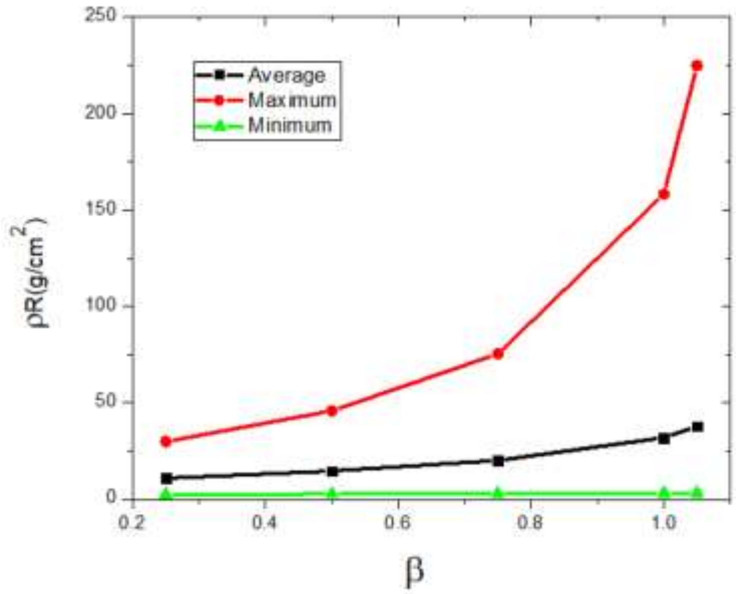

Fig.3. The confinement parameter varies as a function of temperature turbulence.

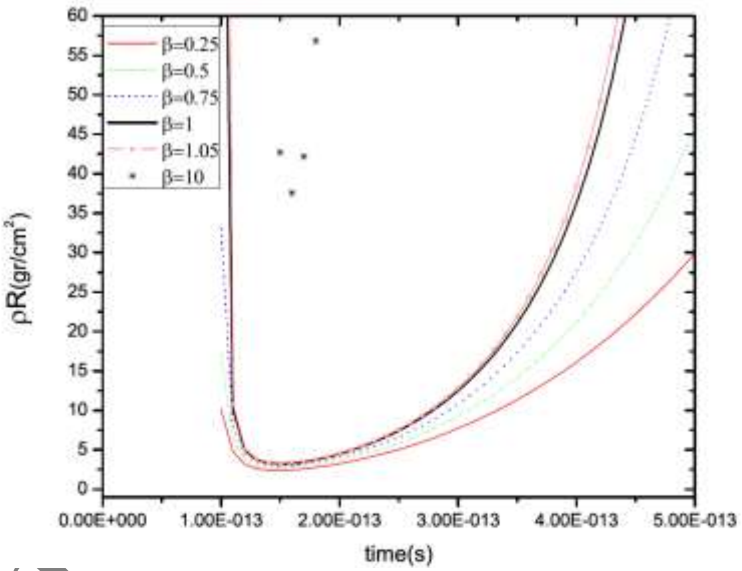

Fig.4. Investigating the temporal changes in the confinement parameter, ρR, in relation to fluctuations in temperature turbulence.

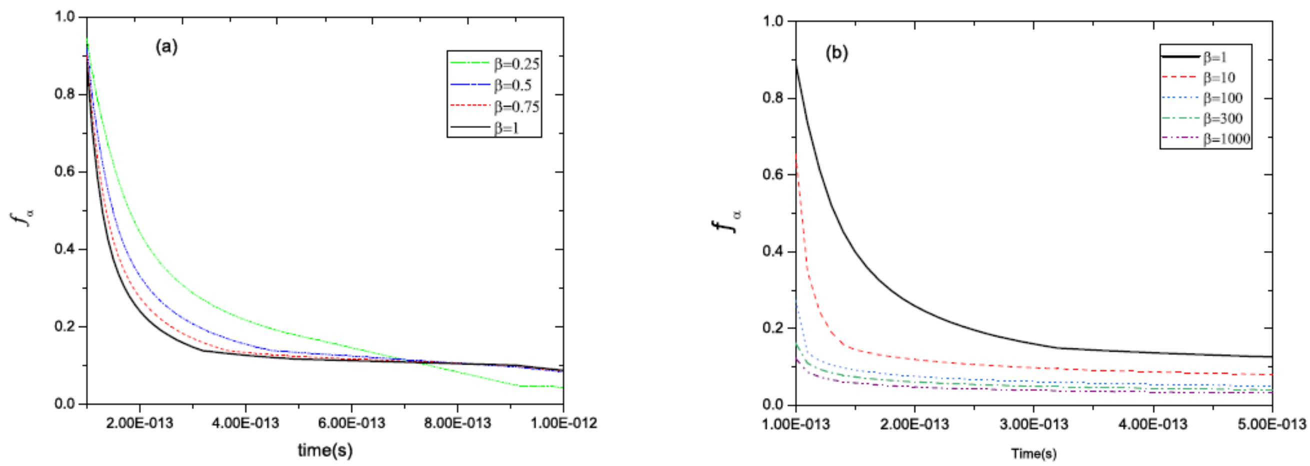

Fig.5. The fraction of fusion energy deposited in the igniter region for the P-11B fuel, f_α, changes over time and with the temperature turbulence, β, under two conditions: a) when β is less than 1, and b) when β is greater than or equal to 1. This leads to a temporal evolution of the confinement parameter, ρR, that is dependent on the varying temperature turbulence.

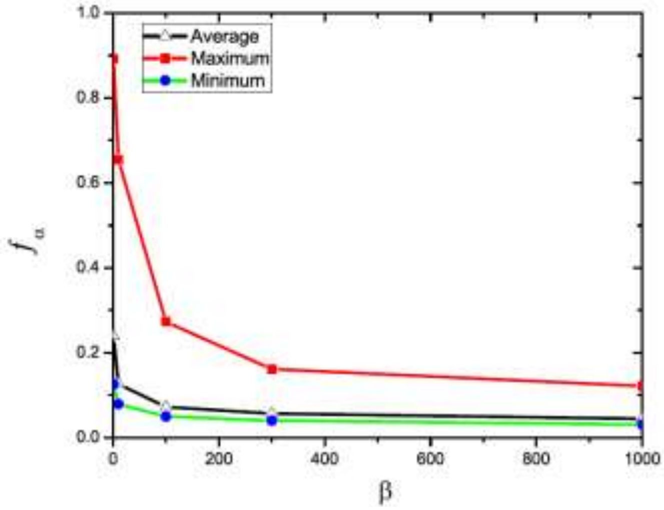

Fig.6. The fraction of fusion energy that is deposited varies in relation to the temperature turbulence.

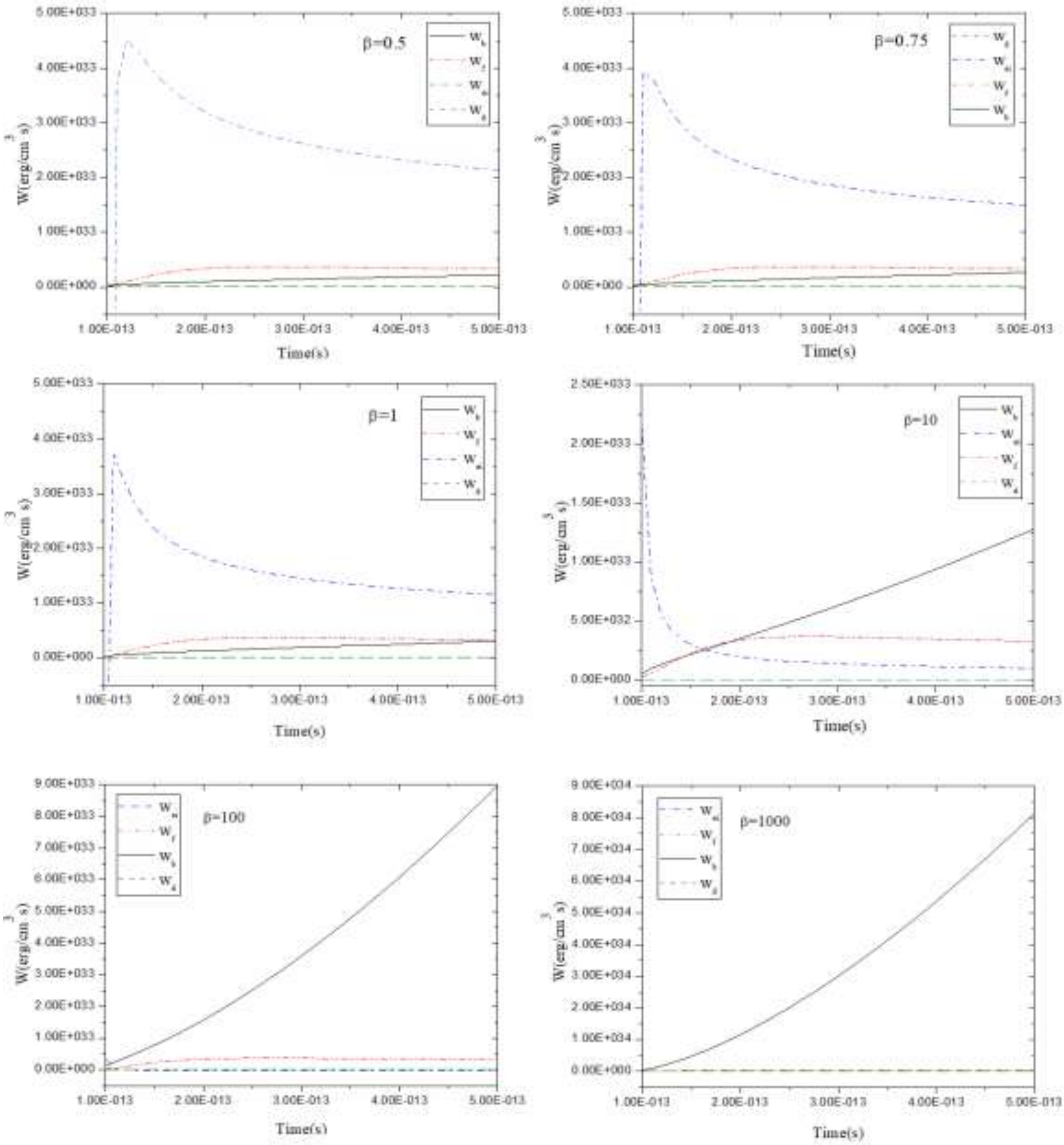

Fig.7. Various energy power density terms for P-11B fuel as a function of time, with variations in the temperature turbulence

parameter, β

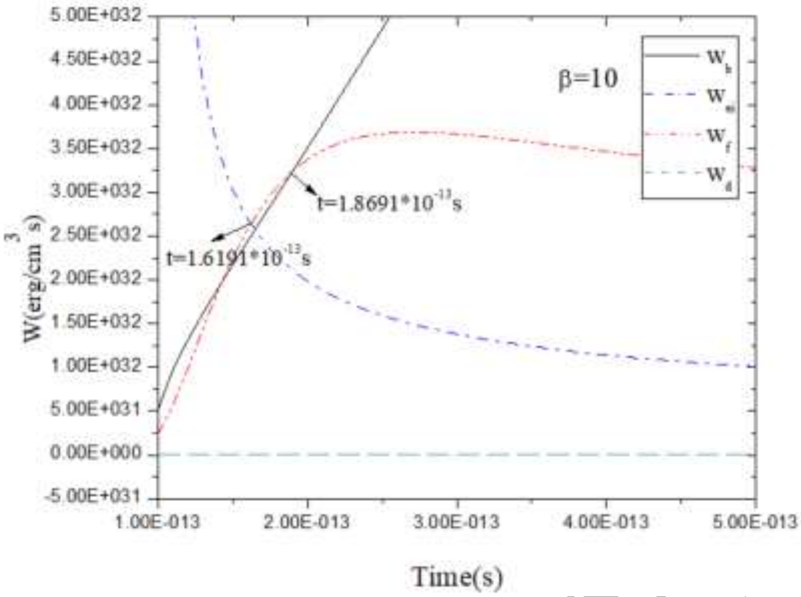

Fig.8. Temporal progression of the energy power density when the temperature turbulence parameter is set to 10.

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