Role of deuteron beam incidence on the neutron-free fuel pellet using helium catalyzed process in enhancing energy gain

S. N. Hosseinimotlagh
Department of Physics, Shi.C., Islamic Azad University, Shiraz, Iran,
e-mail:nasrinhosseini_motlagh@iau.ir; nasrinhosseinimotlagh@gmail.com

A. Shakeri
Department of Physics, Shi.C., Islamic Azad University, Shiraz, Iran.

Received 19 February 2024; accepted 22 March 2025

Fast ignition is recognized as a potential method to achieve the high energy-gain target performance required for commercial inertial confinement fusion. In this article, the deuteron beam driven causes fast ignition, which provides not only the ignition spark of the “hot spot” but also the “bonus” fusion energy through reactions within the target. We have estimated the energy deposited contribution as a bonus resulting from the fusion reactions that occurred based on calculations using a modified energy enhancement factor. To achieve this goal in the ICF plan, the use of pure $D-^3$He fuel is impractical due to the excessive need for energy driven. Therefore, a small amount of D-T fuel is necessary as a “igniter”. Since the $D-^3$He reaction does not produce any neutrons and fuel sources for the D-D reaction are abundant, it is expected that these reactions can be used in advanced fuel fusion reactors. The main interest in the helium-catalyzed $D-^3$He process, in which T and ^{3}He produced by fusion are recycled, is mainly due to the fact that deuterium fuel has essentially unlimited resources on Earth. In the calculation method of this article, without using helium catalyzed process, the fusion gain gradually increases with increasing temperature and reaches a maximum value of about 20 at a temperature of 190 keV, while using helium catalyzed process, it gradually increases with increasing temperature and reaches a maximum value of about 110 at the same temperature.

Keywords: Fusion reactor; helium catalyzed; fast ignition; side reaction; deutron beam.

DOI: https://doi.org/10.31349/RevMexFis.71.051501

1. Introduction

Inertial Confinement Fusion (ICF) is one of the two major branches of fusion energy research. When it was first proposed in the early 1970s, scientists believed that ICF was a practical approach to power generation and that this research area would flourish in the future. Tests conducted during the 1970s and 1980s showed that the efficiency of these devices was much lower than expected and that ignition would not be easy to achieve. During the 1980s and 1990s, many experiments were conducted to understand the complex interaction of high-intensity laser beam and plasma. These things led to the design of newer and much bigger machines that finally achieved ignition energies. In 1994, Tabak *et al.* proposed an idea that was completely different from the traditional method of creating a central hot spot related to ICF [1]. This design separated the process of compressioning the fuel from heating it. They called this method Fast Ignition (FI).

Fast ignition is an attractive design that not only reduces the symmetry constraints of the target capsule explosion, but can also reduce the constraints governing the total energy driven. The fast ignition scheme potentially reduces the energy required for ignition by targeting the production of a hot spot in a way that is substantially more efficient than the compression method used in the central hot spot scheme. In addition, it aims to achieve ignition in the fuel to achieve lower densities. In fast ignition, ignition driven requirements are low for two reasons: tirst, this design aims to achieve ignition by means of a mechanism that is more effective than heating the condensate. Second, it aims to ignite in a denser fuel, resulting in a smaller hot spot mass compared to the conventional central hot spot design. One of the necessary parameters in the design of ICF nuclear fusion reactors is fuel selection. Today, scientists choose $D-^3$He fuel, because it has the advantage of low neutron production and effective conversion of the output fusion energy [1]. And since achieving ignition is a difficult issue, so finding some methods or designs that are caused ignition is very important. In the ICF scheme, the use of pure $D-^3$He fuel is impractical due to the excessive need for energy driven [2]. Hence a small amount of D-T fuel is necessary as a “ignitor”. Since the $D-^3$He reaction does not produce any neutrons [2] and the D-D reaction fuel sources are scarce, it is expected that these reactions can be used in advanced fuel fusion reactors.The main interest is the helium-catalyzed process in $D-^3$He fuel, in which T and ^{3}He produced by fusion are recycled, is primarily due to the fact that deuterium fuel has essentially unlimited resources on Earth. [3]. In addition, there is no need for a tritium generator blanket, and the $D-^3$He helium catalysed reactor has no generator blanket, and the resulting neutron flux of 14 MeV is actually lower than that of the deuterium-tritium (D-T) system. [1-2]. While 2.45 MeV neutrons are added to the neutron flux. Removing some of the tritium before burning can result in even lower neutron fluxes. Helium catalyzed processof $D-^3$He has a low load neutron. that adding a small amount of tritium seeds can reduce the ignition temperature of $D-^3$He fuel and similarly reduces other advanced fuels [4]. Note that T and ^{3}He are produced by the D-D side reaction, and then energy is extracted from the D-T and $D-^3$He reactions. The $D-^3$He reaction will eliminate the need for tritium and produce lower energy neutrons, therefore, it will be easier to shield. Despite this, $D-^3$He reactors have been considered in the long term due to a number of potential advantages, including: unlimited use of deuterium fuel, flexibility of blanket design, simple administration of tritium, and reduction of radiation damage.

Also, since deuteron beams, in addition to heating, cause fueling in ICF fusion reactors, and on the other hand, their stopping in the fuel is more than electrons, and they can create a higher energy density by stopping in a smaller volume of fuel, therefore, the creation of additional fusion energy related to them is a unique feature that can be used to reduce the total required deuteron flux. Or alternately, it will reduce the energy required for the incident laser beam, and this issue can play a significant role in increasing the efficiency of commercial fusion reactors [4]. Therefore, deuterons can not only be ballistically focused, but also can fuse with ions in the target fuel when they slow down and provide an energy gain. Depending on the conditions of the target plasma, this added fusion gain can have a significant contribution [5]. In this article, we use an alternative fuel cycle, *i.e.* $D-^3$He with helium catalyzed, so that we can increase the fusion gain by using the fast laser ignition method and simultaneously irradiating the deuterium beam to the target fuel. Therefore, to achieve this goal, the following topics are presented in order: In the Sec. 2, the fast ignition method is briefly presented. In the Sec. 3 of the ICF reactor, helium catalyzed processrole in $D-^3$He is studied. In the Sec. 4, the dynamics of the computational model used in this article related to the energy gain of fast ignition of fusion plasma with and without helium catalyzed processrole in $D-{}^3$He are given. In the Sec. 5, the estimation of the additional energy gain due to the injection of the deuteron beam into the fuel target of helium catalyzed processin $D-{}^3$He fuel is done by considering the fast ignition along with side reactions, and finally, the conclusion is presented.

2. Fast ignition method

In this method, unlike the central hot spot ignition method, compression and ignition processes are performed separately to reduce hydrodynamic instabilities and achieve higher energy gain. In this method, first the fuel capsule is compressed by means of laser or ion beams to a high surface density of $2-3$ g.cm^2 at low temperature. After that, at a time interval of $10-50$ ps, a laser beam with a power higher than 10^{18} W and a very short wavelength, *i.e.* 0.2 μm, is used for ignition. In the fast ignition method, the capsule gradually compresses. Rayleigh-Taylor instability does not occur in fast ignition and the energy gain in fast ignition is higher than in direct ignition. In general, there are two methods of tunneling and guided cone for fast ignition, in which the aim of both of these methods is to eliminate the large barrier of fast ignition. These methods are briefly introduced below. Fast ignition was initially proposed by Tabak and his colleagues through the tunneling scheme. Fast ignition takes place in a small area of the main fuel [6].

This ignition is isochric and the energy entering the hot spot is generated from the intense short pulse of electrons (or protons) by ultra intense laser radiation. The density of the hot spot of fast ignition can be lower compared to the central hot spot method, as a result, the gain can be higher and the ignition threshold is lower [7]. The duration of the fast ignition pulse should be less than the inertial confinement time controlled by the radius of the hot spot. Transferring the required energy in the allotted time frame is one of the main challenges of fast ignition. After that, the tunnel dug is done by light pressure, and the laser light is focused inside the channel. The maximum laser power will be used to move electrons forward with an average energy absorption of approximately 1 MeV. In the initial method of fast ignition in the form of tunneling, it was found that due to the presence of instabilities during propagation, it is not possible to do it practically and the laser light cannot penetrate much and it returns back. Also, there are problems in the path of the channel towards the dense center, so that the brams tend to return to the lower densities, as a result of which the densest areas are completely lost. The propagation of strong pulses in this method is complicated.

Therefore, to solve these problems, a new method for fast ignition called "conical guided method" has been proposed, which uses a hollow gold cone with a closed tip, which is placed inside a spherical fuel capsule [5]. In this method, a hollow cone is used to provide the ignition laser pulse path to reach the dense fuel. In this case, the laser does not interact with the plasma corona with a lower density, and the explosion occurs around the cone and the compressed plasma at the tip of the cone. The hollow cone causes the laser light to be focused inside it and hot electrons are produced at its tip very close to the dense plasma.

3. ICF reactor with helium catalyzed process in $\mathrm{D}-^{3}\mathrm{He}$

Over the past few decades, research on controlled fusion through fast ignition has developed that are suitable for ignition and promote controlled fusion burning. Fusion cross-section and reaction rate coefficient for D-T is significantly larger than $D-^3$He reaction and D-D reaction [8]. For this reason, the D-T fusion reaction has attracted much interest. Although the large rate factor associated with the D-T reaction is attractive to the fusion researcher, D-T burning presents serious problems.First, the amount of tritium in nature is low and it must be artificially produced by the reaction $n(^6Li.T)\alpha$ and the breeding rate must be sufficient [9]. Second, tritium is unstable and it is a beta-emitter, and thus handling tritium complicates the operation of the ICF fusion reactor. Thirdly, the production of $14.1\ MeV$ neutrons, which are the product of the D-T fusion reaction, activate the structural materials of the reactor and damage them [10]. Fourth, a large mass is required to stop these energetic neutrons, leading to the need for a huge blanket and that must shield the burning D-T plasma. In this paper, we propose a different method for fusion power source, based on alternative fuel cycle, which we call helium catalyzed $D-^3$He. Because the $D-^3$He reaction often destroys the production of energetic neutrons. However, like T, ^{3}He is also not abundant on Earth. It has been pointed out that it can be extracted from the surface of the Moon [11] or on a longer time scale it can be obtained from the planet Jupiter [12]. The $D-^3$He reaction is perhaps the most interesting from this point of view, which eliminates both the issue of tritium generation and the issue of high-energy production neutrons. Therefore, according to the above-mentioned points, in this article we use $D-^3$He fuel. The reaction related to the controlled nuclear fusion of $D-^3$He is as follows:

$$D + {}^3\text{He} \rightarrow {}^4\text{He}(3.6\text{ MeV}) + p\,(14.7\text{ MeV})\,, \tag{1}$$

while its side reactions are [13, 14]:

$$D + D \overset{50\%}{\rightarrow} {}^3\text{He}\ \ (0.82\text{ MeV}) +\ n\ \ (2.45\text{ eV}) \tag{2}$$

$$D + D \overset{50\%}{\rightarrow}\ T\,(1.01\text{ MeV}) +\ p\,(\ 3.02\text{ MeV}) \tag{3}$$

and

$$D\ +\ T \rightarrow {}^4\text{He}\ \ (3.5\text{ MeV}) + n\,(14.1\text{ MeV}) \tag{4}$$

As can be seen, D-D side fusion reaction occurs from two channels with the same probability. The first channel produces ^{3}He while the second channel produces tritium and the produced tritiums fuse with background deuteriums and produce neutrons with high energy of 14.1 MeV, such that it is difficult to control them. Therefore, to solve this problem, we suggest that tritium decays before performing the D-T side fusion reaction and turns into positron and ^{3}He. This ^{3}He, which is the decay product of tritium, is used as fuel again in $D-{}^3$He fusion should be replaced. Charged fusion products immediately distribute their initial kinetic energies among background ions and electrons through Coulomb collisions. Similarly, ions and electrons are injected into the plasma, which instantly equilibrate with the particles in the plasma. Fusion neutrons escape from the plasma along with their initial energies and do not satisft the plasma energy balance. The particle confinement time is the same for all ion species. The electron density is determined by the charge neutralization condition. Plasma volume remains constant. Plasma is spatially homogeneous and it is described by the kinetic-point model.

4. Dynamics of the calculation model related to the energy gain of fast ignition fusion plasma via helium catalyzed process in $D-{}^3$He

The equations of particle and energy balance can be written as follows, considering the fusion of $D-{}^3$He fuel without considering helium catalyzed process:

$$\frac{dn_D}{dt} = -\frac{n_D}{\tau_p} - n_D n_{3\text{He}}\langle\sigma\upsilon\rangle_{D3\text{He}} - n_D n_T\langle\sigma\upsilon\rangle_{DT} -0.5n_D^2\langle\sigma\upsilon\rangle_{DDP} - 0.5n_D^2\langle\sigma\upsilon\rangle_{DDn} + s_D, \tag{5}$$

$$\frac{dn_{3\text{He}}}{dt} = -\frac{n_{3\text{He}}}{\tau_p} - n_D n_{3\text{He}}\langle\sigma\upsilon\rangle_{D3\text{He}} + 0.5n_D^2\langle\sigma\upsilon\rangle_{DDn} + s_{\text{He3}}, \tag{6}$$

$$\frac{dn_\alpha}{dt} = -\frac{n_\alpha}{\tau_p} + n_D n_T\langle\sigma\upsilon\rangle_{DT} + n_D n_{3\text{He}}\langle\sigma\upsilon\rangle_{D3\text{He}}, \tag{7}$$

$$\frac{dn_p}{dt} = -\frac{n_p}{\tau_p} + 0.5{n_D}^2\langle\sigma\upsilon\rangle_{DDP} + n_D n_{3\text{He}}\langle\sigma\upsilon\rangle_{D3\text{He}}, \tag{8}$$

$$\frac{dn_T}{dt} = -\frac{n_T}{\tau_p} - n_D n_T\langle\sigma\upsilon\rangle_{DT} - 0.5n_D^2\langle\sigma\upsilon\rangle_{DDP}, \tag{9}$$

$$\frac{dn_n}{dt} = -\frac{n_n}{\tau_p} + n_D n_T\langle\sigma\upsilon\rangle_{DT} + 0.5n_D^2\langle\sigma\upsilon\rangle_{DDn}, \tag{10}$$

$$\frac{dn_{4\text{He}}}{dt} = \frac{n_T}{\tau_p} - n_D n_{3\text{He}}\langle\sigma\upsilon\rangle_{D3\text{He}} + 0.5n_D^2\langle\sigma\upsilon\rangle_{DDn}, \tag{11}$$

$$\frac{\partial E}{\partial t} = -\frac{E}{\tau_E} + Q_{D3He} n_D n_{3\text{He}}\langle\sigma\upsilon\rangle_{D3He} + Q_{DD} n_D^2\langle\sigma\upsilon\rangle_{DD} + Q_{DT} n_D n_T\langle\sigma\upsilon\rangle_{DT} - P_{\text{rad}.D-\text{He3}} - P_{\text{rad}.D-T} - P_{\text{rad}.D-D}, \tag{12}$$

where the dissipated radiation P_{rad} is expressed as follows:

$$P_{\text{rad}} = P_{\text{brem}} = A_b Z_{\text{eff}}\ n_e^2\sqrt{T}. \tag{13}$$

So that A_b is the bremsstrahlung radiation coefficient, Z_{eff} is the effective atomic number, n_e is the electron density, n is the plasma density and T is the plasma temperature. It is enough to consider the fusion of $D-{}^3$He fuel by considering helium catalyzed process through replacing Eq. (11) with Eq. (14):

$$\frac{dn_{3\text{He}}}{dt} = \frac{n_T}{\tau_p} - n_D n_{3\text{He}} < \sigma\upsilon >_{D3\text{He}} + 0.5n_D^2\langle\sigma\upsilon\rangle_{DD_n} + s_{\text{He3}}, \tag{14}$$

where n_D, $n_{3\text{He}}$, n_α, n_T, n_p, and n_n are the number densities of deuterons, ^{3}He, alphas, tritons, protons, and neutrons, while $P_{D-\text{He3}}$, P_{D-T}, and P_{D-D} are the rate of radiation energy loss due to the aforementioned fusion reactions. τ_p is the particle confinement time, τ_E is the energy confinement time, and E is the energy injected into the fuel and the reaction rate parameter $(j = 1 \sim 4)\,\sigma v j$, which is equal to the product of the fusion cross-section and the relative speed of the fusion nuclei, which is averaged on the Maxwellian distribution function. S_D , and S_{He3} are the number of deuterium and ^{3} Heatoms injected into the plasma per unit volume per unit time. In other words, the $\langle\sigma v\rangle$-parameters represent the reactivity of the fusion reactions mentioned above, and the Q-parameters are the energy resulting from these fusion reactions. Also, G is fusion energy gain, which is determined from the following equation:

$$G = \frac{E}{E'}, \tag{15}$$

where E is the released net energy resulting from the above fusion reactions presented and E' is the laser energy required to start the fusion reaction, which is approximately 10^5 J. Note that to check the energy and particle balance equations in $D - {}^3$He fuel, it is first necessary to check and determine the average value of reactivity. To convert experimentally obtained values into a mathematical relationship, many methods have been proposed and different coefficients have been defined to fit the graph and match the values. We take the help of one of the most common relations, the Bosch and Hill formula, which can be used to obtain the average value of reactivity at different temperatures. The following relation expresses this formula [15]:

$$\langle\sigma v\rangle = C_1 \theta^{-5/6} \xi^2 \exp(-3\theta^{1/3}\xi), \tag{16}$$

rature is represented by T, the cross-section of interaction is given by σ and the relative speed of the fusing particles is shown by v. The value of coefficient θ is determined from Eq. (17):

$$\theta = 1 - \frac{C_2 T + C_4 T^2 + C_6 T^3}{1 + C_3 T + C_5 T^2 + C_7 T^3}, \tag{17}$$

and ξ can be determined from the following equation:

$$\xi = \frac{C_0}{T^{\frac{1}{3}}}, \tag{18}$$

The values of C_0 to C_7 for different fusion reactions are given in Table I [15]

TABLE I. The diagram of temperature variations of the reactivity of different fusion reactions mentioned above has been drawn using Eqs. (16), (17) and (18) its diagram is shown in Fig. 1.

	$T(d,n)^4$He	$D(d,n)^3$He	$D(d,p)T$	^{3}He$(D,p)^4$He
C_1	5.51E-10	5.66E-12	5.43E-12	1.17E-09
C_2	6.42E-03	3.41E-03	5.86E-03	1.51E-02
C_3	-2.03E-03	1.99E-03	7.68E-03	7.52E-02
C_4	-1.91E-05	0.00E+00	0.00E+00	4.61E-03
C_5	1.36E-04	1.05E-05	-2.96E-06	1.35E-02
C_6	0.00E+00	0.00E+00	0.00E+00	-1.07E-04
C_7	0.00E+00	0.00E+00	0.00E+00	1.37E-05
$m_r c^2$ (KeV)	1124572	937814	937814	1124656

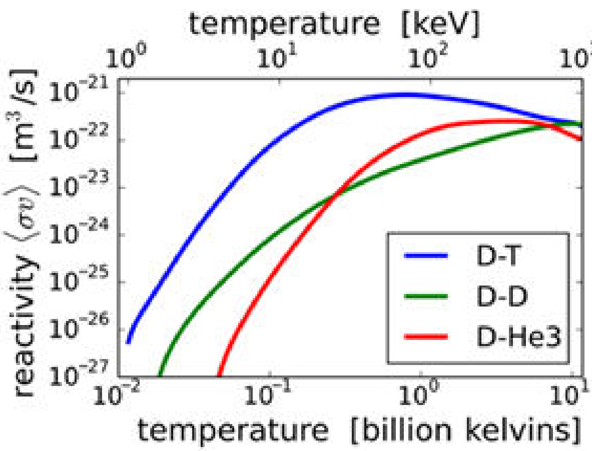

FIGURE 1. Temperature variations of fusion reaction cross-sections $< \sigma v >$ for DD, DT and $D - 3$He (red) [16].

As can be seen from this graph, in the temperature range of 0 to 100 keV, the reactivity increases with increasing temperature, and D-T fusion fuel has the highest reactivity. But note that the main $D - {}^3$He fuel increases its reactivity up to 200 keV. To determine the particle density and the net energy resulting from fusion in the first stage, we solve the non-linear coupled balance differential equation system for the particle (Eqs. (5) to (11) and (14)) and also the energy (Eq. (12)), we in the temperature range of 0.5 to 200 keV. It should be noted that for the numerical solution of the above differential nonlinear kinetic equations 0 have been used the conditions: $S_D = 4.5 \times 10^{22}$ cm^{-3}, $S_{^3\mathrm{He}} = 2.65 \times 10^{22}$ cm^{-3}, $\tau = \tau_P = \tau_\alpha = \ldots = 9 \times 10^{-12}$ s, $\tau_E = 1/4\tau$ and initial condition: $n_D\,(0) = 4.5 \times 10^{22}$ cm^{-3}, $n_{^3\mathrm{He}}\,(0) = 2.65 \times 10^{22}$ cm^{-3}, $E\,(0) = 0$, $n_\alpha(0) = 0$, $n_p(0) = 0$, $n_T(0) = 0$, $n_n\,(0) = 0$ and obtained the temporal dependence of the number density of n_D, $n_{3\mathrm{He}}$, n_T, E and G particles in the temperature range of 0.5 to 200 keV and we have given the results in Figs. 2 and 3, respectively. In addition, the flux of alpha particles, neutrons and protons produced as a result of the fusion reactions presented above are obtained from the following equations, *i.e.* the product of density and velocity:

$$\Phi_p = n_p v_p, \quad \Phi_\alpha = n_\alpha v_\alpha, \quad \Phi_n = n_n v_n, \tag{19}$$

where n_p and v_p, n_α and v_α, n_n and v_n are respectively the density and speed of proton, alpha and neutron particles produced by the above reaction. Considering having n_p, n_α, n_n as a function of time and temperature and using the relations $v_p = \sqrt{2E_p/m_p}$, $v_\alpha = \sqrt{2E_\alpha/m_\alpha}$, and $v_n = \sqrt{2E_n/m_n}$ the produced flux variations of proton, alpha and neutron as a function of time and temperature can be determined.

The results of the Fig. 2: from the comparison of Fig. 2a) and 2b), we find that with and without helium catalyzed process, the density of deuteriums decreases over time due to

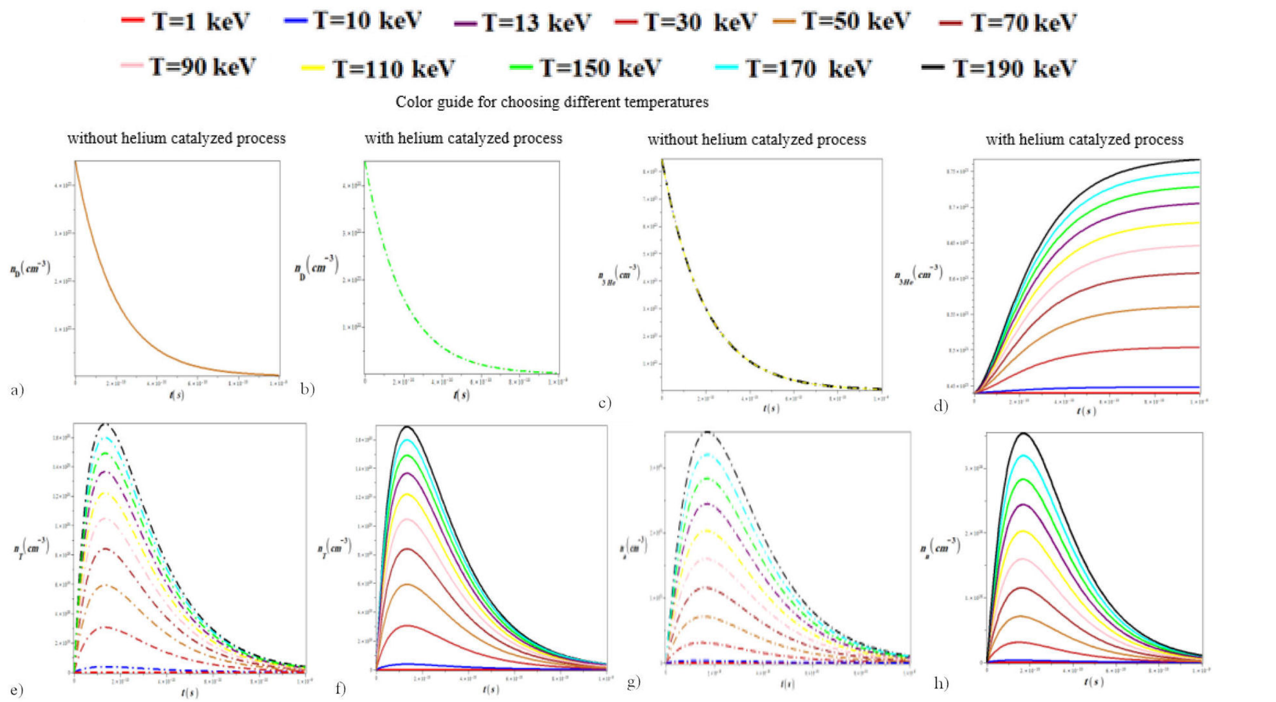

FIGURE 2. Time variations of particle density a), b): deuterons (with (solid color) and without (dotted line) helium catalyszed process) c), d): helium-3 (with (solid color) and without (dotted line) helium catalyszed process) e), f): Tritons ((with (solid color) and without (dotted line) helium catalyszed process) g), h): Neutrons ((with (solid color) and without (dotted line) helium catalyszed process) for different temperatures.

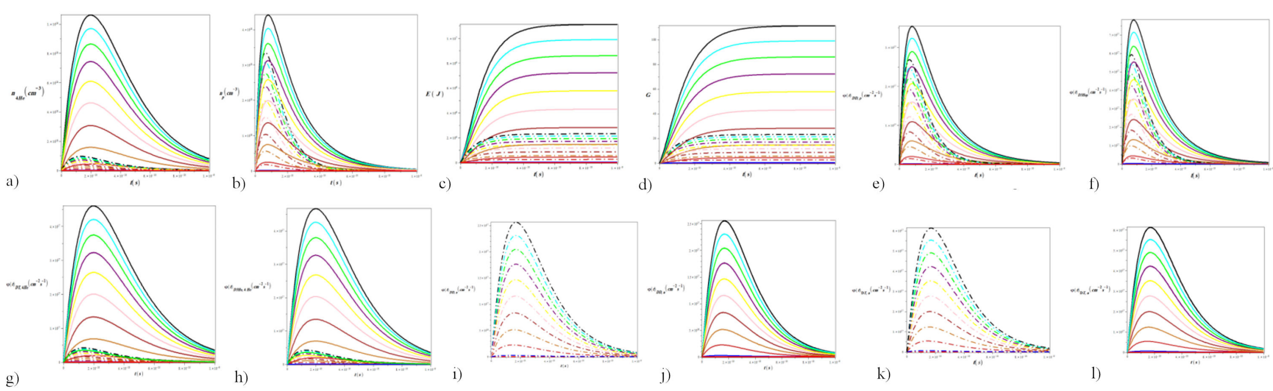

FIGURE 3. Time changes of particle density a), b): alphas and protons (with (solid color) and without (dotted line) helium catalyszed process) c), d): energy and energy gain (with (solid color) and without (dotted line) helium catalyszed process) e), f): flux of proton particles produced from $D-{}^{3}$He and D-D reactions (with (solid color) and without (dotted line) helium catalyszed process) g), h): flux of alpha particles produced from reactions $D-{}^{3}$He and D-T (with (solid color) and without (dotted line) helium catalyszed process) i), j): and l), k): the flux of neutron particles produced from D-D and D-T reactions ((with (solid color) and without (dotted line) helium catalyszed process) for different temperatures.

the consumption of deuteriums and finally reaches the characteristic value of the stable state, and temperature variations do not have much effect on this density for with and without helium catalyzed process. From the comparison of diagrams in 2c), we can see that without helium catalyzed process, the density of helium-3 decreases with time growing due to the consumption of helium-3 and finally reaches the characteristic value of the steady state, and temperature variations have little effect on this density in the state without helium catalyzed process. If comparing the 2-d graphs related to the state with helium catalyzed process, it can be seen that because the density of helium-3s due to the D-T reaction increases over time, the density of helium-3s increases with the time growing and also with increasing temperature, its production rate increases because the reactivity of the mentioned reactions increases with increasing temperature. From the comparison of graphs 2e), 2f), 2g) and 2h), we find that with the time increasing due to the side fusion reaction D-D, the amount of produced tritium and similarly due to the side fusion reaction D-D and D-T the amount of produced neutrons increases first ,and then, due to the reduction of the main fuel consumption, the amount of D-D side fusion reaction for tritiums and the amount of D-D and D-T side fusion reaction for neutrons are reduced, as a result, the amount of tritiums and neutrons available are reduced and finally reach the characteristic value of steady state.(for both cases with and without helium catalyzed process). Also, with increasing temperature, their production rate increases because the reactivity of the The results of the graphs in Fig. 3: according to graphs 3a) and 3b), the density of produced alpha and proton particles increases with time because the main fuel $D-{}^3$He and secondary fuels D-D and D-T are consumed and then due to the consumption of these fuels the amount of produced alpha and proton particles are reduced. (for both modes with and without helium catalyzed process) According to graphs 3c) and 3d), the energy density and energy gain from the main reaction and side reactions for both cases with and without helium catalyzed processes increases with time because the main fuel $D-{}^3$He and side fuels D-D and D-T are consumed, and as a result, the fusion energy and energy gain from them increases and finally reaches the characteristic value of the steady state.

According to the diagrams 3e) and 3f) and the flux density of produced proton particles from the main reaction $D-{}^3$He and the side reaction D-D for both cases with and without helium catalyzed process first increases and then decreases with the time growing. Because at first the main fuel $D-{}^3$He and the side fuel D-D are consumed and as a result the proton production flux resulting from them increases, but after the aforementioned fuels are consumed, their fusion rate decreases and as a result the produced proton flux reduces.According to graphs 3g) and 3h), the flux density of produced alpha particles from the main reaction $D-{}^3$He and the side reaction D-T for both cases with and without helium catalyzed processes first increases and then decreases with the time increasing. Because at first the main fuel $D-{}^3$He and the side fuel D-T are consumed and as a result the flux of produced alpha particles from them increases. But after the mentioned fuels are consumed, their fusion rate is reduced and as a result, the amount of produced alpha particles flux is reduced. According to graphs 3i), 3y), 3k) and 3l), the flux density of neutron particles produced from side reactions D-D and D-T for both cases with and without helium catalyzed processes first increases and then decreases with the time raising, because at first the side fuels of D-D and D-T are consumed and as a result the flux of produced neutrons by them increases, but after the aforementioned fuels are consumed their fusion rate is reduced and as a result the flux of produced neutrons is reduced.

It is necessary to mention that in all the graphs given in Fig. 3, the values of all the fulfilled quantities related to the state without helium catalyzed process are lower than the state with helium catalyzed process, and also with increasing temperature, their production rate increases because the reactivity of the main reaction $D-{}^3$He increases with increasing temperature up to 200 keV. In this method, without using helium catalyzed process, the fusion gain gradually increases with increasing temperature and reaches a maximum value of about 20 at a temperature of 190 keV, while with the use of helium catalyzed process, it increases gradually with increasing temperature and reaches a maximum value of about 110 at a temperature of 190 keV.

5. Estimation of the added energy gain due to deuteron beam injection to the fuel target using helium catalyzed process in $D-{}^3$He fuel considering fast ignition

Deutrons in the fusion during with fuel ions produces a bonus energy gain. Depending on the conditions of the target plasma, this added energy gain can have a significant contribution. This added energy increases the total energy gain of the system. The value of G as the energy gain, the ratio of the total fusion energy produced E_f through the beam-target interactions to the input energy of the ion injected into the plasma E_I, is defined as follows [17]:

$$G_{D+{}^3\mathrm{He}} = n_{{}^3\mathrm{He}} \frac{\int_{E_{th}}^{E_I} S\left(E\right) dE}{E_1}. \tag{20}$$

In this relation, E_{th} and E_I are the average energy of the background plasma $(E_{th} = 2K_BT)$ and the initial energy of the injected ion, respectively.

$$\int_{E_{th}}^{E_I} S\left(E\right) dE,$$

is the fusion production energy due to both neutrons and charged particles. $S(E)$ is the fusion probability of an ion with energy E, which slows down as much as dE. This probability is calculated through the following relationship [18]:

$$S\left(E\right) = \sum_k K_k \left[\langle\sigma v(E)\rangle_b\right]_{IK} \left(E_f\right)_{IK} \left(\frac{dE}{dt}\right), \tag{21}$$

where dE/dt is the energy dissipation rate time of the injected ion, which is defined as follows for the pre-compressed $D-{}^3$He fuel (ignoring the energy distressing of the injected ions during slowing down):

$$\frac{1}{n_{{}^3\mathrm{He}}}\left(\frac{dE}{dt}\right)_{D+{}^3\mathrm{He}} = -\frac{Z_1^2 e^4 m_e^{\frac{1}{2}} E \ln \Lambda_{D+{}^3\mathrm{He}}}{3\pi \left(2\pi\right)^{\frac{1}{2}} \varepsilon_0^2 m_1 \left(K_B T_e\right)^{\frac{3}{2}}} \times \left[1 + \frac{3\sqrt{\pi} m_1^{\frac{3}{2}} \left(K_B T_e\right)^{\frac{3}{2}}}{4 m_k m_e^{\frac{1}{2}} E^{\frac{1}{2}}}\right], \tag{22}$$

where m_e is the mass of the electron and m_I is the mass of the injected ion and they are in atomic mass units. Figure 4 shows that $dEdt$ decreases with increasing electron temperature and deuteron beam energy. $\sigma vEbIK$ is the average fusion reactivity for the injected ion I with index k, which has atomic fraction K_k in the target, $\left(E_f\right)_k$ is the energy released in a fusion and T_e is the electron temperature of the target.

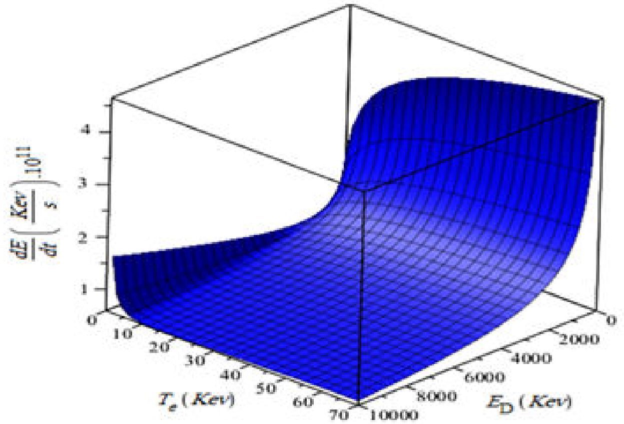

FIGURE 4. The dE/dt variations in terms of electron temperature and deuteron energy in the pre-dense helium catalysed process in fuel $D-{}^{3}$He with a density of 300 g.cm^{-3}

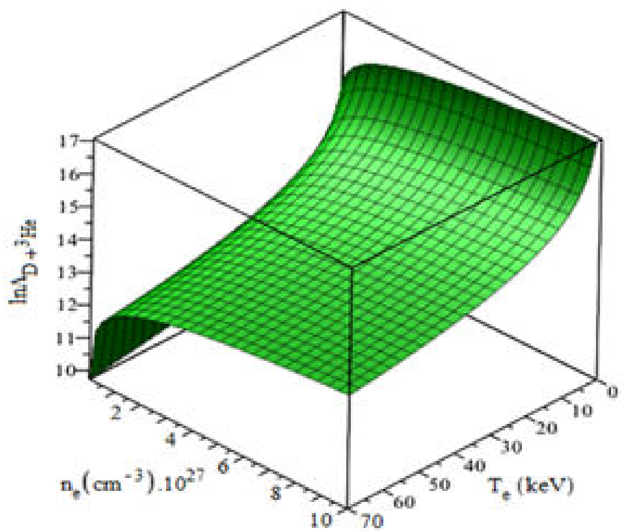

FIGURE 5. Coulomb logarithm variations in terms of electron temperature and different densities of $D-{}^{3}$He fuel.

By calculating Eq. (21) for the desired fuel and inserting it into Eq. (20), it is observed that $n_{^3\text{He}}$ is removed from the equation and G is almost independent of the target density. But the Coulomb logarithm depends on T_e and target density ρ. For high energy ions $\ln\Lambda_{D+^3\text{He}}$ is written as follows:

$$\ln\Lambda_{D+^3He} \approx 14.8 - \ln\left(\sqrt{n_e}/T_e\right), \qquad (23)$$

where T is in keV, ρ and n_e are the target and electron number density in terms of g.cm^{-3} and cm^{-3}, respectively. The only reason for the significant dependence G parameter on density is Coulomb logarithm. Two- and three-dimensional variations of $D-{}^{3}$He Coulomb logarithm in terms of T_e and density in the range of $300-500$ g.cm^{-3} are shown in Fig. 5. It is clearly seen that the Coulomb logarithm for the desired fuel has a lower value in ρ and larger n_e, but it increases fastly with T_e.

in Eq. (21), is the energy released in the fusion reaction which is carried by fast neutrons and charged particles. But for heating the hot spot, the surface density (ρr, r is radius of the hot spot and ρ is density) of the hot spot is too low to significantly slow down the neutrons, so only charged particles are involved in this. Therefore, according to D-T and $D-{}^{3}$He reactions, for D-T reactions, only 20% of the fusion energy is carried by alpha particles in the target, and for $D-{}^{3}$He reaction, all the fusion energy that is carried by proton and alpha particles, it is useful for heating, while it is useful for the D-D reaction in both fuels, approximately 63% of the total energy. In order to avoid mistakes, we introduce a new factor to show the multiplication of energy in order to heat the hot spot by charged particles, and therefore the percentage of bonus energy due to D-T and D-D fusion is $Y_{D+T} = 20\% G_{D+T}$ and $Y_{1D+D} = 63\%\ G_{D+D}$, respectively. And similarly for the pre-condensed fuel $D-{}^{3}$He and also for the D-D fusion reaction we have $Y_{D+^3\text{He}} = 20\% G_{D+^3\text{He}}$ and $Y_{2D+D} = 63\%\ G_{D+D}$, respectively. Therefore, the total energy that can be placed inside the target is obtained from the following equation, which is equal to the sum of the deuteron energy and the energy of the charged particles produced by deuteron-target fusion (bonus energy):

$$E_{\text{total}} = E_D\,(1+Q)\,. \qquad (24)$$

Therefore, for the side reaction D-T and the main reaction $D-{}^{3}$He we have:

$$\begin{aligned} E_{\text{total}\ D+T} &= E_D\,(1+Y_{D+T}+Y_{1D+D}) \\ &= E_D\,(1+20\%G_{D+T}+63\%\ G_{D+D})\,, \qquad (25) \end{aligned}$$

$$\begin{aligned} E_{\text{total}\ D+^3\text{He}} &= E_D\,(1+Y_{D+^3\text{He}}+Y_{2D+D}) \\ &= E_D\,(1+20\%G_{D+^3\text{He}}+63\%\ G_{D+D})\,. \qquad (26) \end{aligned}$$

As can be seen, the E_D and Y parameters play an important role in the bonus energy and the total energy deposited by the deuteron beam. It should be noted that E_{total} is the total deposited energy by the ion beam plus the beam-target fusion contribution in the hot spot, and it is not equal to the total energy entering the target (concentration laser energy plus fast ignition energy to the total target) which is often mentioned in energy studies.

TABLE II. Bonus energy percentage (Y_{D+T} and $Y_{D+^3\text{He}}$) in the average initial deuteron energy and different hot spot temperatures of the D-T side reaction and the main $D-{}^{3}$He reaction with a density of 300 g.cm^{-3}.

hot spot temperature in fuel D-T			hot spot temperature in fuel $D-{}^{3}$He				
70 KeV	20 KeV	10 KeV	70 KeV	20 KeV	10 KeV		
30	4	4	34	20	6	1 MeV	average
9	2	1.5	18	12	5	4 MeV	initial
5	1.5	1.5	12	5	3	7 MeV	deutron
1.8	1.7	1	1.7	1.6	1	10 MeV	energy

TABLE III. Total deposited energy in the average initial deuteron energy and different hot spot temperatures of the side reaction D-T and the main reaction $D-{}^3$He with a density of 300 g.cm^{-3}.

hot spot temperature in fuel D-T			hot spot temperature in fuel $D-{}^3$He				
70 KeV	20 KeV	10 KeV	70 KeV	20 KeV	10 KeV		
1.30	1.04	1.03	1.44	1.22	1.06	1 MeV	average
2.18	2.04	2.02	2.40	2.22	2.06	4 MeV	initial
3.15	3.03	3.03	3.39	3.18	3.06	7 MeV	deutron
10.18	10.17	10.1	10.18	10.17	10.1	10 MeV	energy

In Tables II and III, the percentage of bonus energy and total displacement energy (sum of deuteron energy and bonus energy) in the average initial deuteron energy and different hot spot temperatures due to the side reaction D-T and the main reaction $D-{}^3$He is brought, respectively. As it is known, since $Y_{D+{}^3\text{He}}$ is more than Y_{D+T}, the percentage of bonus energy and total deposited energy due to the main reaction of $D-{}^3$He is more than the side reaction of D-T, and in both fuels these parametrs are more in smaller E_D and higher T_e. In other words, E_{total} has a significant increase compared to E_D when T_e is larger and E_D is smaller.

In a more realistic situation, deuterons with more energy should first reach the cold fuel and increase its temperature. Then, low-energy deuterons arrive and create a significant fusion gain through beam-target reactions at a new elevated temperature. Therefore, despite the fact that the added deposited energy from beam-target fusion is not very clear in the initial conditions, but when the temperature of the hot spot increases, it gradually becomes more important and finally, reaches to a significant energy contribution [19]. This issue, when higher plasma temperatures reduce the stopping power parameter, in turn allows slower low-energy deuterons to penetrate more into the fuel.

6. Conclusion

In this article, the fast ignition method of nuclear fusion reaction $D-{}^3$He in two cases with and without helium catalyzed process is used to increase the energy gain of the fusion reactor because the reaction $D-{}^3$He does not produce any neutrons, and D-D reaction fuel sources are abundant. It is expected that these reactions can be used in advanced fuel fusion reactors. In the calculation method in this article without using helium catalyzed process increases gradually with increasing temperature and reaches a maximum value of about 20 at a temperature of 190 keV, while with the use of helium catalyzed process it increases gradually with increasing temperature and reaches a maximum value of about 110 at the same temperature. In fact, fast ignition is recognized as a potentially promising method to achieve the high-energy gain target performance required for commercial inertial confinement fusion. Here we consider the deuteron beam driven as a fast ignition agent that provides not only the "hot spot" ignition spark but also the "bonus" fusion energy through in-target reactions. In this study, we estimated the impact of deposited energy caused by the fusion reactions that happened based on calculations using a modified energy amplification factor. which in Tables II and III percentege of bonus energy and total deposited energy per average initial deuteron energy and different hot spot temperature related to side reaction D-T and main reaction $D-{}^3$He in density 300 g.cm^{-3} are satisfied.

Acknowledgments

This work is supported by the Islamic Azad University of Shiraz.

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Funding

All costs of this article for publication will pay by authors.

1. M. Tabak *et al.*, Ignition and high gain with ultra powerful lasers, *Physics of Plasmas* **1** (1994) 1626
2. K. Yamazaki, T. Oishi, and K. Mori, Environmental and economic assessments of magnetic and inertial fusion energy reactors, *Nuclear Fusion* **51** (2011) 103004
3. L. Wittenberg *et al.*, A review of 3He resources and acquisition for use as fusion fuel, *Fusion Technology* **21** (1992) 2230
4. T. Kondo *et al.*, Economic Evaluation of DT, D-3He, and Catalyzed DD Fusion Reactors, *Plasma and Fusion Research* **7** (2012) 2405067
5. R. Kirkwood *et al.*, A review of laser-plasma interaction physics of indirect-drive fusion, *Plasma Physics and Controlled Fusion* **55** (2013) 103001
6. M. Tabak *et al.*, Fast ignition: Overview and background, Fusion science and technology **49** (2006) 254
7. M. Temporal *et al.*, Effects of alpha stopping power modelling on the ignition threshold in a directly-driven inertial confine-

ment fusion capsule, *The European Physical Journal D* **71** (2017) 1

8. W. M. Nevins, A review of confinement requirements for advanced fuels, *Journal of Fusion Energy* **17** (1998) 25
9. A. C. Chamberlain, Tritium, p. 153169, Cambridge Series in Chemical Engineering (Cambridge University Press, 1991).
10. A. Hasegawa, L. Chen, and M. Mauel, A D-3He fusion reactor based on a dipole magnetic field, *Nuclear Fusion* **30** (1990) 2405
11. J. Santarius *et al*., Could advanced fusion fuels be used with today's technology?, *Journal of fusion energy* **17** (1998) 33
12. J. S. Lewis, Platinum apples of the asteroids., *Nature* **372** (1994)
13. H.-S. Bosch and G. M. Hale, Improved formulas for fusion cross-sections and thermal reactivities, *Nuclear fusion* **32** (1992) 611
14. C. Friskney and J. Turnbull, The characteristics of fission gas release from uranium dioxide during irradiation, *Journal of Nuclear Materials* **79** (1979) 184
15. J. Shea, A plasma formulary for physics, technology, and astrophysics [Book Review], *IEEE Electrical Insulation Magazine* **19** (2003) 52
16. A. Solodov *et al.*, Hot-electron preheat and mitigation in polardirect- drive experiments at the National Ignition Facility, *Physical Review E* **106** (2022) 055204
17. J. J. Honrubia and J. Meyer-ter Vehn, Fast ignition of fusion targets by laser-driven electrons, *Plasma Physics and Controlled Fusion* **51** (2008) 014008.
18. S. Nakai and K. Mima, Laser driven inertial fusion energy: present and prospective, *Reports on Progress in Physics* **67** (2004) 321.
19. F. Condamine *et al*., Commissioning results from the highrepetition rate nanosecond-kilojoule laser beamline at the extreme light infrastructure, *Plasma Physics and Controlled Fusion* **65** (2022) 015004.