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Tritium Content of a DT Pellet in Inertial Confinement Fusion

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Abstract

A numerical and an analytical estimations, and a one-dimensional hydrodynamic simulation present that the 30% order of reduction of the tritium content in a *DT* pellet can bring the sufficient energy output in a *DT* inertial confinement fusion reactor. In other words, the tritium content can be reduced significantly without a significant reduction in the *DT* fusion energy output. This new result also means that the tritium inventory can be reduced significantly before and during the reactor operation in the *DT* inertial confinement fusion. This result comes from the cotribution of a *DD* reaction to the *DT* reaction.

Key words: tritium content, inertial confinement fusion, tritium reduction, DT fusion, fusion reaction, pellet study

1.Introduction

In deuterium (D)-tritium(T) inertial confinement fusion (ICF) a pellet is compressed to about a 1000 times as high as the solid density[1] and burned with the peak temperature of 50 $\sim$ 100keV level. On the other hand, tritium is an unstable radioactive isotope of hydrogen. Therefore we have to breed tritium in a fusion reactor. Because the reaction rate is proportional to the product of the number density of deuterium and tritium, in the DT inertial confinement fusion it has been considered that the tritium content should be equal to that of deuterium in a DT fuel pellet, except for some researches[2] for the advanced fuel[3] in which a density-radius product of ρR is quite large compared with the typical value of $\rho R = 2 \sim 4g/cm^2$ in the DT ICF. However the deuterium-deuterium reaction which produces tritium (see (2)) at the high temperature of 50 $\sim$ 100keV level, also contributes to the real reaction process.

In this paper, a numerical and an analytical estimation, and a one-dimensional simulation present that a reduction of 30% order of tritium content in a DT fuel pellet can bring the sufficient fusion energy comparable to that in a pellet which contains the equal deuterium and tritium content. In our analyses we include the advanced fusion reactions (DD, DHe^3, TT and THe^3) in addition to the DT reaction.

2.Reduction of Tritium Content

Let us first present the reactions[4] contributing to the DT-based reaction:

$$D + T \longrightarrow H_e^4 + n \tag{1}$$

$$\begin{array}{rcl} D + D & \longrightarrow & T + P(50\%) \\ & \searrow & H_e^3 + n(50\%) \end{array} \tag{2}$$

$$D + H_e^3 \longrightarrow H_e^4 + p \tag{3}$$

$$T + T \longrightarrow H_e^4 + 2n \quad (4)$$

$$T + H_e^3 \longrightarrow H_e^4 + D(43\%) \quad (5)$$

Here H_e^4 is Helium, ${H_e}^3$ an isotope of Helium, p a proton and n a neutron. The content of important elements in a fuel pellet is estimated by the following reaction equations:

$$\begin{aligned} dn_T/dt &= -n_D n_T < \sigma v >_{DT} + n_D^2 < \sigma v >_{DD} /4 \\ &\quad -n_T^2 < \sigma v >_{TT} - n_T n_{H_e^3} < \sigma v >_{TH_e^3} - n_T/\tau \end{aligned} \quad (6)$$

$$\begin{aligned} dn_D/dt &= -n_D n_T < \sigma v >_{DT} - n_D n_{H_e^3} < \sigma v >_{DH_e^3} \\ &\quad -n_D^2 < \sigma v >_{DD} + 0.43 \times n_T n_{H_e^3} < \sigma v >_{TH_e^3} - n_D/\tau \end{aligned} \quad (7)$$

$$\begin{aligned} dn_{H_e^3}/dt &= n_D^2 < \sigma v >_{DD} /4 - n_D n_{H_e^3} < \sigma v >_{DH_e^3} \\ &\quad -n_T n_{H_e^3} < \sigma v >_{TH_e^3} - n_{H_e^3}/\tau \end{aligned} \quad (8)$$

In the above equations $< \sigma v >$, which depends on the temperature only, shows the reaction rate for each reaction and t the time. The relation of $\nabla \cdot (n_j \boldsymbol{v}) \simeq n_j/\tau$ is also used, where j=D, T or H_e^3, and τ is the confinement time which is $R/(3C_s)$. Here C_s is the sound speed and R is the radius of a spherical fuel pellet.

In the numerical estimation for the reduction of tritium content we compute the time sequence of n_T, n_D and n_{He}^3 by solving Eqs.(6)-(8) during the burning phase. Here we assume that the initial fuel density is a 1000 times of the solid density (n_s). As a parameter the initial ρR is changed from 2 to 4 g/cm^2 which is the typical parameter range in order to burn the fuel in the DT inertial confinement fusion. Here ρ is the mass density. The temperature is estimated by the following equation[5] with the initial temperature of 10keV:

$$3n\frac{dT}{dt} = KT^{7/2}/R^2 - R_a n^2 T^{1/2} - nT/\tau + E_{s-h} \quad (9)$$

In the right hand side of the above equation the first term represents the electron heat conduction loss, the second the radiation (Bremsstrahlung) loss, the third the fuel-expansion loss and the last the self-heating by the fusion products except neutron. Here K and R_a are constant[6,7]. In our model being employed in this paper radiation and neutrons escape freely from the pellet. This is based on a fact that the Rosseland mean free path[7] l_R is much larger than the pellet radius: For a typical parameter set of T=10keV and n=1000n_s, l_R=39.9cm$\gg R$. Therefore this assumption is valid for a pellet without a heavy tamper. The contribution of neutron is also negligible bacause of the low ρR. Charged particles of fusion products deposit their whole energy given by the reactions instanteneously; Among these fusion products alpha particle being produced by the DT reaction is a dominant candidate for heating the fuel. In our parameter range the contribution of DT-alpha particle to heating the fuel is more than 90%. The most important reaction contributing to heating the fuel is (1) and the next is (2). Among the charged fusion products in (1) and (2) the most energetic one is proton in (2). However we neglect its transport effect on heating the fuel, because of the low contribution ratio compared with that of the DT-alpha particle. The mean free path l_α of DT-alpha particle is described by $0.04T(\mathrm{keV})/\rho$ approximately[5]. For our parameter range, $l_\alpha < R$. Our assumption being employed is based on this fact. We also employ a one-temperature model; As is well known, ions are heated first by the fusion products during the burning phase[8]. The ion-electron energy-relaxation time τ_{ie} is estimated as follows: For 50keV of the ion temperature and 25keV of the electron temperature, τ_{ie}=11.0psec. This value of τ_{ie} is small compared with the whole burning time(see Fig.1). However it is not very small. In order to check the validity of this one-temperature model and to include the radial dependency of physical quantities precisely, we also perform the two-temperature one-dimensional hydrodynamic simulation at the end of this chapter.

Figure 1 presents the time sequence of the temperature TkeV and the fusion output energy E_f J/cm^3 for $\rho R = 2.0$ g/cm^2. In this particular case the tritium content is 42.5% in a fuel, that means 15% reduction of the tritium content. Figure 2 shows the fusion energy output E_f versus the reduction δ of tritium content, which is defined as follows:

$$n_{D0} = n_0/2 + \delta, n_{T0} = n_0/2 - \delta \tag{10}$$

Here n with a suffix of 0 represents the number density at $time = 0$ and n_0 means the initial total number density. In Fig.2 each pellet radius is slightly different from that of each other in order to keep the specified ρR exactly, when the tritium content is changed. Therefore the decrease in the tritium content introduces the decrease in ρ and the slight increase in the pellet radius. This increase in the pellet radius contributes to make the confinement time τ longer and then to make the energy output increase. In order to check this effect, we also performed the similar parameter study in which each pellet radius is fixed to that of the pellet containing the equal deuterium and tritium content in each specified ρR. The results are shown in Fig.3. Figure 3 also shows that the reduction of tritium content can reach 20 $\sim$ 30% order. These figures present that the reduction of 30% order of tritium content in a fuel pellet can produce the sufficient fusion energy output comparable to that in a pellet which contains the equal deuterium and tritium content. The reduction of tritium can reach 30% without a significant decrease of the fusion energy output as shown in Figs.2 and 3. This fact comes from the contribution of the deuterium-deuterium reaction, which produces tritium, to the deuterium-tritium reaction. This result means that the fusion energy output is rather insensitive to the tritium content in the parameter range in the DT ICF

We also perform an analytical estimation for the optimum content of tritium. In order to do so, we use the simplified reaction equations with Eqs.(10):

$$
\begin{aligned}
dn_T/dt &\simeq -n_D n_T <\sigma v>_{DT} + n_D^2 <\sigma v>_{DD}/4 \\
&\simeq n_T^2(-<\sigma v>_{DT} + <\sigma v>_{DD}/4)
\end{aligned} \tag{11}
$$

$$
\begin{aligned}
dn_D/dt &\simeq -n_D n_T <\sigma v>_{DT} - n_D^2 <\sigma v>_{DD} \\
&\simeq -n_D^2(<\sigma v>_{DT} + <\sigma v>_{DD})
\end{aligned} \tag{12}
$$

In this analysis we assume that the temperature is constant and $\delta << n_0$. Then we obtain

$$
\delta/(n_0/2) = (5/32)(n_0\tau)^2 <\sigma v>_{DT}<\sigma v>_{DD} /(1 + n_0\tau <\sigma v>_{DT}/2)^2 \tag{13}
$$

for the optimum content of tritium in a DT ICF pellet from the condition of $dn_D n_T/d\delta = 0$. This result shows that δ is positive and the reduction of tritium content brings sufficient fusion energy. For an example parameter set of T=100keV, n_0=4.5×10^{25}/cm^3 and τ=100psec, $\delta/(n_0/2)$=0.014. This result suppports the result of the numerical analyses being presented above, although a number itself for the optimum δ is rather small compared with the numerical one because of its crude approximation.

In addition to these analyses, we also performed a one-dimensional hydrodynamic simulation[9], in order to confirm our results obtained by the above analyses. In this simulation the two-temperature model is employed with the following assumptions: Based on the above discussions about the assumptions being employed, neutrons and radiation escape freely, and charged particles of fusion products deposit their energy locally and instantaneously. The pellet has no tamper. As an initial condition we employ the constant-pressure model[10] in which the temperature of the inner hot spot is 5keV, that of the outer part is 1keV and the density ratio between these two parts is 1:5. In our simulation ρR of the hot spot is 0.5g/cm^2 and the density in the outer part is 1000n$_s$. The total ρR is 4g/cm^2. The equation-of-state being employed is the ideal one, because of the high temperature during the burning phase. The pellet radius is fixed to that of the pellet which contains the equal deuterium and tritium content. The simulation results are presented in Fig.3 by square signs. These results reproduce and confirm well the estimation results presented above.

3.Summary

In this paper, we presented the study for the tritium content in a *DT-ICF* fuel pellet, including the advanced fusion reactions in addition to the *DT* reaction. We performed this work numerically and analytically. We found that in the *DT ICF* a reduction of 30% order of tritium content in a fuel pellet can realize the sufficient fusion energy comparable to that in a pellet which contains the equal deuterium and tritium content. This result is also supported by the one-dimensional hydrodynamic simulation. The purpose of this paper is to point out this result and to point out that accordingly the tritium inventory can be reduced significantly before and during the operation of the fusion reactor.

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Figure Captions

Fig. 1. The time t sequence of temepature T (a solid line) and fusion output energy E_f (a dotted line) for ρR=2g/cm^2. In this example case the tritium content is 42.5% in a fuel, that means 15% reduction of the tritium content.

Fig. 2. The fusion energy output E_f versus the tritium content. In this analysis each pellet radius is changed slightly in order to keep the specified ρR exactly, when the tritium content is changed. About 30% reduction of tritium can still bring the sufficient fusion energy in the DT-ICF parameter range.

Fig. 3. The fusion energy output E_f versus the tritium content. In this case the pellet radius is fixed to that of the pellet which has the equal deuterium-tritium content in each specified ρR. About 30% reduction of tritium can also bring the sufficient fusion energy. Squre signs show the results for ρR=4g/cm^2 by a one-dimensional hydrodynamic simulation. Figure 3 presents that the results by the numerical estimation and by the one-dimensional simulation agree well with each other.

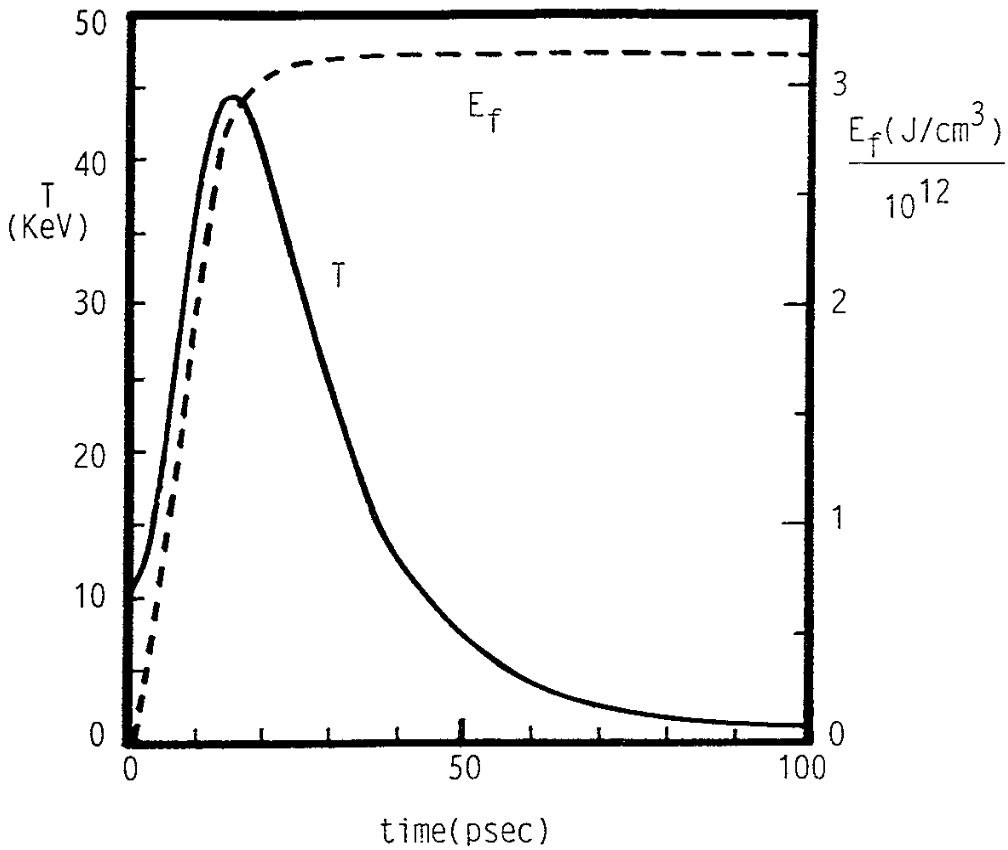

Fig.1

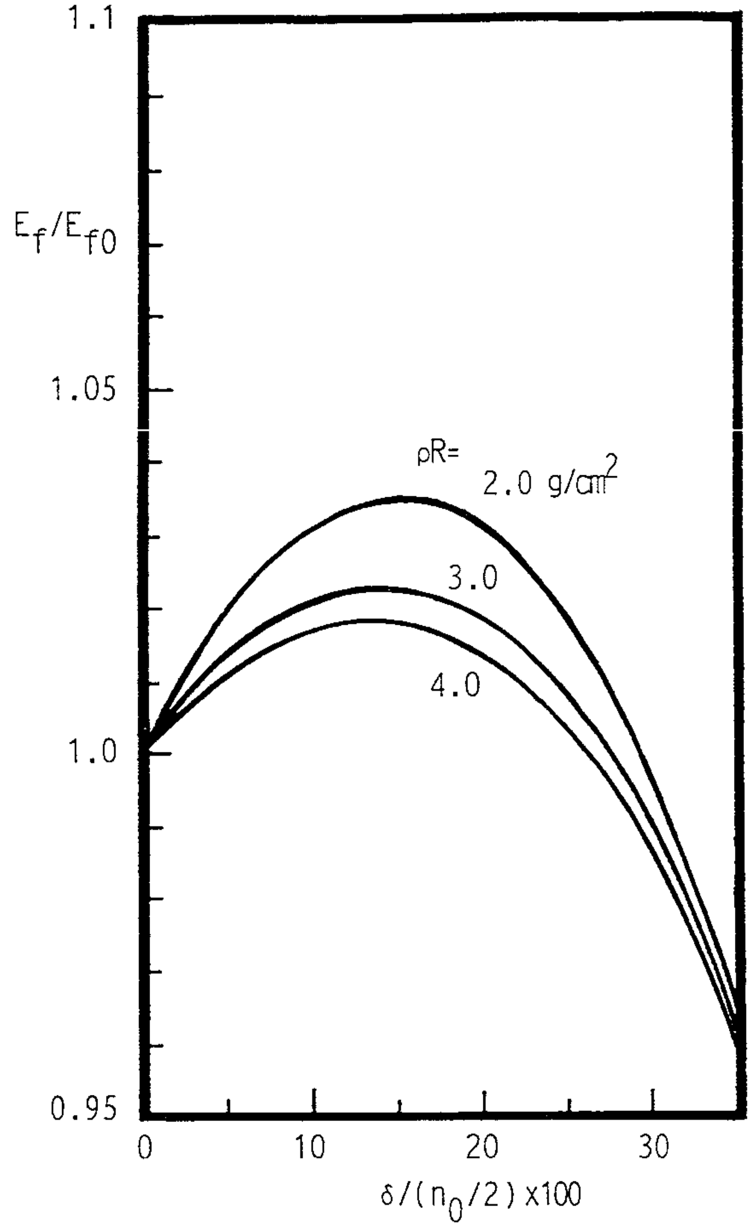

Fig.2

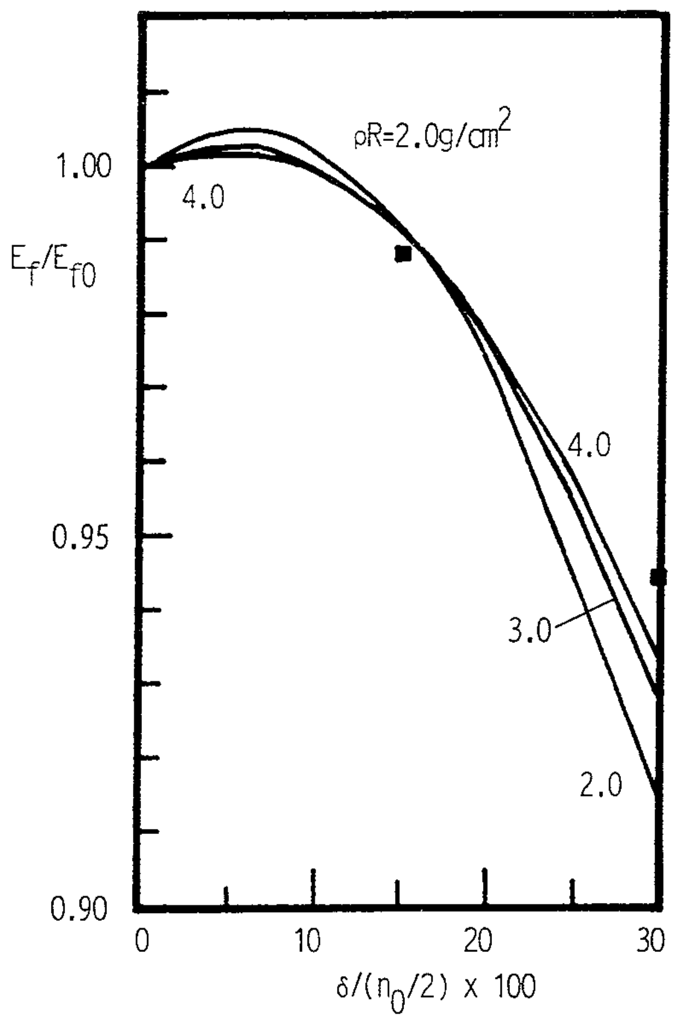

Fig.3

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