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Effect of tritium reduction in determining energy gain by using R-matrix method direct laser fusion in D-T reaction

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Abstract The laser fusion criterion is known as the ρR-Criterion, also called high-gain condition. This parameter is temperature dependent and can be calculated by R-matrix method. This method is applied for determining improved fusion cross-section for the reactions $T(d,n)^4He$, $^3He(d,p)^4He$, D(d,p)T, $D(d,n)^3He$. In this paper the time dependent reaction rate equations for fusion reaction $T(d,n)^4He$ are solved and by using the obtained results we computed the fusion power density, energy gain versus temperature and ρR-parameter. The obtained results show that a suitable combination may be a deuterium fraction f_D=0.65 and f_T=0.35 which would lead 30% reduction in the tritium content of the fuel mixture, and this choice would not change the energy gain value very much. Finally, the obtained energy gain for D-T reaction by using R-matrix is in good agreement with other theories.

Key words Deuterium-tritium reaction, Direct laser fusion, Plasma, Cross section

CLC numbers O571.44, $TL61^+2$

1 Introduction

The principle of laser fusion is implosion, which aims to increase the fuel density at which the fusion reaction occurs so rapidly that fusion burning is completed faster than the expansion of the compressed fuel. Therefore, this process is called inertial confinement fusion (ICF). ICF by a laser is called laser fusion. There are mainly two different schemes for pellet implosion, i.e. direct and/or indirect drive. In "direct drive implosion", the surface of the fuel pellet is directly irradiated. In "indirect drive implosion", the driver energy is converted to soft X-rays, and is absorbed on the surface of the fuel to generate ablation pressure to drive the implosion.

In this work, we have mainly focused on the case of direct-drive implosion: when an intense laser light impinges uniformly on a spherical fuel pellet, the laser energy is absorbed on the surface to generate a high temperature plasma, and an extremely high pressure is generated. This pressure accelerates outer shell of the target toward the target center as schematically shown in Fig.1. Mechanism of the acceleration is the same as a rocket propulsion. When the accelerated fuel collides at the center, compression and heating occur. If the dynamics are sufficiently spherical symmetric, the central area is heated and a fusion reaction starts.

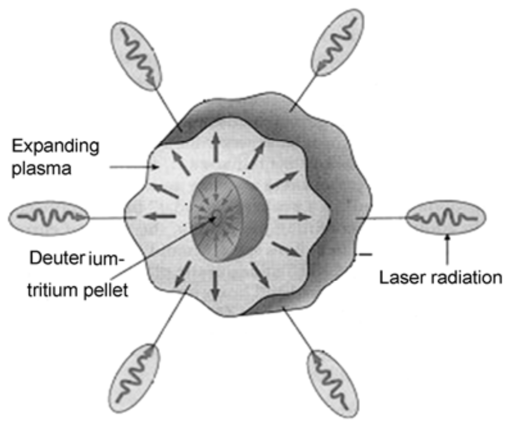

Fig.1 The concept of a laser driven implosion.[1]

In this paper the authors survey the major areas of research. Section I relates the determination of fusion cross section by R-matrix method, while Section II

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describes the reactivity parameterization for different fusion reactions of D(d,n)^{3}He, D(d,p)T, T(d,n)^{4}He, and ^{3}He(d,n)^{4}He. Section III discusses the energy gain and ρR parameter, Section IV gives the basic equations for D-T reaction, and Section V shows details of our calculations on the energy gain. The final section presents an overview of what is known.

2 Determination of cross section by using R-matrix analyses

Empirical measurements of fusion reaction rates are only possible when energies approaching the Coulomb barrier, i.e., in the tens of keV range. However, these results can be extrapolated to the lower electron volt temperatures with the use of quantum mechanical scattering theory. Indeed, fusion reactions between two nuclei can be divided into two parts, which are approximately independent of each other, namely the atomic physics of the nuclei approaching each other, and the nuclear physics valid if they are close enough to feel the nuclear forces. The strong energy dependence of the fusion cross section is mainly due to the repulsive Coulomb potential. As long as the energy available in the center of mass frame is much smaller than the Coulomb barrier, reactions are possible only because of the tunneling effect, and the cross-section is proportional to the tunneling probability:

$(\sigma \propto \exp\left(-\frac{B_{\mathrm{G}}}{\sqrt{E}}\right))$.

The cross-section data from the R-matrix are fitted using the following parameterization formula:[2-5]

$$\sigma = S(E)\frac{1}{E}\exp\left[-\frac{B_{\mathrm{G}}}{\sqrt{E}}\right] \tag{1}$$

where the astrophysical constant $S(E)$ varies slowly with the center of mass energy E. The S-values calculated from the R-matrix cross-sections with Eq.(1) were fitted with a Pade polynomial:

$$S(E) = \frac{A_1 + E(A_2 + E(A_3 + E(A_4 + EA_5)))}{1 + E(B_1 + E(B_2 + E(B_3 + EB_4)))} \tag{2}$$

The numerical values of A_1, A_2, A_3, A_4, A_5, B_1, B_2, B_3, and B_4, for nuclear fusion reactions of D(d,n)^{3}He, D(d,p)T, T(d,n)^{4}He, and ^{3}He(d,n)^{4}He, are given in Table 1.[2] Also where $B_{\mathrm{G}} = \pi\alpha Z_1 Z_2\sqrt{2m_{\mathrm{r}}C^2}$ is the Gamov constant, expressed in terms of the fine structure constant, $\alpha = \frac{e^2}{\hbar C} \approx \frac{1}{137.03604}$, and the reduced mass of the particles, $m_{\mathrm{r}}C^2$ in keV, E denotes the energy available in CM frame and Z_1e, Z_2e are the nuclei charges. Fig.2 shows variation of $S(E)$ with the relative energy of the reacting particles for fusion reactions D(d,n)^{3}He, D(d,p)T, T(d,n)^{4}He, and ^{3}He(d,p)^{4}He.

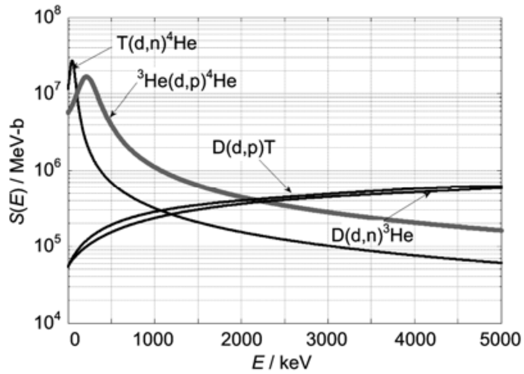

Fig.2 The variations of S-function with CM energy for different fusion reaction D(d,n)^{3}He, D(d,p)T, T(d,n)^{4}He, and ^{3}He(d,p)^{4}He.

Table 1 The values of A_1, A_2, A_3, A_4, A_5, B_1, B_2, B_3, B_4 for fusion reactions D(d,n)^{3}He, D(d,p)T, T(d,n)^{4}He, and ^{3}He(d,p)^{4}He [5]

Coefficient	T(d,n)^{4}He	^{3}He(d,p)^{4}He	D(d,p)T	D(d,n)^{3}He
$B_0/\sqrt{\mathrm{keV}}$	34.3827	68.7508	31.3970	31.3970
A_1	6.927×10^{4}	5.7501×10^{6}	5.5576×10^{4}	5.3701×10^{4}
A_2	4.454×10^{3}	2.5226×10^{3}	2.1054×10^{2}	3.3027×10^{2}
A_3	2.050×10^{6}	45.566	-3.2638×10^{-2}	-0.12706
A_4	5.2002×10^{4}	0	1.4987×10^{-6}	2.9327×10^{-5}
A_5	0	0	1.8181×10^{-10}	-2.5151×10^{-9}
B_1	63.8	-3.1995×10^{-3}	0	0
B_2	-0.995	-8.5530×10^{-6}	0	0
B_3	6.981×10^{-5}	0	0	0
B_4	1.728×10^{-4}	0	0	0

3 The reactivity parameterization

The fusion rate depends on the relative velocity of the reacting particle and since in a plasma the ions have not single velocity but a velocity distribution, the reaction rate density in a thermal gas/plasma can be expressed as:[2,3]

$$\frac{\mathrm{d}R}{\mathrm{d}V}=\frac{n_i n_j}{1+\delta_{ij}}<\sigma v> \tag{3}$$

where n_i, n_j are number densities of the two nuclei species, δ_{ij} is the Kronecker delta function. With $f(v_i)$ being the velocity distribution of a particle and g being the relative velocity ($g=v_i-v_j$), we obtain:

$$\langle\sigma v\rangle=\int\sigma(|g|)gf_1(v_i)f_2(v_j)\mathrm{d}v_i\mathrm{d}v_j \tag{4}$$

The thermal reactivity for different fusion reactions calculated numerically, on the basis of the new R-matrix cross-sections:[5]

$$<\sigma v>=C_1\theta\sqrt{\zeta/(m_\mathrm{r}c^2T^3)}\,\mathrm{e}^{-3\xi} \tag{5}$$

where

$$\theta=\frac{T}{\left[1-\dfrac{T\left(C_2+T(C_4+TC_6)\right)}{1+T\left(C_3+T(C_5+TC_7)\right)}\right]} \tag{6}$$

and

$$\zeta=\left(\frac{B_\mathrm{G}^2}{4\theta}\right)^{1/3} \tag{7}$$

The parameters C_1, C_2, C_3, C_4, C_5, C_6, C_7 resulting from fitting method are shown in Table 2. The reactivity $\langle\sigma v\rangle$ is in $\mathrm{cm^3{\bullet}s^{-1}}$ when T is the ion temperature in keV. By using Eq.(5), Eq.(6), Eq.(7) and Table 2 we can calculate $\langle\sigma v\rangle$ for different fusion reactions: D(d,n)^{3}He, D(d,p)T, T(d,n)^{4}He, and ^{3}He(d,p)^{4}He. The results are given in Table 3. Also the temperature dependence of $\langle\sigma v\rangle$ for these reactions is shown in Fig.3. From this figure we see that the mixture of deuterium (D) and tritium (T) are considered most promising as a first fusion fuel ,since the DT fusion reaction has the largest thermal reactivity at low temperatures.

Table 2 The numerical values of parameters C_1, C_2, C_3, C_4, C_5, C_6 and C_7 [5]

Coefficient	T(d,n)^{4}He	^{3}He(d,p)^{4}He	D(d,p)T	D(d,n)^{3}He
C_1	1.17302×10^{-9}	5.051036×10^{-10}	5.65718×10^{-12}	5.43360×10^{-12}
C_2	1.51361×10^{-2}	6.41918×10^{-3}	3.41267×10^{-3}	5.85778×10^{-3}
C_3	7.51886×10^{-2}	-2.022896×10^{-3}	1.99167×10^{-3}	7.688222×10^{-3}
C_4	7.60643×10^{-3}	-1.91080×10^{-3}	0	0
C_5	1.35000×10^{-2}	1.35776×10^{-4}	1.05060×10^{-5}	-2.96400×10^{-6}
C_6	-1.06750×10^{-4}	0	0	0
C_7	1.36600×10^{-3}	0	0	0

Table 3 Thermal reactivity for all reactions as a function of ion temperature (to be continued in next page)

E / keV	$\langle\sigma v\rangle_\mathrm{DT}$ /cm^3•s^{-1}	$\langle\sigma v\rangle_{\mathrm{D}^3\mathrm{He}}$ /cm^3•s^{-1}	$\langle\sigma v\rangle_\mathrm{DD,T}$ /cm^3•s^{-1}	$\langle\sigma v\rangle_{\mathrm{DD},^3\mathrm{He}}$ /cm^3•s^{-1}
1	6.27×10^{-27}	3.10×10^{-32}	9.65×10^{-29}	9.66×10^{-29}
2	2.83×10^{-25}	1.41×10^{-29}	3.04×10^{-27}	3.05×10^{-27}
3	1.81×10^{-24}	2.73×10^{-28}	1.57×10^{-26}	1.57×10^{-26}
4	5.86×10^{-24}	1.74×10^{-27}	4.37×10^{-26}	4.35×10^{-26}
5	1.35×10^{-23}	6.46×10^{-27}	8.97×10^{-26}	8.90×10^{-26}
6	2.53×10^{-23}	1.73×10^{-26}	1.55×10^{-25}	1.53×10^{-25}
7	4.14×10^{-23}	3.76×10^{-26}	2.39×10^{-25}	2.35×10^{-25}
8	6.17×10^{-23}	7.15×10^{-26}	3.42×10^{-25}	3.33×10^{-25}
9	8.75×10^{-23}	1.23×10^{-25}	4.62×10^{-25}	4.48×10^{-25}
10	1.13×10^{-22}	1.97×10^{-25}	5.99×10^{-25}	5.76×10^{-25}

Table 3 (continued)

E / keV	$\langle\sigma v\rangle_{\rm DT}$ /cm^3•s^{-1}	$\langle\sigma v\rangle_{\rm D^3He}$ /cm^3•s^{-1}	$\langle\sigma v\rangle_{\rm DD,T}$ /cm^3•s^{-1}	$\langle\sigma v\rangle_{\rm DD,^3He}$ /cm^3•s^{-1}
20	4.31×10^{-22}	3.26×10^{-24}	2.65×10^{-24}	2.41×10^{-24}
30	6.65×10^{-22}	1.32×10^{-23}	5.44×10^{-24}	4.76×10^{-24}
40	7.93×10^{-22}	3.09×10^{-23}	8.54×10^{-24}	7.28×10^{-24}
50	8.54×10^{-22}	5.37×10^{-23}	1.18×10^{-23}	9.84×10^{-24}
60	8.76×10^{-22}	7.88×10^{-23}	1.50×10^{-23}	1.24×10^{-23}
70	8.67×10^{-22}	1.04×10^{-22}	1.82×10^{-23}	1.49×10^{-23}
80	8.64×10^{-22}	1.27×10^{-22}	2.13×10^{-23}	1.73×10^{-23}
90	8.46×10^{-22}	1.48×10^{-22}	2.44×10^{-23}	1.97×10^{-23}
100	8.24×10^{-22}	1.67×10^{-22}	2.74×10^{-23}	2.21×10^{-23}

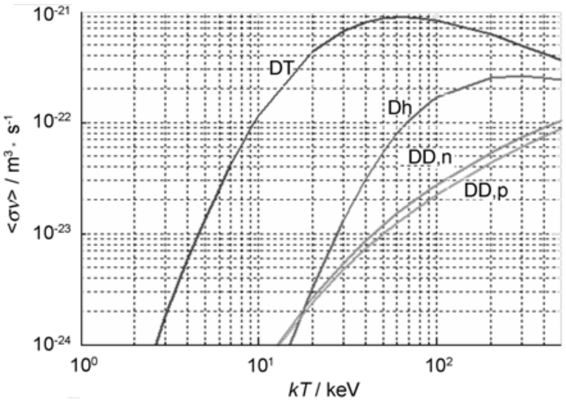

Fig.3 The temperature dependence of $\langle\sigma v\rangle$ for different fusion reactions D(d,n)^{3}He, D(d,p)T, T(d,n)^{4}He, and ^{3}He(d,p)^{4}He.

4 Energy gain and the *ρR* parameter

Inertial confinement fusion (ICF) uses laser beam or particle beams (called drivers) to heat frozen D-T pellet (radius R), either directly or indirectly via conversion into X-rays, to the necessary fusion temperature. The heating pulses are typically 1 to 2 ns long. The fusion energy gain (target gain) is defined as:

$$G=\frac{E_{\rm fu}}{E_{\rm in}} \tag{8}$$

where $E_{\rm fu}$ is the fusion output energy from the compressed fuel pellet and $E_{\rm in}$ is the laser energy irradiated onto the fuel pellet, that is,[6,7]

$$E_{\rm in}=\frac{4}{3}\pi R_0^{\ 3}(n_{\rm e}+n_{\rm i})\frac{3}{2}kT \tag{9}$$

where $n_{\rm e}$, $n_{\rm i}$ are the electron and ion density respectively, and $n_{\rm e}$=$n_{\rm i}$; $(4/3)\pi R_0^3$ is the initial volume of the fusion pellet and T is the ion temperature. The number of reactions taking place in D-T plasma per unit volume per unit time is given by:

$$R_{\rm DT}=f_{\rm D}f_{\rm T}\langle\sigma v\rangle_{\rm DT}\,n_{\rm i}^2 \tag{10}$$

where $\langle\sigma v\rangle_{\rm DT}$ is the DT reaction rate which is a function of ion temperature; also $f_{\rm D}$, $f_{\rm T}$ and $n_{\rm i}$ denote the fraction of deuterium ions and tritium ions and the total number of density, respectively. The quantity which characterizes the efficiency of a DT fusion reaction is power density $P_{\rm DT}$ (the energy released per time in a unit volume):

$$\begin{aligned}P_{\rm DT}(t)&=R_{\rm DT}\times Q_{\rm DT}\\&=f_{\rm D}f_{\rm T}n_{\rm i}^{\ 2}(t)\langle\sigma v\rangle_{\rm DT}\times Q_{\rm DT}\end{aligned} \tag{11}$$

In this equation, $Q_{\rm DT}$=17.6 MeV is the energy released in a DT fusion reaction and the fusion output energy is given by:

$$\begin{aligned}E_{\rm fu}&=\int_0^\tau P_{\rm DT}(t)\mathrm{d}t\\&=f_{\rm D}f_{\rm T}Q_{\rm DT}\int_0^\tau n_{\rm i}^{\ 2}(t)\langle\sigma v\rangle_{\rm DT}\mathrm{d}t\end{aligned} \tag{12}$$

High yield energy gain depends on the number of fusion reactions that occur in the time before the fuel disassembles, i.e., during the time the fuel is confined on account of its finite mass. A good approximation for the initial confinement time τ_E is then the time it takes for an ion to move over the distance R, and its thermal speed V_{thi}, taken as the sound speed $\left(\frac{kT}{m}\right)^{\frac{1}{2}}$. The ICF burn criterion is known as ρR-criterion, also called high-gain condition, and is essentially obtained by requiring that almost all the fuel contained in the pellet is indeed burned, i.e. that the number of reactions that take place during the time interval τ_E equals the number of fuel deuterons or tritons.

The standard form reads:[1,2]

$$\rho R \geq 4\left(mkT\right)^{\frac{1}{2}}\left\langle \sigma v\right\rangle^{-1} \tag{13}$$

where m is the mean ionic mass, the mass density $\rho=nm$, and $\langle \sigma v\rangle$ is the fusion reaction rate constant. For D-T reaction $\rho R \geq 3\frac{g}{cm^2}$ at T=50 keV. Experiments show that satisfying Eq.(13) might be sufficient to achieve the high value of G needed. Based on the experimental progress and on the steady advances in systems efficiency, it is predicted that ignition should be possible with a driver energy of 0.5-1 MJ, whereas high gain reactor operation becomes feasible with a 5-10 MJ of driver energy.[1]

5 Basic equations for D-T reaction

We now make a further approximation in neglecting all side reactions (D-D, T-T, etc) due to their small fusion cross-section, with this we obtain the particle balance equations:[2]

$$\frac{\mathrm{d}n_{\mathrm{D}}}{\mathrm{d}t} = S_{\mathrm{D}} - n_{\mathrm{D}}n_{\mathrm{T}}\left\langle \sigma v\right\rangle_{\mathrm{DT}} - \frac{n_{\mathrm{D}}\left(t\right)}{\tau_{\mathrm{D}}} \tag{14}$$

$$\frac{\mathrm{d}n_{\mathrm{T}}}{\mathrm{d}t} = S_{\mathrm{T}} - n_{\mathrm{D}}n_{\mathrm{T}}\left\langle \sigma v\right\rangle_{\mathrm{DT}} - \frac{n_{\mathrm{T}}\left(t\right)}{\tau_{\mathrm{T}}} \tag{15}$$

where τ_{D}, τ_{T} are the deuterium and tritium confinement time, also S_{D}, S_{T} are the magnitude of the deuterium and tritium injection rate per unit volume, respectively. By choosing $S=S_{\mathrm{D}}=S_{\mathrm{T}}$, $\tau=\tau_{\mathrm{D}}=\tau_{\mathrm{T}}$, $n_{\mathrm{i}}=n_{\mathrm{D}}+n_{\mathrm{T}}$ and combination of Eq.(14) with Eq.(15) we have: $\frac{\mathrm{d}n_{\mathrm{i}}}{\mathrm{d}t} = 2S - \frac{n_{\mathrm{i}}\left(t\right)^2}{2}\left\langle \sigma v\right\rangle_{\mathrm{DT}} - \frac{n_{\mathrm{i}}\left(t\right)}{\tau}$.

This equation is known as Riccatti equation and by solving this equation, we obtain:

$$n_{\mathrm{i}}\left(t\right) = \frac{(\frac{c}{2b}+W)(n_0+\frac{c}{2b}-W)\mathrm{e}^{-2bWt}}{(n_0+\frac{c}{2b}+W)-(n_0+\frac{c}{2b}-W)\mathrm{e}^{-2bWt}} - \frac{(\frac{c}{2b}-W)(n_0+\frac{c}{2b}+W)}{(n_0+\frac{c}{2b}+W)-(n_0+\frac{c}{2b}-W)\mathrm{e}^{-2bWt}} \tag{16}$$

where

$a=2S$,

$b = 2f_{\mathrm{D}}f_{\mathrm{T}}\left\langle \sigma v\right\rangle_{\mathrm{DT}}$,

$c = \frac{1}{\tau}$,

$W = \sqrt{\frac{c^2}{4b^2}+\frac{a}{b}}$,

and n_0 is the total ion density at t=0, $n_{\mathrm{i}}(t)$ is temperature dependent, and can be determined by using data in Table 3. Fig.4, Fig.5, and Fig.6 show the variations of $n_{\mathrm{i}}(t)$ with time for different temperatures at $n_0=10^3 n_{\mathrm{s}}$, where n_{s} is the solid density ($n_{\mathrm{s}}=5.38\times10^{22}\mathrm{cm}^{-3}$). These figures show that by increasing the temperature from 10 keV to 60 keV the variation of $n_{\mathrm{i}}(t)$ with time is increased, but from 60 keV to 100 keV, the variation of $n_{\mathrm{i}}(t)$ with time decreases because at kT=60 keV, $\langle \sigma v\rangle_{\mathrm{DT}}$ has a maximum value. Similarly, the power density at kT=60 keV has a maximum value (see Figs.7,8,9).

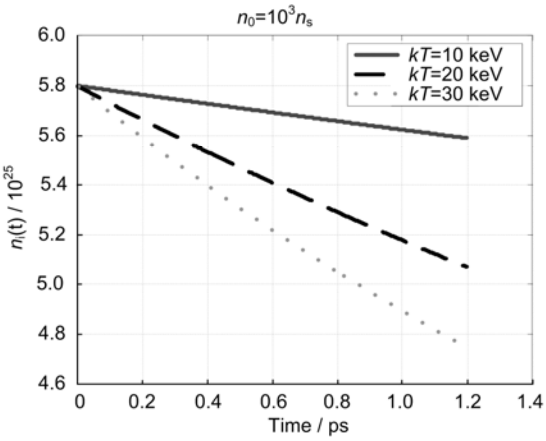

Fig.4 The time variations of $n_{\mathrm{i}}(t)$ at the temperature range of 10keV≤kT≤30keV.

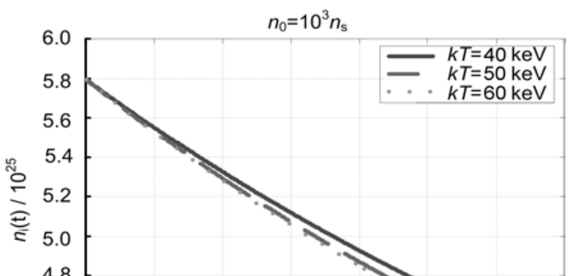

Fig.5 The time variations of $n_i(t)$ at the temperature range of 40keV≤kT≤60keV.

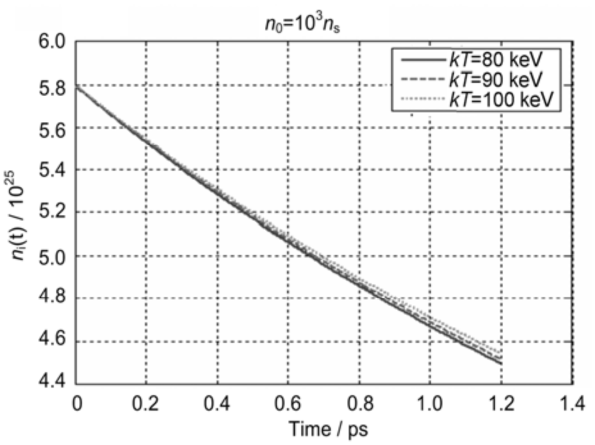

Fig.6 The time variations of $n_i(t)$ at the temperature range of 80keV≤kT≤100keV.

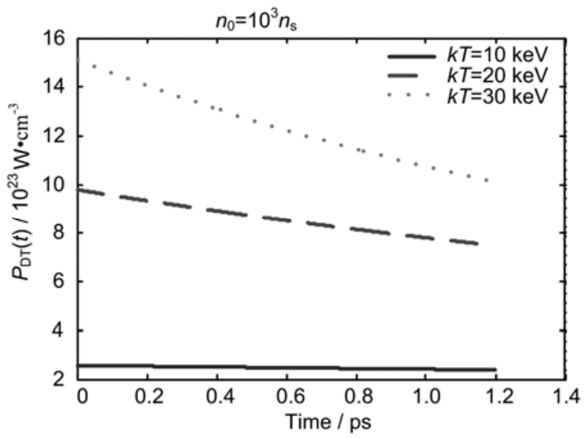

Fig.7 The time variations of power density at the temperature range of 10keV≤kT≤30keV.

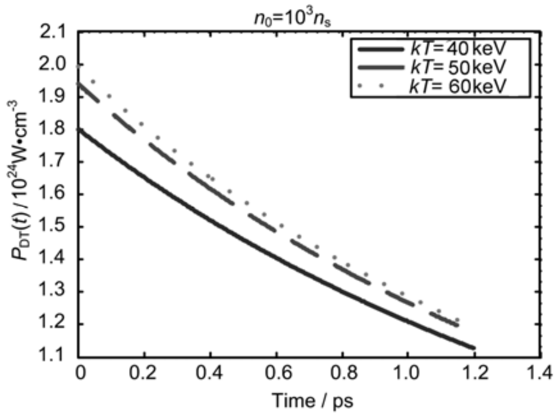

Fig.8 The time variations of power density at the temperature range of 40keV≤kT≤60keV.

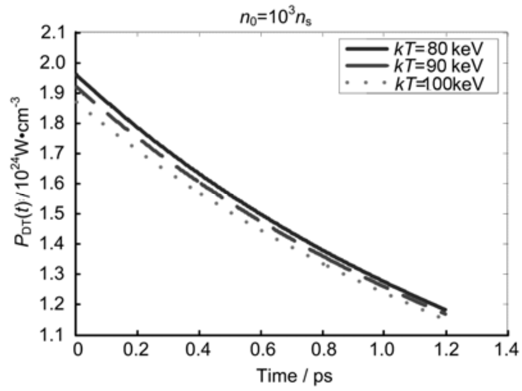

Fig.9 The time variations of power density at the temperature range of 80keV≤kT≤100keV.

6 Energy gain calculations

Our calculations show that the optimum energy gain is dependent on the choice of f_D, f_T and temperature. Fig.10 shows the variations of energy gain with temperature and fraction of f_D/f_T, and similarly Fig.11 shows the variations of energy gain with ρR-parameter and fraction of f_D/f_T. Note that it is highly probable that the first generation of fusion reactors will use a DT fusion cycle. The environmental and safety aspects of such a reactor system are of great importance. The major problem in D-T fusion is tritium handling and the tritium inventory required to run the power plant. This is because tritium is a radioactive material, which is difficult to contain, and any accident leading to release of tritium would cause radioactive hazards. The safety of the power plant can be increased considerably by minimizing the tritium inventory, which is primarily determined by the daily consumption of the fuel. Designing tritium lean target as discussed below can substantially reduce daily consumption of tritium.[8] Our calculations show that if we select f_D=f_T=0.5 we have optimum gain at different temperatures, but by choosing f_T=0.35 and f_D=0.65 the energy gain is decreased approximately 8%-10%. According to this assumption, the reduction in tritium concentration is approximately 30% (Table 4).

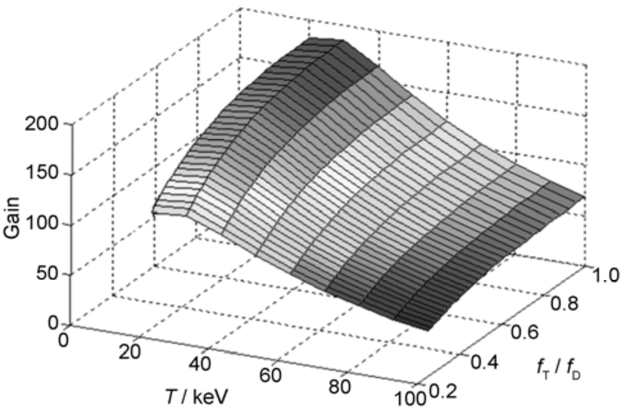

Fig.10 Variations of energy gain with temperature and fraction of f_T/f_D.

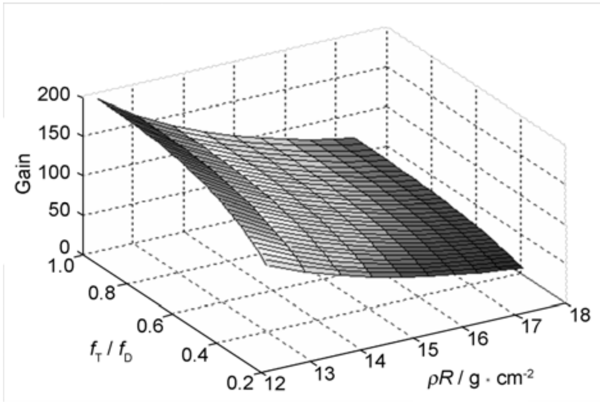

Fig.11 Variations of energy gain with ρR-parameter and fraction of f_T/f_D.

Table 4 Reductions in G for f_T=0.35/f_D=0.65 at different kT values as compared with the case of f_T=f_D=0.5

kT /keV	G(f_T=f_D=0.5)	G(f_T=0.35, f_D=0.65)	Reduction in G /%
10	95	87	8.42
20	181	164	9.39
30	184	168	8.70
40	164	150	8.53
50	141	129	8.51
60	110	121	-10.00*
70	94	103	-9.57
80	81	89	-9.88
90	71	78	-9.86
100	62	68	-9.68

* A negative reduction means an increment

7 Conclusion

Our calculations show that energy gain is strongly temperature dependent, because E_{in} and $\langle \sigma v \rangle$ are temperature dependent. For T(d,n)^{4}He fusion reaction, R-matrix theory shows that at the temperature range of 60 keV≤kT≤70 keV, $\langle \sigma v \rangle_{DT}$ is maximized, thus the fusion power density, P_{DT}, will have maximum value at this temperature range. By comparing the obtained results from our theoretical method with the other theory,[7] we conclude that for fusion reaction T(d,n)^{4}He at temperature kT=10keV and selecting f_D=f_T=0.5 our theoretical method gives G=95 and $\rho R=15.52\dfrac{g}{cm^2}$, but the other theory at the same conditions gives G=65 and $\rho R=12.5\dfrac{g}{cm^2}$. The little differences between two theories are due to neglecting the bremsstrahlung radiation in our theory. On the other hand, our calculations show that at temperature kT=30 keV with selecting f_D/f_T=1, energy gain is G=184, but at kT=30 keV and by choosing f_T=0.35 and f_D=0.65, the energy gain is G=168. From these physical conditions we can therefore conclude that, a suitable combination may be a deuterium fraction f_D=0.65 and f_T=0.35 which would lead to 30% reduction in the tritium content of the fuel mixture, but 8% reduction in the gain, and this choice will not change the energy gain value very much. Finally, we conclude that the R-matrix theory is good selection for determining the energy gain.

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