Ignition and Burn Characteristics of D-³He-Fueled Fast Ignition Targets

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Abstract. The possibility of igniting D³He plasma in the fast-ignition, inertial confinement fusion scheme is discussed. Use of a small amount of DT fuel as an igniter is indispensable in order to mitigate the requirement on driver energy. Simulations have been made for a DT/D³He fuel compressed to 4000 times the liquid density by incorporating a newly-developed neutron diffusion code into FIBMET, a 2D fusion ignition and burning code. The DT igniter is placed at the edge of the compressed fuel. The work shows that it is possible to obtain sufficient pellet gains (~60) with realistic driver energy below 10 MJ. The essential role of DT fusion neutron is clarified. The possibility to reduce the amount of DT fuel is discussed.

1. Introduction

Although nuclear fusion reactors adopting D³He fuel provide many advantages, such as low neutron generation and efficient conversion of output fusion energy [1], the achievement of ignition is a difficult problem. It is therefore of particular importance to find some methods or schemes that relax the ignition requirements. In the inertial confinement fusion (ICF) scheme, the use of pure D³He fuel is impractical because of the excessive requirement on driver energy [2]. A small amount of DT fuel as an “igniter” is hence indispensable.

Our previous burn simulation for DT/D³He fuels showed that the pellet gain, the ratio of output fusion energy to driver energy, is ~50. Subsequent implosion simulation, however, showed that after void closure the central DT fuel is ignited while the bulk of the main D³He fuel is still imploding with high velocities [4]. This pre-ignition of DT fuel leads to a low compression of the main fuel and prevents the DT/D³He fuel from obtaining the requested gain.

To reduce further the requirement on the driver energy, in the present paper, we propose to adopt the fast ignition scheme [5]. To this end we incorporated a newly-developed neutron diffusion code into FIBMET, a 2D fusion ignition and burning code [6]. A crucial role of DT fusion neutrons in heating the D³He main fuel is clarified. The importance of nuclear elastic scattering of energetic protons as fuel-ion heating mechanism is also demonstrated. The burn properties are compared with those previously obtained for DT/D³He pellet models in the central spark ignition scheme [3, 7].
2. Model Description

2.1. Collision Processes and Outline of Simulation Code

The thermonuclear reactions occurring in DT/D³He plasmas are $T(d, n)²He$, $D(d, p)T$, $D(d, n)³He$, and $³He(d, p)⁴He$. The particles emitted from these reactions collide with the plasma species, depositing their energy. For charged particles, the dominant process is, of course, Coulomb scattering. However, in collisions of highly energetic particles (e.g., 14.7-MeV protons), the contribution from nuclear elastic scattering (NES) becomes significant. The stopping range of 14.7-MeV protons in D³He plasmas is considerably shortened by the inclusion of NES. For $³He$ or alpha particles, the NES effect is negligible. To treat the energy transport of energetic protons, we extended the alpha-particle diffusion routine so as to include NES. The neutron heating is also essential in the DT/D³He fuel burning [3] and then we incorporated into the FIBMET a newly-developed multi-group neutron diffusion code. In the present code, however, the neutron interactions with tritons in the igniter region are not included.

2.2 Initial Pellet Condition and Assumptions

Figure 1 shows the “initial” state of fuel in a DT/D³He pellet configuration and parameters of the initial core plasma (in the case of $ρ = 4000 ρ_L$) and heating laser. The pellet with a temperature of $T_i = T_e = 0.2$ keV was assumed to have been compressed to $ρ = 4000 ρ_L$ (i.e., $640$ g/cm$^3$). Such a compression is, of course, not an easy task. Still, it is indispensable in order to burn D³He fuel with reasonable driver energy. The radiation temperature at the start of the calculation was set to be the same as bulk electron temperature. The coupling efficiency from the implosion laser to the target core plasma was assumed as 10% and that from the heating laser to the imploded core as 30%. The heating laser energy transferred to the compressed core is thus estimated to be 70.4 kJ.

![Diagram of Initial Core Plasma Configuration](image)

**Figure 1.** Initial core plasma configuration, parameters of typical pellet and heating laser conditions.

3. Results and Discussion

The ignition and burn characteristics are examined with a view to achieving pellet gains higher than 50 with a “moderate” total (i.e., implosion plus heating) driver energy ($< 10$ MJ). At the beginning, we show in figure 2 the pellet gains obtained for various-sized fuel pellets ($ρR_{tot} = 8-12$ g/cm$^2$) as a function of the igniter $ρR$ value for the case of $ρ = 4000 ρ_L$. It is seen that the critical $ρR_{DT}$ required to ignite the outer D³He fuel is $3.7$ g/cm$^2$. In the case that $ρR_{DT}$ is small ($< 3$ g/cm$^2$), the main D³He fuel does not burn; the fusion output energy is almost determined by the burning of the DT igniter. The pellet gain is hence small with increasing $ρR_{tot}$. On the other hand, in the region where $ρR_{DT} > 4$ g/cm$^2$, the main fuel is ignited and hence the burn fraction is determined by the total $ρR$ value. Consequently, the pellet gain becomes larger with increasing $ρR_{tot}$.

The results for a typical pellet configuration ($ρR_{DT} = 3.7$ g/cm$^2$, $ρR_{tot} = 10$ g/cm$^2$, $ρ = 4000 ρ_L$) are summarized in Table 1. The driver energy and the fusion output energy are 6.9 MJ (6.7 MJ for implosion and 0.2 MJ for heating of the compressed core) and 427 MJ, respectively. The pellet gain $G$ is hence estimated to be 61.9. The values in the parentheses ($G = 26.6$, for example) result from the
calculations neglecting the NES of 14.7-MeV protons. It can be said the NES plays a quite important role in determining the burn characteristics of D$_3$He fuel. (The same was previously found in the analysis of D$^3$He fusion based on the central spark ignition scheme [3].) Neglecting the NES effect results in a significant underestimation of the pellet gain (by ~60% in this pellet model).

The time evolution of volume-integrated fusion power generation in the same pellet configuration is illustrated in figure 3(a). At first the DT igniter burns and then ($t > 25$ ps) the D$^3$He main fuel begins to burn. About 70% of the fusion energy production is due to the D-$^3$He reaction. To make clear the crucial role of neutron heating and NES, we also made calculations by neglecting the energy deposition of NES –figure 3(b) and neutron heating –figure 3(c). In figure 3(d), we neglected both neutron heating and NES. As shown, in these cases the D$^3$He main fuel is not sufficiently ignited. So we can conclude that considering neutron heating and NES is essential to estimate burn characteristics.

Now let us compare the above results with those previously obtained for DT/D$^3$He pellet models in the central spark ignition scheme [3, 7]. In Ref. 3, a quasi-isobarically compressed state was assumed as “initial” state of DT/D$^3$He pellet ($\rho \sim 4000 \rho_L$, $T_i = T_e = 1$keV, $\rho_{spark} \sim 2000 \rho_L$, $T_{spark} = 5$keV). In that case, required driver energy was ~30MJ, pellet gain was ~50, and the neutron fraction of fusion output energy was ~4%. From the comparison with these results, it is found that the driver energy for achieving the pellet gain of 50 or more can be fairly reduced by adopting the fast ignition scheme. On the other hand, the fraction of fusion output energy carried by neutrons is increased than in the case of central ignition pellets [3, 7]. One of the reasons would be that in this scheme the DT igniter should be placed not in the center but at the edge of the pellet; to compensate the loss of neutrons from the pellet surface, a larger amount of DT igniter is required.

![Figure 2](image-url)  
**Figure 2.** Pellet gains of various-sized pellet as a function of igniter \(\rho R\) value.

**Table 1.** Burn characteristics of a typical DT/D$^3$He fuel pellet.

| Parameter                                      | Value  |
|------------------------------------------------|--------|
| Initial fuel energy [MJ]                       | 0.67   |
| Driver energy [MJ]                             | 6.9    |
| Fusion energy production [MJ]                  | 427 (184) |
| Contribution from T(d,n)$^3$He [%]             | 29.0 (63.1) |
| D(d,n)$^3$He [%]                               | 1.1 (1.2) |
| D(d,p)/T [%]                                   | 1.6 (1.6) |
| $^3$He(d,p)$^4$He [%]                         | 68.2 (34.1) |
| Output energy carried by Plasma particles [%]   | 56.7 (30.7) |
| Radiation [%]                                  | 20.2 (21.1) |
| Neutrons [%]                                   | 23.1 (48.2) |
| Pellet gain                                    | 61.9 (26.6) |
4. Concluding Remarks

We have examined the burn characteristics of DT/D$_3$He pellet models in the fast-ignition (FI) scheme, assuming “initial” states to be compressed to 4000 times the liquid density. It was found that considering neutron heating and NES is essential to estimate burn characteristics and by adopting the FI scheme, it is possible to achieve sufficient pellet gains (>50) with reasonable driver energy (<10MJ). The fraction of fusion output energy carried by neutrons, however, is increased compared with the case of central spark ignition. The neutron energy fraction may be further reduced by considering the optimal shape of the DT igniter. If a cylindrical igniter is adopted, for example, a part of it can be placed deeper into the main fuel than in the case of the spherical igniter, and the neutron loss from the pellet surface would be decreased.

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