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Influence of DT Fuel Composition on the Energy Output and its Implications on Reactor Safety and Environmental Acceptability

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Abstract- This paper presents one-dimensional numerical simulations of compression and thermonuclear burn of an indirect drive inertial fusion target that contains 0.5 mg DT fuel and is suitable for use in an ignition type facility where one is interested in a low energy gain of the order of 1 - 30. The sensitivity of the energy output on the fuel composition has also been studied by using different combinations of the fractions of deuterium and tritium atoms. It has been found that the energy output is relatively insensitive to a reduction in the tritium content of the target by up to 40 %. This means that one may be able to use low tritium targets in inertial fusion reactors which will lead to an overall reduction of tritium inventory that in turn can have important implications for the reactor safety.

1. Introduction

Use of low tritium targets are believed to have a number of important advantages including lower tritium inventories, lower tritium breeding ratios and smaller tritium mass leftover among the target debris that has to be evacuated from the reactor chamber after each shot. All these effects add to the safety, economy and environmental acceptability of an inertial confinement fusion (ICF) reactor. Moreover construction of a highly homogeneous mixture of solid deuterium and tritium fuel is a difficult technical problem [1]. A substantial reduction in the tritium content could be helpful in this respect.

In a previous paper[2] we showed analytically that the output energy from a thermonuclear DT plasma is quite insensitive to a substantial reduction in the tri-

tium content of the target. For example, if one uses a fuel mixture that contains 60 % deuterium atoms and 30 % tritium atoms, which means a 20 % reduction in the tritium content as compared to the equimolar case, the output energy will only be reduced by 4 %. Where the temperature and the plasma density is kept constant. Similarly a 40 % reduction in the tritium content would only lead to a 16 % reduction in the output energy. This can be seen from the following equation which gives the number of DT reactions taking place per unit volume per unit time

$$R_{DT} = (\sigma v)_{DT} f_D f_T n_i^2 \quad (1)$$

where $(\sigma v)_{DT}$ is the DT reaction rate, f_D and f_T are the fractions of deuterium and tritium atoms respectively and n_i is the total ion number density.

This model was checked with the help of numerical simulations that were carried out using a one-dimensional, three-temperature, Lagrangian computer code MEDUSA-KAT[3]. We did burn calculations of DT plasmas using ignition conditions that represent a volume ignition model as well as a central ignition model. Good agreement was found between analytic results and computer simulations.

In later papers [4,5] we reported more detailed simulation results that not only treated the plasma burn phase but considered full target implosion including the compression phase. We designed a reactor-size, indirect drive ICF target with 4.45 mg DT fuel and used different compositions of deuterium-tritium fuel. These results were found to be even more optimistic than those presented in [2]. This is because at the time when the hot spot ignites, the bulk of the fuel surrounding the hot spot still is imploding with high velocity. The hot spot is therefore compressed by the surrounding fuel until the pressure in the hot spot becomes high enough to stop this inward motion. In case of low tritium fuel, the rate of energy production in the hot spot is low according to Eq.1 and therefore the hot spot temperature increases at a slower rate. Consequently the rate of increases of hot spot pressure is lower which leads to a higher compression. This partially compensates for the reduction in the tritium level. For further details see [2,4,5].

In the present paper we report simulation results of compression and thermonuclear burn of an indirect drive ICF target that contains 0.5 mg DT fuel. This fuel mass is suitable for an ignition type facility, a project that is under consideration by the European Union [6]. Use of low tritium targets in such a facility may also lead to some of the advantages anticipated in case of ICF reactors. We therefore have carried out a parameter study of the energy output as a function of the fraction of the tritium atom in the fuel. The results confirm that in case of this target one should be able to use DT fuel with a substantially reduced tritium content.

In section 2 we discuss target initial conditions and input pulse parameters while the simulation results are reported in section 3. Conclusions drawn from this work

are noted in section 4.

2. Target Design and Input Pulse Parameters

The target design is shown in Fig.1 while the target parameters are given in Table 1. It is an indirect target with a capsule that consists a 0.5 mg solid DT shell filled with a low density equimolar DT gas. The fuel shell is followed by a carbon ablator shell. The capsule is surrounded by a solid gold casing that forms a hohlraum around the capsule. The inner capsule radius is 1.9 mm and the casing-to-capsule surface area ration is 9.

Figure 1: Target initial conditions

The input temperature pulse shape is shown in Fig.2 and the precise pulse parameters are listed in Table 2. The hohlraum is filled with black body radiation at $t=0$ and this homogeneous radiation field drives the target implosion. In these calculations we are not interested in the problems of conversion and symmetrization but we wish to study the target implosion and sensitivity of energy output to the fuel composition.

Inner Fuel Radius	$R_1 = 1.900 \text{ mm}$
Outer Fuel Radius	$R_2 = 1.948 \text{ mm}$
Outer Ablator Radius	$R_3 = 2.128 \text{ mm}$
Hohlraum Radius	$R_4 = 6.128 \text{ mm}$
Hohlraum Wall Thickness	$R_5 - R_4 = 6.9 \text{ } \mu\text{m}$
DT Fuel Mass	0.5 mg
DT Fuel Density	0.224 g/cm^3
Ablator Mass (Solid C)	21 mg
Ablator Density	2.20 g/cm^3
Casing Mass (Solid Au)	62 mg
Casing Density	19.0 g/cm^3

Table 1: Target Parameters

Figure 2: Input Pulse Shape

3. Simulation Results

In Table 3 we present simulation results of the target implosion using an equimolar deuterium-tritium mixture. It is seen that the capsule absorbs 0.88 MJ radiation energy whereas 0.99 MJ radiation energy is lost in the hohlraum wall. The implosion yields 63 MJ output thermonuclear energy so that the capsule gain is about 70 while the target gain is of the order of 30.

In Table 4 we give energy output for three different combinations of f_D and f_T . It is seen that unlike the results reported in [4,5] the energy output obtained in simulations, E_{OS} is of the same order as that predicted by Eq.1. This shows that bigger the fuel mass is, more insensitive the energy output becomes to f_T .

Table 5 shows that the low tritium targets have higher fractional burn of tritium

Prepulse Temperature	$T_1 = 100 \text{ eV}$
Prepulse Power	$P_1 = 10 \text{ TW/cm}^2$
Maximum Temperature	$T_2 = 300 \text{ eV}$
Maximum Power	$P_2 = 830 \text{ TW/cm}^2$
Prepulse Duration	$\tau_1 = 15 \text{ nses}$
Main Pulse Duration	$\tau_2 = 4 \text{ nses}$
Shape Factor	$p_1 = 2.0$
Shape Factor	$p_2 = 20.0$

Table 2: Pulse Parameters

and as a result a smaller tritium mass is left in the target debris that needs to be evacuated after each shot. This may make the process of tritium recovery more efficient and cleaner which may improve the overall efficiency of the ignition facility.

Radiation Energy Absorbed By Target	$E_t = 1.87 \text{ MJ}$
Radiation Energy Absorbed By Capsule	$E_c = 0.88 \text{ MJ}$
Radiation Loss Through Hohlraum Wall	$E_w = 0.99 \text{ MJ}$
Thermonuclear Energy Output	$E_0 = 63.0 \text{ MJ}$
Fractional Burn	$\phi = 37 \%$
Capsule Gain	$G_c = 71$
Target Gain	$G_t = 33$
Fuel ρR	0.81 gm/cm^2
Tamper ρR	1.30 gm/cm^2
Total ρR	2.11 gm/cm^2

Table 3: Summary of Results

f_D	f_T	$E_{OS} \text{ (MJ)}$ Simulation Results	$E_{OA} \text{ (MJ)}$ By Eq.1
0.50	0.50	63	
0.60	0.40	61	60
0.70	0.30	53	53

Table 4: Energy Output As a Function of Tritium Fraction f_T

No	Tritium Fraction f_T	Initial Tritium Mass (mg)	Final Tritium Mass (mg)	Tritium Fractional Burn(%)
1	0.50	0.300	0.190	36
2	0.40	0.250	0.140	44
3	0.30	0.195	0.100	48

Table 5: Tritium Burn Parameters(initial Fuel Mass = 0.5 mg)

4. Conclusions

In this paper we present numerical simulation results of compression and thermonuclear burn of an indirect drive ICF target suitable for use in an ignition type facility. We have shown that using a DT fuel mixture with a substantially reduced tritium content we can still produce sufficient output energy to operate the ignition facility. Use of such low level tritium targets would reduce the overall consumption of tritium which is very attractive from the safety point of view. Moreover the tritium fractional burn in such targets is much higher than that in the equimolar DT targets. This means that the tritium mass leftover after the implosion in case of low tritium targets will be much smaller, that will make the tritium recovery process cleaner.

Acknowledgements

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