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Simultaneous Effects of Temperature and Temporal Changes of Tritium Reduction on the Energy Gain of DT Fuel Pellet Using DCI

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Abstract

NIn this paper, we study on the behavior of Deuterium-Tritium(D-T) plasma nuclear fusion reaction in terms of variations of time and temperature, in the presence of deuterium-tritium sources using DCI. One of the important problems in the human life is obtaining clean energy. Therefore, by solving the time and temperature dependent balance equations on the system of D-T fusion using DCI we determine the optimum physical conditions with low tritium consumption rate to obtain the total energy gain with the value of greater than 200.

Keywords: Plasma; Double Cone; Time; Gain; Temperature; Ignition

Introduction

The ICF program has focused its attention on “central hot spot” ignition, whereby a hollow spherical shell of DT ice containing DT gas is compressed, creating a central hot spot surrounded by a dense shell of cold DT [1]. The alpha particles from fusion in the hot ignition spark create a propagating fusion burn in the cold fuel. The target gain that can be achieved is limited by the high investment of energy in compression of the fuel and the threshold energy for ignition is high because the spark density is much lower than the fuel density in isobaric ignition. These factors set the minimum size of the driver and push the energy input for high gain to a few mega joules. Gain values are higher for direct drive than for indirect drive due to coupling efficiency differences, but it appears difficult to obtain gains greater than 100 , and values of a few tens are more conservative. While there are several drivers that promise high enough efficiency for the driver efficiency-target gain product to lead to an acceptable commercial inertial fusion energy (IFE) power plant.

The fast ignitor (FI) may be that concept [2]. With FI the compression and ignition steps are separated. A target of DT is compressed to high density at low temperature by lasers or particle beams. A second, very high intensity beam delivers the energy used to ignite the compressed core and heats an ignition spark at the density of the cold fuel in isochoric ignition. The FI concept promises much higher gain for the same driver energy than isobaric hot spot ignition. In addition, the “ignition threshold” that occurs at about $1\mathrm{MJ}$ for hot spot ignition may be reduced to $\sim 100\ \mathrm{kJ}$ [3]. These changes in the drive requirements for inertial fusion give rise to a cascading sequence of changes to the concept for inertial fusion energy that may lead to a much more attractive inertial fusion power plant with a much easier development pathway.

Deuterium-Tritium fusion appears to be the best and most effective way to produce energy. By fusing the two isotopes of hydrogen in to the heavier element helium large quantities of energy are released. One of the disadvantage of D-T fusion is that tritium must be created. Tritium has a half-life of a little more than ten years so there are no naturally occurring atoms left on earth. Tritium is normally bred from lithium 6 atoms by shooting them with a neutron. [4-8] In order to fusion to be economically an attractive energy source it is necessary that the energy from thermonuclear reaction exceeds both the energy invested in achieving it and the losses due to radiation, reactor wall, conversion inefficiencies, etc. A simple estimate of the driver efficiency and target gain can be obtained using energy bookkeeping approach (Fig.1). P_{th}, the power after converting the thermal energy to electrical energy.

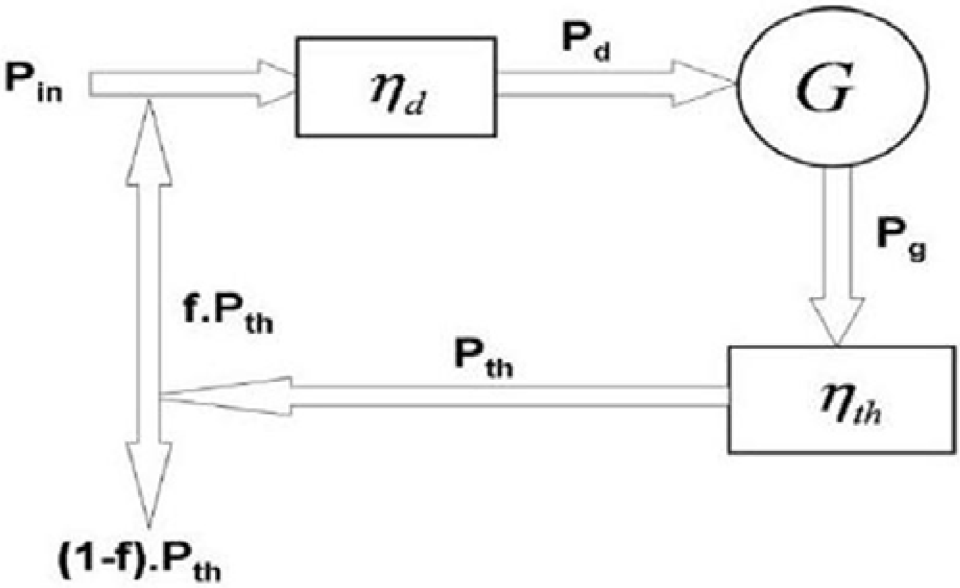

Figure 1: Power cycle. P_{in}, the input power (this could be the electrical power from the outlet). P_d, the power at the output of the driver. P_g, the power from thermonuclear fusion

Let P_{in} be the electrical power that we intend to invest in achieving fusion and let η_d be the efficiency of conversion of this power to laser light power P_d. If we define the target gain as the ratio of the power obtained from the fusion reaction to the driver power, then: $P_g = GP_d = G\eta_d P_{in}$ taking into account the conversion efficiency from thermal to electrical power, the available electrical power is given by: $P_{th} = \eta_{th} P_g = G\eta_{th}\eta_d P_{in}$. A fraction $fG\eta_{th}\eta_d P_{in}$ of this power is used to run the driver and the remaining fraction $(1-f)G\eta_{th}\eta_d P_{\text{in}}$ is send to the customers. The closer the factor $(1-f)$ to unity, the more electricity is available to customers. This can be achieved by using small values of f, however, f has a lower bound determined by the equation: $P_{in} = f_{\min} G\eta_{th}\eta_d P_{in} \rightarrow f_{\min} = \frac{1}{G\eta_{th}\eta_d}$. Using a typical η_{th} value of 40% and recycling less than $1/4$ of the power to run the driver, we get, $G\eta_d \geq 10$.Solid state lasers for example have an efficiency of 1-10% [9] and to fulfill the available condition, gains of 100-1000 are needed.

While major advances have been made in fusion research through inertial confinement fusion, significant challenges remain with ignition. To meet these challenges, a double-cone ignition (DCI) design is proposed in this article (see figure2).[10] In double-cone ignition design for ICF two head-on gold cones are applied to confine D-T fuel pellet ignited by high intensity laser pulses. The design is composed of four progressive controllable processes: i) quasiisentropic compression, ii) acceleration, iii) head-on collision and iv) fast heating of the compressed fuel. The quasi-isentropic compression runs inside two head-on cones. In the next step of compression, the DT fuel pellets in the cones are accelerated to forward velocities of few hundreds of kms^{-1}. Head-on collision of the compressed and accelerated fuel pellets from the cone tips convert the forward kinetic energy to the thermal energy of the colliding fuel pellets with an increased density. [11-18] The pre-heated high-density fuel pellets can keep its status for a time period of about 200 ps. Within this period, electrons with MeV energy produced by ps heating laser pulses, guided by a ns laser-generated strong magnetic field further heat the fuel efficiently. Then, the fuel pellets can gain an ignition temperature of greater than $5\mathrm{keV}$ with magnetically assisted heating of MeV electrons produced by the heating laser pulses. [19-23]

In this work, the main goal is utilizing of DCI design for calculating the optimum total energy gain in D-T mixture with low tritium consumption rate. Because, as we know tritium fuel is rare, radioactive and expensive. Therefore, firstly we introduced the balance equations on the D-T plasma fusion secondly at the available physical conditions by computer programing we solve these nonlinear point kinetic equations and finally we compute the optimum value of total energy gain with selecting low tritium consumption rate.

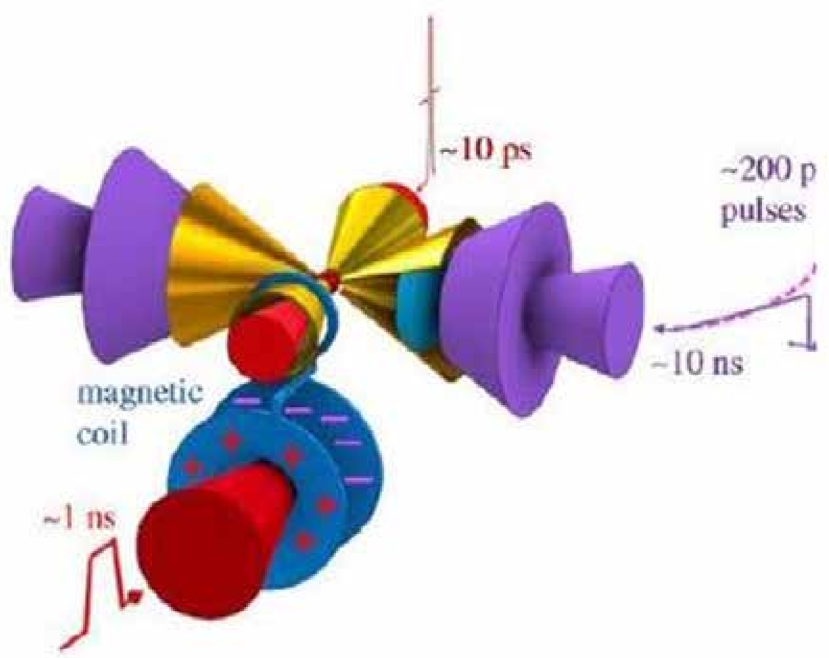

Figure 2: Schematic of the DCI. The fuel is initially installed at the inlet of the two main cones in horizontal directions. Two processes of acceleration and compression are performed on the main cones. Between the cones, a vacuum space of approximately 100 micrometers is embedded for the collision process. An additional pair of cones can be placed on the vertical plate to conduct laser pulses of ps, PW and produce hot electron beams. If a magnetic field ignition design is adopted, only two additional cones are taken along the direction of the magnetic field. [10]

Balance equations and physical parameters in the D-T system

In a plasma including deuterium and tritium, the nuclear fusion product of these nuclides are neutron and alpha particles. During the process of fusion, produced neutrons nearly escape from plasma fusion without any interaction but alpha particles remain inside the fusion plasma and increase the plasma energy. Note that we consider the steady injection of deuterium and tritium into the core with rate of S_D, and S_T, also , we consider $\tau_T, \tau_D, \tau_\alpha$, as a half-life of tritium, deuterium and alpha particles, respectively, such that $\tau_D = \tau_T = \tau_p$ thus the balance equations of particle density of deuterium $n_D(\mathrm{x})$, tritum $n_T(\mathrm{x})$ and alpha $n_\alpha(\mathrm{x})$, respectively, are given by:

$$\frac{dn_D(x)}{dt} = S_D - n_D(x)n_T(x) < \sigma V >_{DT} (x) - \frac{n_D(x)}{\tau_p} (1)$$

$$\frac{dn_T(x)}{dt} = S_T - n_D(x)n_T(x) < \sigma V >_{DT} (x) - \frac{n_T(x)}{\tau_p} (2)$$

$$\frac{dn_a}{dt} = n_D(x)n_T(x) < \sigma V >_{DT} (x) - \frac{n_\alpha(x)}{\tau_\alpha} (3)$$

With defining relative quantity $f_D(\mathrm{x}) = \frac{n_{D(x)}}{n_e(x)}, f_T(\mathrm{x}) = \frac{n_{T(x)}}{n_e(x)}, f_\alpha(\mathrm{x}) = \frac{n_{\alpha(x)}}{n_e(x)}$ in which, $n_e(\mathrm{x})$ is plasma density and defined as $n_e(\mathrm{x}) = n_D(\mathrm{x}) + n_T(\mathrm{x}) + 2n_\alpha(\mathrm{x})$, so we will have $f_D + f_T + 2f_\alpha = 1$. Also, with assuming that f_D, f_T are independent of time the equations (1)and (2) are converted to

$$f_D(x)\frac{dn_e(x)}{dt} = S_D - f_D(x)f_T(x)n_e^2(x) < \sigma V >_{DT} - \frac{f_D(x)n_e}{\tau_P}$$

$$f_T\frac{dn_e(x)}{dt} = S_T - f_D(x)f_T(x)n_e^2(x) < \sigma V >_{DT} - f_T(x)\frac{n_e(x)}{\tau_P}$$

We assume that $S_{DT} = S_D + S_T$ and by adding the two equations of (4) and (5) we obtain:

$$\frac{dn_e(x)}{dt} = \frac{S_{DT}}{f_D + f_T} - \frac{f_D f_T}{f_D + f_T} n_e^2(x) < \sigma V >_{DT} - \frac{ne(x)}{\tau_P} (6)$$

Where $< \sigma v >_{DT}$ is the average reactivity of deuterium-tritium fusion reaction. Which is:

$$< \sigma V >_{DT} = 3.68 * 10^{-18} \frac{1}{T^{2/3}} \exp\left(-\frac{19094}{T^{1/2}}\right) [m^3/\mathrm{sec}]$$

Figure 3 shows the variations of $\mathrm{D} - \mathrm{T}$ average reactivity versus temperature

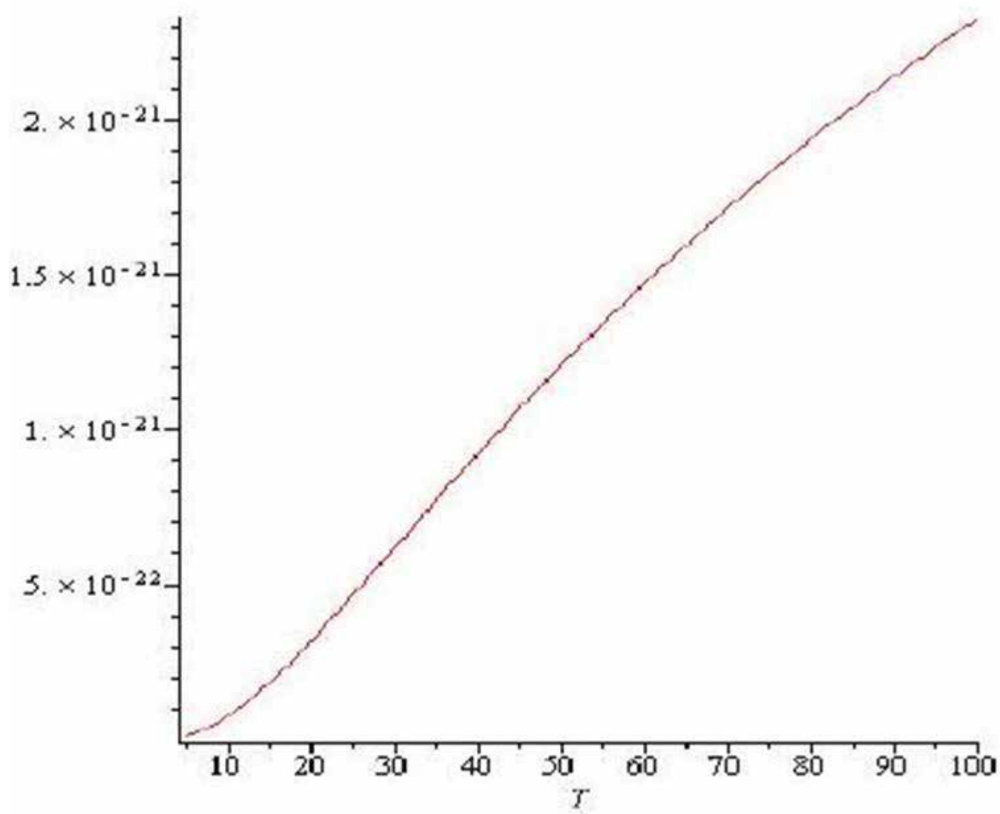

Figure 3: Variations of $< \sigma \mathrm{V}_{DT}$ in terms of temperature

We solve the above equations in terms of time by assuming that $S_T = S_D = 2.2 * 10^{20} m^{-3} S^{-1}$ and $\tau_p = 2$ s and $T = 100$KeV. In Figure. 4a, the time variations of plasma density for some specific f_T is shown. From this figure ,we see clearly that by increasing the time and f_T the plasma density is increased and from a special time by increasing the time for each value of f_T the plasma density is constant. Also, in figure.4b the three dimensional variations of plasma density are given.

Also, figures.5,6 and 7 show that the three dimensional variations of deuterium, tritium and alpha particle density in terms of time and tritium fraction.

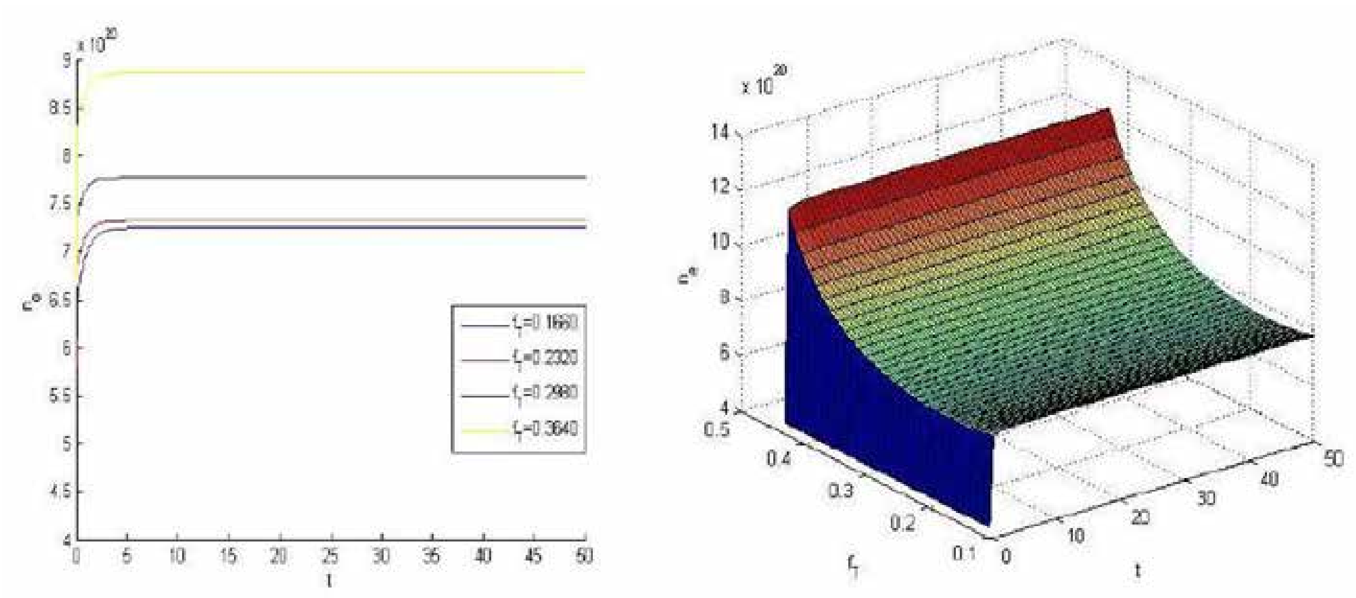

Figure 4: a:Two and b:three dimensional variation of plasma density in terms of time for different values of f_T

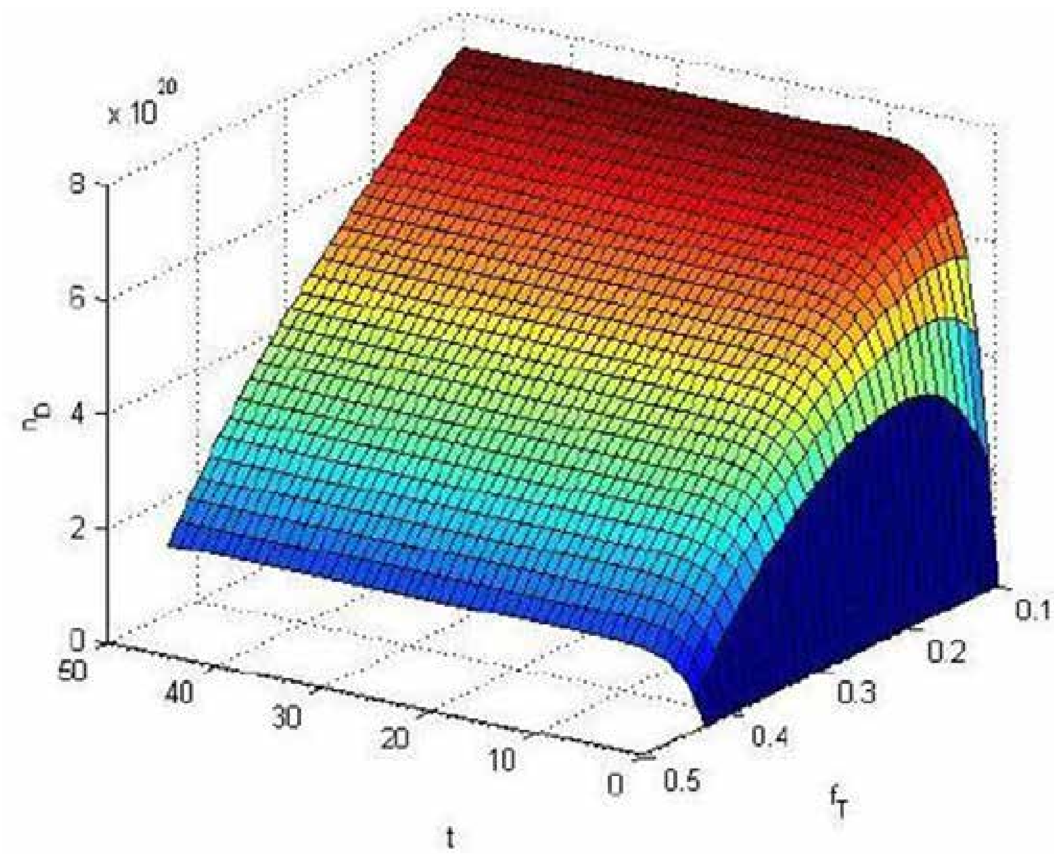

Figure 5: Three dimensional variations of deuterium density versus time and f_T

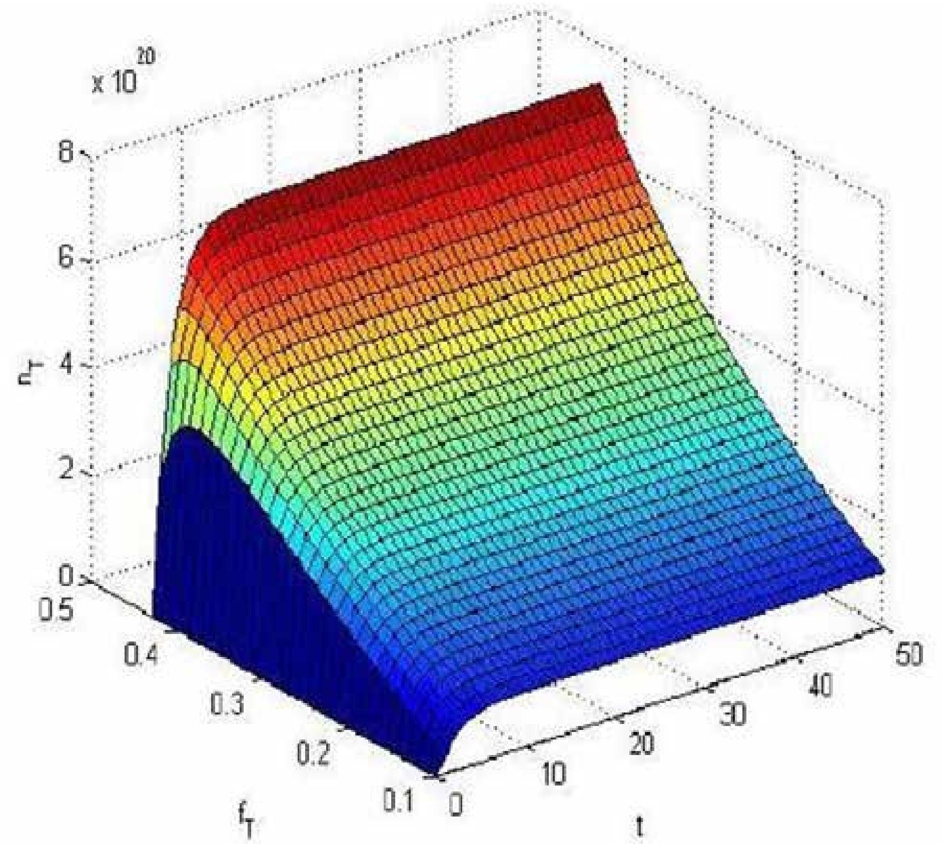

Figure 6: The three dimensional variations of tritium density versus time and f_T

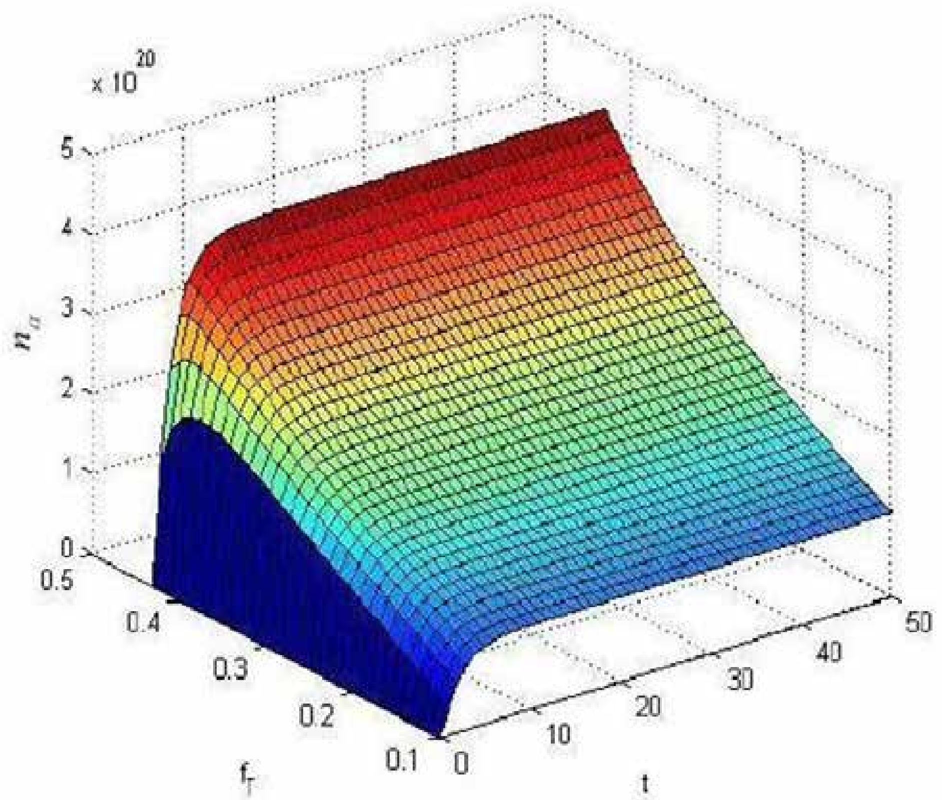

Figure 7: The three dimensional variations of alpha particle density versus time and f_T

From these figures and our calculated numerical values of n_D, n_T and n_α in terms of time and f_T we find that by increasing time n_D, n_T and n_α are increased also in a constant time by increasing f_T, n_T and n_α are increased but n_D is decreased. Because by increasing f_T from equation of $f_D = 1 - f_T - 2f_\alpha, f_D$ is decreased and thus n_D is decreased. But, if in system there are no any source injection of deuterium and tritium, then the density of deuterium and tritium are reduced while the density of alpha particles is increased.

The other parameter in this reaction is known as burn consumption fraction that is given by:

$$\varphi = \frac{\int_0^\tau (S_D + S_T)dt' + n_e^o - n_e(\tau)}{\int_0^\tau (S_D + S_T)dt' + n_e^o}$$

Where n_e^0 is plasma density at time $t = 0$. On the other hand mass density of plasma is defined as

$$P = \sum_i m_i n_i = n_D m_D + n_T m_T + n_\alpha m_\alpha = n_e(t)[f_D 2(Amu) + f_T 3(Amu) + f_\alpha 4(Amu)]$$

Finally, we will have

$$P = n_e(t) \times 1.66 \times 10^{-24}[2f_D + 3f_T + 4f_\alpha]$$

Calculation of power and energy density for D-T fusion reaction in the presence of the deuterium and tritium sources

Another important issue that should be consider about fusion plasma of deuterium-tritium, is behavior of total power in fusion system.

Total power includes $P_\alpha, P_{oh}, P_{\text{ext}}, P_{\text{berms}}, P_{\text{loss}}, P_{sync}$ which are defined in the following ,respectively:

a) P_α: is the portion of transmitted power to high energy alpha particles produced from D-T reaction that is deposited into the plasma.

b) P_{oh} :is a thermal power

c) P_{ext} : the total power that is given to the system by an external factor.

d) P_{berms} :is the portion of loss power that is due to Bremsstrahlung radiation

e) P_{loss} :is the portion of transmitted power to alpha particle, during the D-T reaction because of escaping alpha particle from fusion plasma that is not deposited in the chamber.

f) P_{sync} : is the portion of loss power that is due to synchrotron radiation.

So due to being loss ,$P_{sync}, P_{berms}, P_{\text{loss}}$ and being productive $P_\alpha, P_{oh}, P_{\text{ext}}$, we have the following equilibrium energy density:

$$\frac{dw(x)}{dt} = \frac{P_{ext}}{V} + P_{oh} + P_\alpha - P_{\text{loss}} - P_{brems} - P_{sync}$$

with: [4,3]

$$\left.\begin{array}{r} P_\alpha = 5.6 \times 10^{-13} n_{(o)}^2 f_D f_T < \sigma V >_{DT} \left[\frac{w}{m^3}\right] \\ P_{brems} = 5.4 \times 10^{-37} n_e^2(o) Z_{ff} \sqrt{T_e(o)} \\ P_{\text{loss}} = \frac{3}{2} \times 106 \times 10^{-19} n_e^{(o)} T_e (1 + f_D + f_T)/\xi_E \left[\frac{w}{m^3}\right] \end{array}\right]$$

In these relations temperature is in keV and we have: [4,5]

$$T_e(x) = \frac{T_e(o)}{1 + \alpha_T}$$

$$n_e(x) = \frac{n_e(o)}{1 + \alpha_n}$$

Where $d_n = 0.5, \alpha_T = 1, z_{eff} = \frac{1}{n_{z(0)}} \sum_z n_z^2(x) \cong 2, \tau_E = 1.4$.[see ref.6] .In figs.8,9 and 10 the variations of $P_\alpha, P_{\text{berms}}$ and P_{loss} in terms of time for several values of f_T are given.

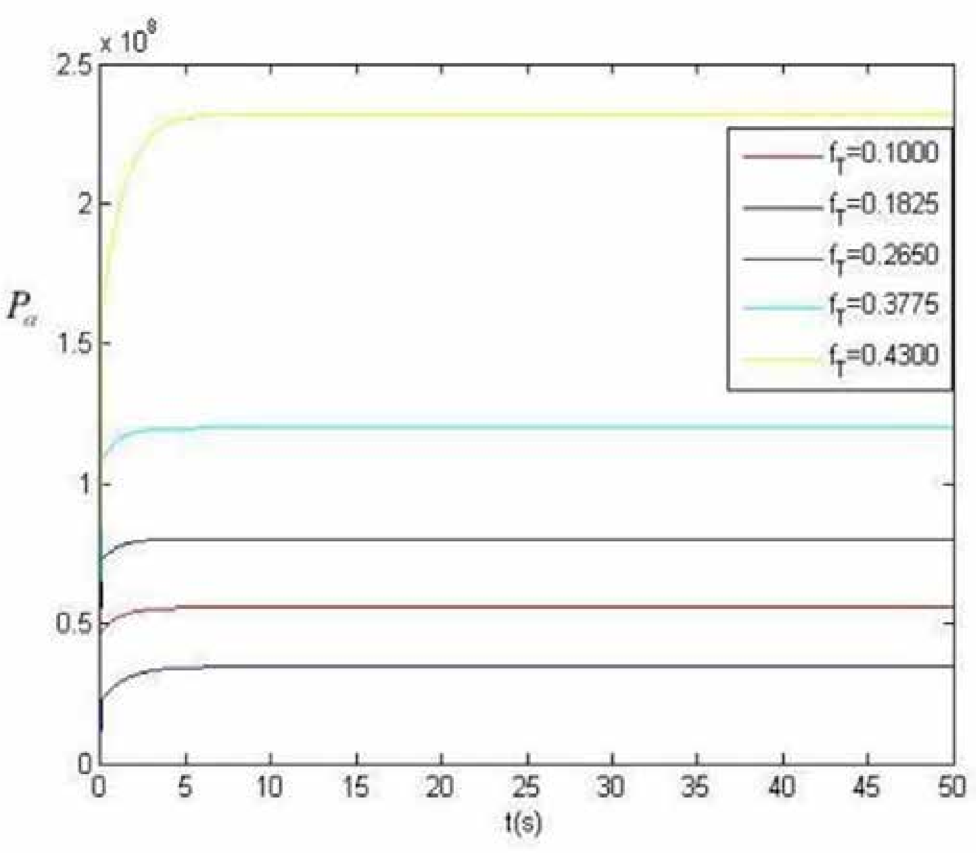

Figure 8: Two dimensional variations of P_α versus time for several values of f_T

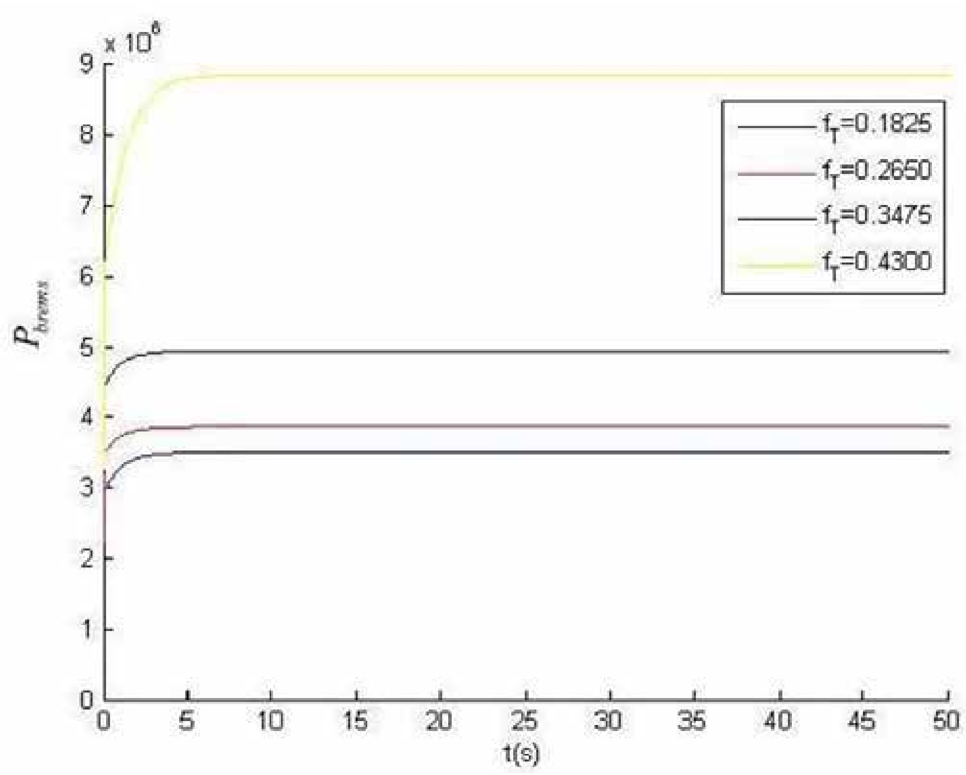

Figure 9: Two dimensional variations of P_{berms} versus time for several values of f_T

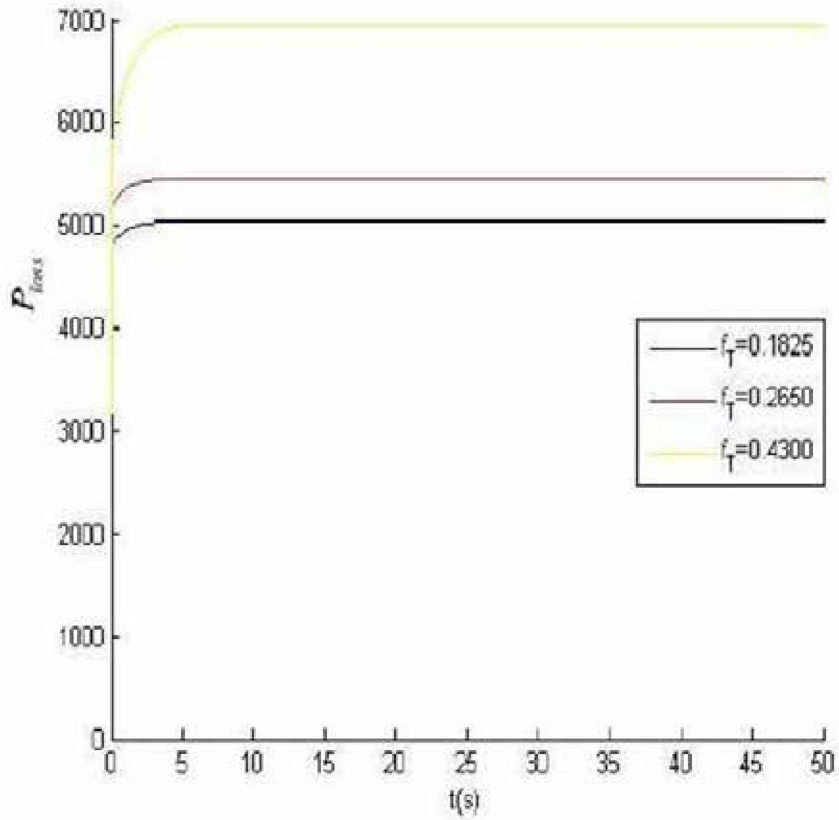

Figure 10: Two dimensional variations of P_{loss} versus time for several values of f_T

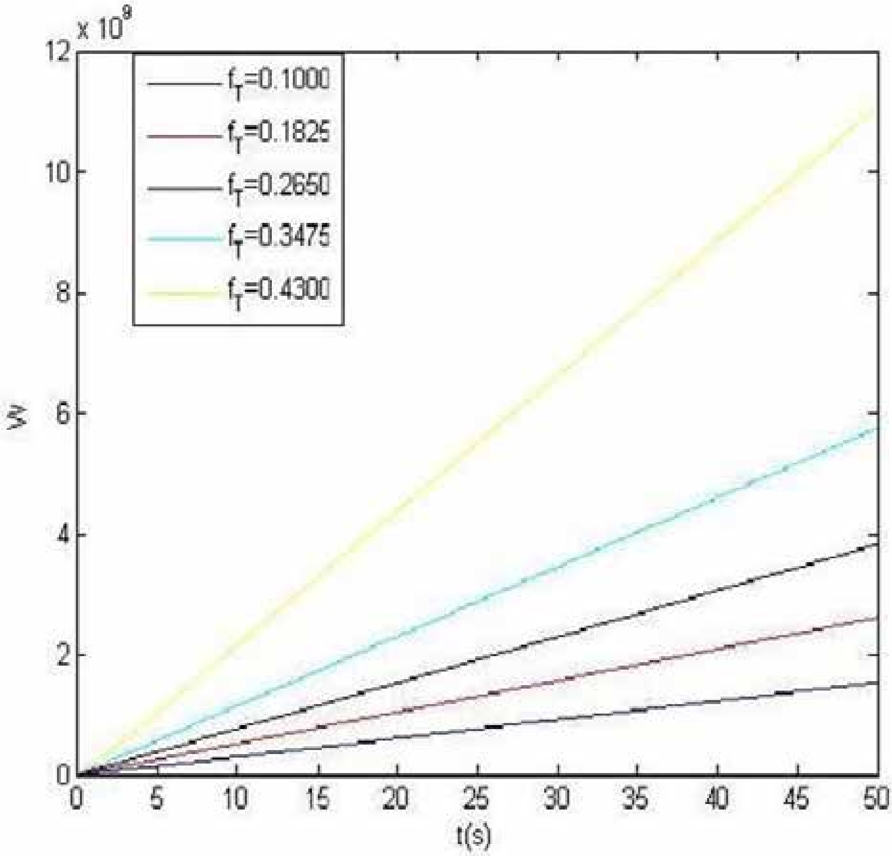

Figure 11: Variations of energy density in terms of time for several f_T

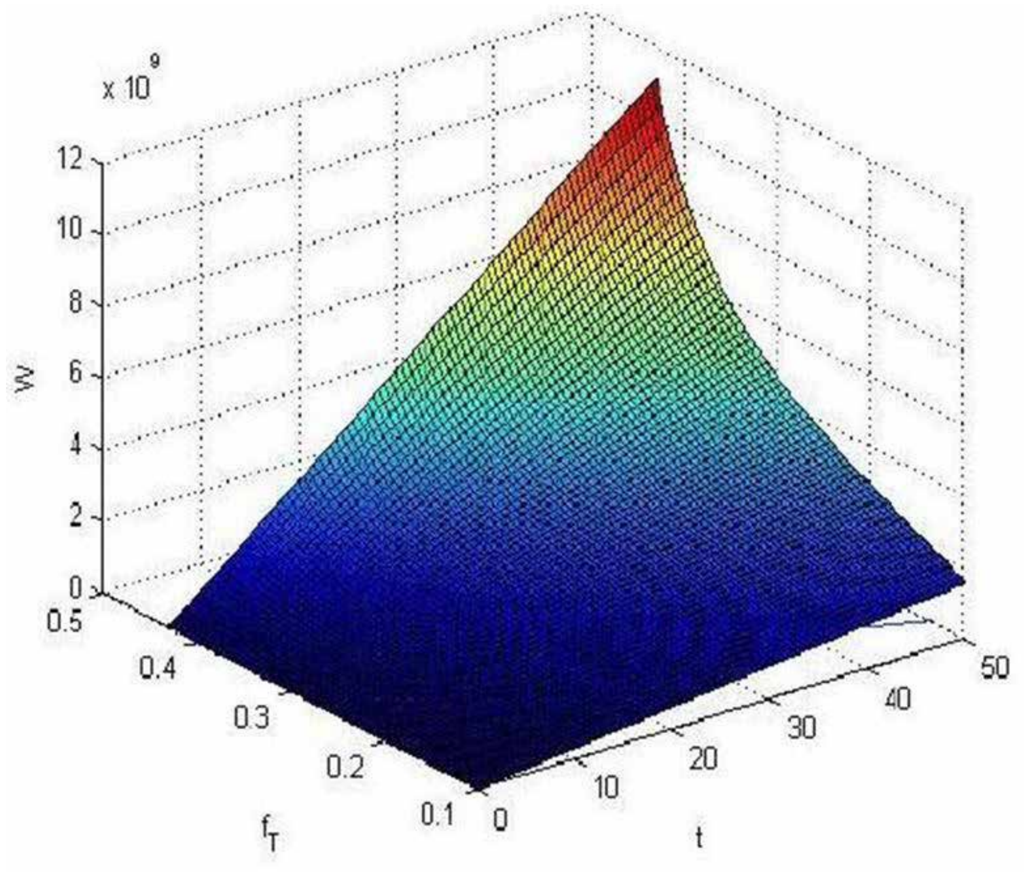

Figure 12: Three dimensional variations of energy density in terms of time and f_T

We see clearly from these figures ,by increasing f_T, n_e is increased and thus by enhancement of n_e according to $\mathrm{n}_\alpha = \mathrm{f}_\alpha \times \mathrm{n}_\mathrm{e}, n_\alpha$ is raised therefore P_α is increased. Also by increasing f_T, f_α and f_D are decreased therefore by observing relation $f_D = 1 - f_T - 2f_\alpha$, therefore by increasing f_α and f_T, f_D is reduced. On the other hand by increasing f_T, n_e is raised and n_e is dominant on the $f_D + f_T$, finally P_{loss} is increased by enhancement f_T. Also, P_{berms} by increasing time is increased because by raising time , plasma density is increased ,therefore the collisions of charged particles are increased thus the energy is dissipated in the form of radiation. In Figure 11, the variations of energy density in terms of time for several f_T is shown.

Also in Figure 12 , the three dimensional variations of energy density in terms of time and f_T is given.

Study on the temperature effects on the tritium-deuterium fusion

Another point that should be referred to in tritium-deuterium fusion is the effect of temperature changes in terms of time, to achieve this goal ,by doing time derivative from equation $n_e(\mathrm{x}) = n_D(\mathrm{x}) + n_T(\mathrm{x}) + 2n_\alpha(\mathrm{x})$ we have:

$$\frac{dn_e(x)}{dt} = \frac{dn_D(x)}{dt} + \frac{dn_T(x)}{dt} + 2\frac{dn_\alpha(x)}{dt}$$

By inserting relations (1), (2), (3), in this relation we have:

$$\frac{dn_e(x)}{dt} = S_{DT} - \frac{n_D(x) + n_T(x)}{\tau_P} - 2\frac{n_\alpha(x)}{\tau_\alpha}$$

However, we know that energy density for a system with density n and temperature T, is:

$$w = 3/2nT$$

where is T is in Kev. So the plasma energy density is given by:

$$\mathrm{w(x)} = 3/2^{[n_e T_e} + (n_D + n_T + n_e)T_i].$$

In which T_e is electronic temperature and T_i is ionic temperature. By derivation of this equation respect to time we obtain:

$$\frac{dw(x)}{dt} = \frac{3}{2}\left[\begin{matrix}\frac{dn_e(x)}{dt}T_e(x) + n_e(x)\frac{dT_e(x)}{dt} + \left(\frac{dn_D(x)}{dt} + \frac{dn_T(x)}{dt} + \frac{dn_\alpha}{dt}\right)T_i +] \\ (n_D(x) + n_T(x) + n_\alpha(x))\frac{dT_i(x)}{dt}\end{matrix}\right]$$

and with assuming that quantity $\gamma_e = \frac{T_i(x)}{T_e(x)}$ is constant and using relation

$n_e(x) = n_p(x) + n_T(x) + 2n_\alpha(x)$ we have:

$$\frac{dw(x)}{dt} = \frac{3}{2}T_i(x)\left(\left(1+\frac{1}{\gamma_e}\right)\frac{dn_e(x)}{dt} - \frac{dn_\alpha(x)}{dt}\right) + \frac{3}{2}\frac{dT_i(x)}{dt}\left((1+1/\gamma_e)n_e(x) - n_\alpha(x)\right)$$

If we replace equation (11) in the left hand side of equation (22) we obtain:

$$\frac{dT_i(x)}{dt} = \frac{1}{\frac{3}{2}(1+1/\gamma_e - f_\alpha)n_e(x)}(p_\alpha - p_{\text{brems}} - p_{\text{loss}}) - \frac{T_i}{(1+1/\gamma_e - f_\alpha)n_e(x)} \times \left(\left(1+\frac{1}{\gamma_e}\right)\frac{dn_e(x)}{dt} - \frac{dn_\alpha(x)}{dt}\right)$$

By obtaining T_i from above equations and using the equation $T_e = T_i/\gamma_e$ we can calculate T_e.in the Figure 13 the variations of T_i (ionic temperature) versus time for different values of f_T is shown.

Also fuel energy gain of D-T fusion reaction is given by:

$$G_F = \frac{Y m \varphi \times 10^{-3}}{m\alpha C_a \rho^{\frac{2}{3}} + 0.14\rho_{100}^{-1.85}}$$

In the Table.1 numerical values of different parameters for calculation energy gain is given.

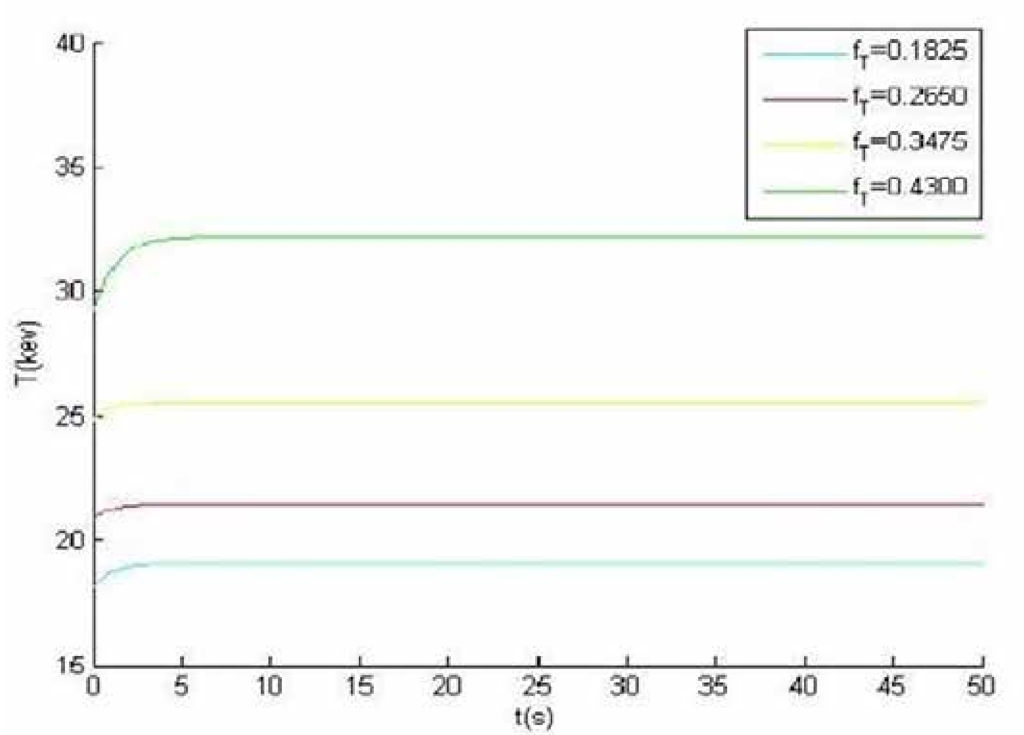

Figure 13: Variations of T_i (ionic temperature) versus time for different values of f_T. From this figure we see that , for each value of f_T by raising time T_i is increased to a maximum value and then becomes constant because by increasing time system achieve a steady state and by increasing f_T the number of fusion reactions are increased therefore more energy is released and temperature of system is increased.

Table 1: Numerical values of different parameters for calculation energy gain

Parameter	DT
Y	335
$C_d MJ \cdot g^{-1} \left(\frac{g}{c^3}\right)^{-\frac{2}{3}}$	0.32
α	
M(mg)	1.24

In the figure 14, the variation of energy gain versus temperature for different values of f_T is shown. From this figure we conclude that, by increasing temperature energy gain is increased because by enhancement temperature the fusion cross section increases therefore the number of fusion reactions are increased also φ is increased .Finally the total energy gain is given by:

$$G_{DT} = \eta G_F = \left(\eta_c \frac{Ed_c}{Ed} + \eta_{ig} \frac{Ed_{ig}}{Ed}\right) G_F$$

By assuming that $\eta_c \approx \eta_{ig}$ and $E_{dig} << E_d$ we will have:. $G_{DT} \approx \eta_c G_F$ In the figure 15 the three dimensional variations of total energy gain in terms of f_T and temperature is shown.

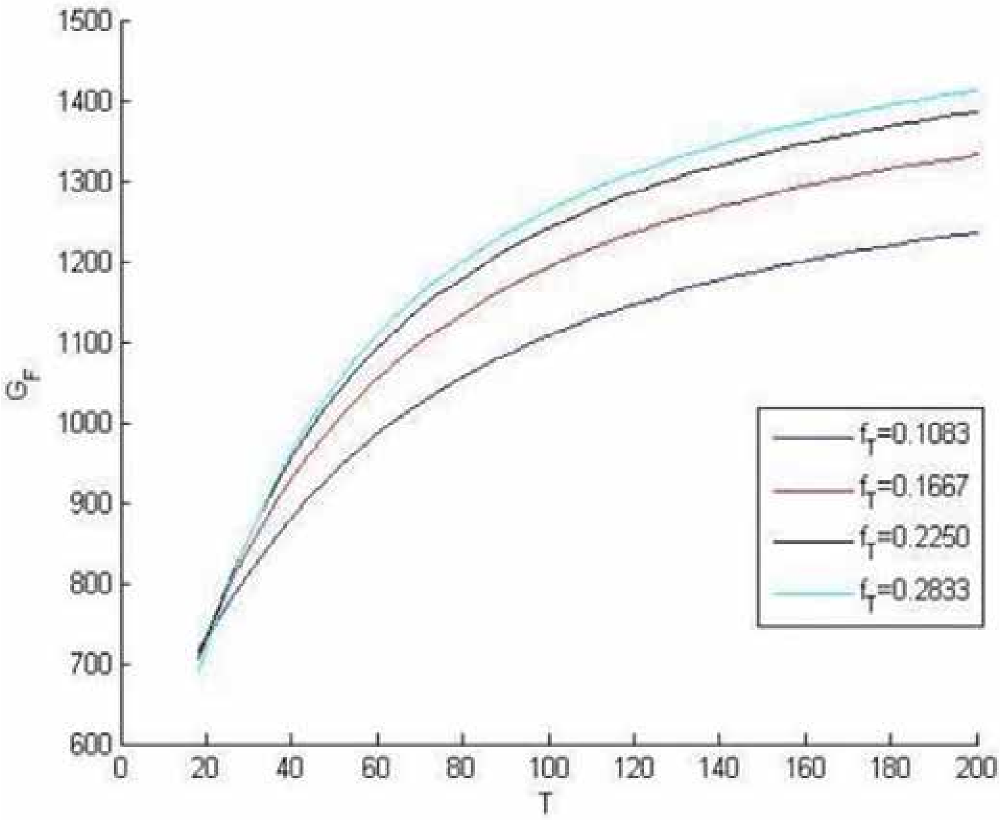

Figure 14: Variations of energy gain versus temperature for different values of f_T at $\rho R = 1.2$

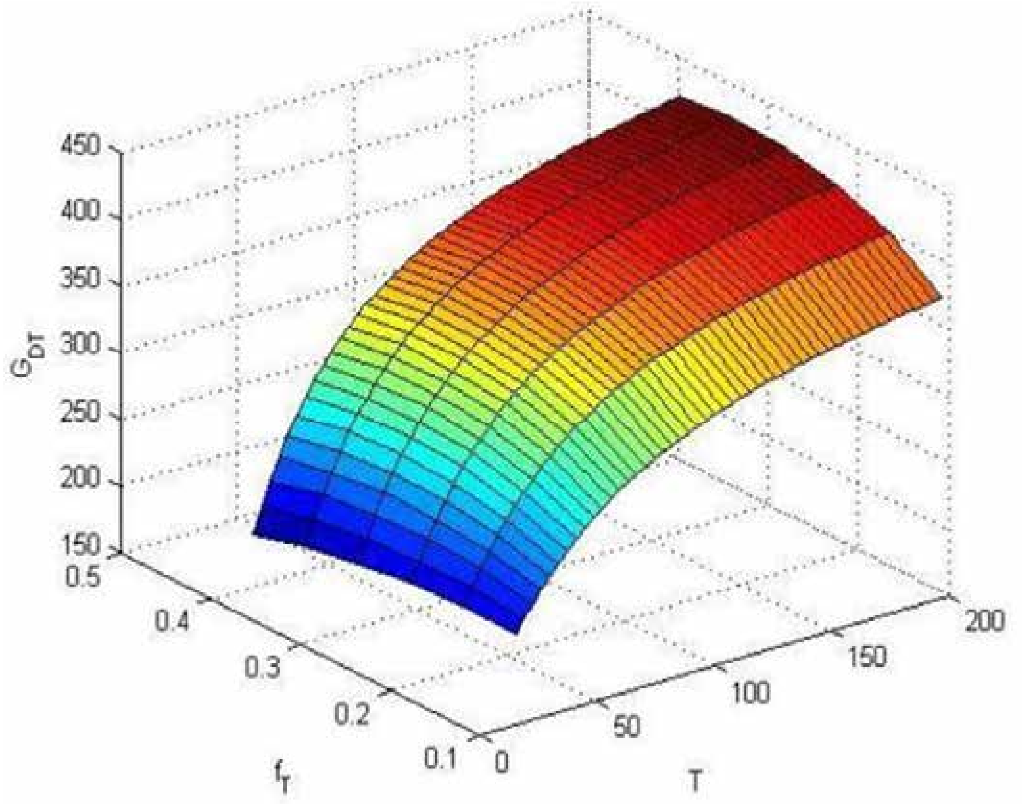

Figure 15: The three dimensional variations of total energy gain in terms of f_T and temperature at

$\rho R = 1.2 \frac{g}{cm^2}, \eta_c = 0.3$

Also in Table2, the numerical values of total energy gain versus at available physical conditions is given. Our calculations show that by increasing ρR and constant f_T the total energy is increased and maximized at $\rho R = 1.2 \frac{g}{cm^2}$.In Table 2 the maximum values of total energy gain in the interval $[\rho R_1, \rho R_2]$ at different values of f_T are given. Table2: the maximum values of total energy gain in the interval $[\rho R_1, \rho R_2]$ at different values of f_T

and $\eta_c = 0.3$

$\rho R2$	$\rho R1$	f_T	G_{DT}^{max}
2.184	0.852	0.0500	284.33
2.379	0.780	0.0792	310.64
2.617	0.733	0.1083	329.86
2.823	0.703	0.1375	344.29
2.970	0.682	0.1667	355.24
3.072	0.667	0.1958	363.49
3.146	0.655	0.2250	369.57
3.195	0.648	0.2542	373.79
3.225	0.643	0.2833	376.38
3.238	0.641	0.3125	380.79

From this table we see that at all different values of f_T there is an interval of $[\rho R_1, \rho R_2]$ such that in this interval the total energy gain is greater than 200.

Notice that in our calculations we use the data inside the Table 3.

Table 3: The proposed laser parameters for DCI design which is used here

	Beam number	Energy per beam	duration
ps lasers	8	2.5 kJ/10ps/1ω	$1-10$ps
ns lasers	32	8 kJ/10 ns/1ω	$0.2-20$ ns

Conclusion

In this paper, by solving the balance equations for deuterium-tritium fusion reaction in the presence of deuterium-tritium source by utilization of DCI design, for the first time, we obtained the time dependent particle density. Then we determined the total energy of the system. We see that by reducing f_T the energy density is decreased but their amount are still considerable. If we analyze the system from economical point of view we conclude that decreasing the f_T is an important point because tritium is rare ,radioactive and expensive fuel . Also we saw that by decreasing f_T the total energy gain of the system is decreased but even with selecting low f_T and making a system with ρR in the suggested interval $[\rho R_1, \rho R_2]$ we can get the energy gain more than 200 . Therefore from this work we conclude that using of DCI design the energy gain is increased respect to cone guided ignition . Therefore, it is hoped that the use of DCI design in the future can lead us to more energy efficiency, but in the meantime, more research is needed on the fabrication of such fuel pellets and the challenges that govern it.

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