Effect of Internal Breeding of Tritium and Helium-3 on the Ignition of an ICF Fuel Pellet

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Abstract

Self-heating condition and following ignition in an Inertial Confinement Fusion (ICF) fuel pellet is evaluated by calculating the power equations, dynamically. In fact, the self-heating condition is a criterion that determines the minimum parameters of a fuel (such as temperature, density and areal density) that can be ignited. Deuterium is the main component of ICF fuels as large amounts of it are naturally available. In addition, the use of deuterium as a fuel in ICF causes the production of tritium and helium-3. However, pure deuterium has a high ignition temperature ($T \geq 40$ keV) which makes it inefficient. In this paper, the power equations are solved, dynamically, and it has been indicated that internal tritium and helium-3 production at early evolution of compressed deuterium fuel causes ignition at lower predicted temperatures.

Key words: Inertial Confinement Fusion, Pure Deuterium, Self-Heating Condition, Ignition, Time Evolution.

1 Introduction

Inertial Fusion Energy (IFE) research is approaching a critical juncture in its history with high expectations that ignition and physical feasibility will be demonstrated soon in related facilities around the world. The main components of the ICF fuel pellets are the hydrogen isotopes, Deuterium and Tritium (DT). The fusion reaction of deuterium and tritium turns out to be the easiest approach to fusion because of a relatively large cross section and a very high mass defect. As a result the DT mixture is the fuel with the lowest ignition temperature and has the highest specific yield. Since the most practical nuclear fusion reaction for power generation seems to be the DT reaction, the sources of these fuels are important. The deuterium part of the fuel does not pose a great problem
because about 1 part in 5000 of the hydrogen in seawater is deuterium\(^4\).

While large amounts of deuterium are naturally available in ocean water and then makes up 156 ppm of hydrogen on earth, tritium can be bred from the lithium isotope \(^6\)Li which is also available in great quantities on earth\(^5\). However, the tritium is an unstable artificial isotope, decaying to \(^3\)He with a half life of 12.3 years, and as a result needs to be produced within the DT fuel cycle\(^6\). Therefore, the tritium production has most significant radiological problem in future DT fusion reactors\(^7\). In a more mature fusion power economy, the tritium breeding ratio (TBR) will be adjusted to a point closer to unity with just enough extra to cover decay and any losses\(^8\). Furthermore, energetic neutron (14.1 MeV) that it yield from DT reaction is another problem.

Helium-3 is a helium isotope that is light and non-radioactive. Nuclear fusion reactors using helium-3 could provide a highly efficient form of nuclear power with virtually no waste and negligible radiation. Nuclear fusion using helium-3 would be cleaner, as it does not produce any spare neutrons. Although the helium-3 is almost non-existent on earth, it does exist on the moon\(^9\). Lacking an atmosphere, the moon has been bombarded for billions of years by solar winds carrying helium-3\(^10\).

One requirement of traditional inertial fusion energy (IFE) power plant designs is the need to breed large quantities of tritium to replace that which is burned. By using the pure deuterium as fuel, the complex tritium breeding blanket would not be necessary and the tritium inventory in the reactor would be substantially reduced. This means increased safety and smaller environmental impact in case of accidents. In addition, the reduced number of 14.1 MeV neutrons and the softer neutron spectrum would ease the problems related to neutron induced damage, mostly due to neutrons with energy above 4-5 MeV. However, burning of pure deuterium, requiring very high temperature and large areal density \(\rho R\), and the ignition of pure deuterium seems unrealistic in ICF because of high ignition temperature \((T \geq 40 \text{ keV})\)\(^{11,12}\). It has been shown that laser-induced nuclear fusion
processes can be occur in ultra-dense deuterium\textsuperscript{13–15}. The deuteron fast ignition is an alternative way to nuclear energy production by deuterium fusion\textsuperscript{16–18}. In this paper, we indicate that the deuterium fuel can be ignited below the deuterium ignition temperature via a process which will be explained throughout the paper.

2 Self-Heating Following Ignition

In laser-driven inertial confinement fusion, spherical capsules are compressed and heated to high enough temperatures and densities for fusion reactions to occur\textsuperscript{11,12}. First, the laser irradiation leads to surface ablation and drives the fuel implosion. As the imploding material stagnates in the center, its kinetic energy is converted into internal energy. At this time, the fuel consists of a highly compressed shell enclosing a hot spot of igniting fuel in the center (Fig. 1). A burn wave starting from the hot spot then ignites the whole fuel, which explodes. Since ignition is occurred from center of the hot spot, this scheme is named "central hot spot".

There are two forms of the imploded fuel at the ignition conditions, namely isobaric and isochoric. The isochoric assembly is a configuration in which hot spot and cold fuel have the same uniform density. This is in contrast to the isobaric hot spot scenario, where it is essential that the hot spot area and the surrounding cold fuel remain in pressure equilibrium during compression. In fact, the pressure distribution over the stagnating fuel is not really uniform, but drops to low values at the outer boundary. The isobaric model is therefore overestimating the energy invested into the cold fuel layer. Simulations of the ignition conditions in (\(\rho R, T\))-space show that the isochoric compression requires a higher \(\rho R\) than in the isobaric case, because the cold fuel layer works as a tamper suppressing the expansion of the central plasma regions\textsuperscript{19}. Nevertheless, isochoric conditions convenient for the alternative fast ignition approach that it can lead to a fuel gain a factor 2-3 larger.
than the usual hydrodynamic ignition by a central isobaric hot spot\textsuperscript{20}.

### 2.1 Hot Spot Self-Heating Condition

Let us consider the schematic case illustrated in Fig. 1. The laser pulse has compressed fuel homogeneously to density $\rho = 5000$, and now the thermonuclear reaction starts in a hot spot with a areal density $\rho R$ and temperature $T$. The rate of change of the internal energy density $E$ of the hot spot is,

$$\frac{dE}{dt} = P_f - P_B - P_C - P_e - P_m$$

\(P_f\) is the power density deposited by the fusion products, \(P_m\) is the contribution due to mechanical work, \(P_C\) is the power density due to inverse Compton scattering, \(P_B\) and \(P_e\) are, respectively, the power densities lost by radiation and by thermal conduction. Each power has been introduced in its details in previous studies\textsuperscript{21,22}. According to Eq. (1), the hot spot temperature increases when,

$$P_f > P_B + P_C + P_e + P_m$$

that is, the power deposition by fusion products exceeds the sum of all power losses. This equation is solved numerically for pure deuterium fuel with $\rho = 5000$ (gcm$^{-3}$) density. The dashed area in Fig. 2 displays the region in the $\rho R - T$ plane, where Eq. (2) is satisfied and solid line represents a solution when the inequality is replaced by an equality. Instantaneous power balance allows to determine whether a hot spot cools or heats and thus, the Eq. (2) is called hot spot self-heating condition. Below the self-heating area power losses dominate the power balance. Indeed, if the initial parameters lie within this region or are even just on the boundary then expect the temperature increases and thus allows more fusion reactions to take place. Note that this equation is a static equation.
and temperature of electrons and ions in its solution are considered identical.

![Figure 1: Schematic picture of the compressed ICF fuel pellet to form the hot spot surrounded by cold fuel for ignition.](image)

2.2 Ignition and Time Evolution

Now we perform a time-dependent calculation of the fusion processes of a DT$_x$ $^3$He$_y$ configuration fuel pellet, where $x$ is the ratio of the tritium to deuterium and $y$ is the ratio of the helium-3 to deuterium particle numbers at initial time ($t = 0$). When the fusion reactions taking place, the total number density of particles of species $k$, $n_k$, is governed by the equation,

$$\frac{dn_k}{dt} = \sum_j a^j_k n_j(1)n_j(2) < \sigma v >_j$$  \hspace{1cm} (3)

where $< \sigma v >_j$ is the Maxwell averaged reaction rate of reaction $j$, and $a^j_k$ is the number of particles of species $k$ created or destroyed in the reaction $j$. Six species are considered in this calculation: D, $^3$He, T, p, $^4$He and n.
Figure 2: Self-heating conditions, Eq. (2), in the $\rho$ R-T plane for a deuterium hot spot in isochoric configuration at $\rho = 5000$ (g cm$^{-3}$) density.

For the ignition and time evolution, it is important to take into account the different evolutions of the ion and electron temperatures. The electron energy losses by the bremsstrahlung radiation, inverse Compton effect and thermal conduction. Therefore, the ion temperature will be higher than the electron temperature and an energy flow from the ions to the electrons by collisions is expected. The corresponding energy balance involving the ion and the electron internal energy densities $E_i$ and $E_e$, respectively, are described by the following equations,

$$\frac{dE_i}{dt} = \frac{3}{2} \frac{d}{dt} (n_i T_i) = \sum_j \sum_k (1 - \eta_{jk}^j) f_{jk}^j P_{fk} - P_{ie} - P_{mi}$$  \hspace{1cm} (4)

$$\frac{dE_e}{dt} = \frac{3}{2} \frac{d}{dt} (n_e T_e) = \sum_j \sum_k (1 - \eta_{jk}^j)(1 - f_{jk}^j) P_{fk} + P_{ie} - P_B - P_C - P_e - P_{me}$$  \hspace{1cm} (5)

where $T_i (n_i)$ and $T_e (n_e)$ are the ion and electron temperature (number density), respectively, $\eta_{jk}^j$ is the energy leakage probability of the product $k$ created in the reaction $j$ and $f_{jk}^j$ is the fraction of the energy of the product $k$ created in the reaction $j$ that is deposited.
into the plasma ions. Since the electron and ion temperatures are different, ion-electron power density, $P_{\text{ie}}$, is inserted to account for the flow of energy between them.

Let us consider, for example, pure deuterium fuel with initial configuration of density $\rho_0 = 5000$ gcm$^{-3}$, areal density $\rho_0 R_0 = 15$ gcm$^{-2}$ and initial ion, electron temperatures given by $T_i = T_e = 29$ keV. Corresponding the Fig. 2, these parameters are out of self-heating conditions (black point in Fig. 2) and thus the temperature expected to decrease and the fuel can not achieve ignition. To evaluate the fuel evolution, the fig. 3 is drawn by solving the equations 3, 4 and 5, numerically. These equations are coupled and must be solved simultaneously. The figure shows that the temperature first decreases slightly and then soon ($t \approx 1.5$ ps) increases to reach very high values. Therefore, ignition can also be achieved by a hot spot with initial conditions outside the self-heating region. In this case, at first the hot spot cools, and later self-heats and ignites. It seems this early ignition at time evolution of compressed fuel is a surprising event that need more exact analysis.

To find out what happen, the figures 4 and 5 are drawn until ignition time ($0 \leq t \leq 1.5$ ps). These figures show that density is decreased because of fuel expansion (fig. 4), and the tritium and helium-3 are produced due to deuterium reactions (D(D,p)T and D(D,n) $^3$He), (fig. 5). In general, at the ignition time the fuel parameters are,

$$\begin{align*}
N_D &= 1.65 \times 10^{20} \\
N_T &= 4.14 \times 10^{17} \\
N_{^3\text{He}} &= 7.50 \times 10^{17} \\
\rho &= 4984 \text{ gcm}^{-3} \\
\rho R &= 14.9 \text{ gcm}^{-2} \\
T_i &= 25.35 \text{ keV}
\end{align*}$$

This means the pure deuterium fuel (DT$_{x=0}$ $^3$He$_{y=0}$) with density $\rho_0 = 5000$ gcm$^{-3}$, areal density $\rho_0 R_0 = 15$ gcm$^{-2}$ and temperature $T_0 = 29$ keV at the initial time ($t=0$ ps),
is converted to the fuel DT$_{x=0.0025}$ $^3$He$_{y=0.0045}$ with density $\rho = 4984$ gcm$^{-3}$, areal density $\rho R = 14.9$ gcm$^{-2}$ and temperature $T_i = 25.35$ keV at ignition time (t=1.5 ps). Now we recalculate the self-heating condition (Eq. (2)) for this new configuration. Figure 6 is drawn for the time of (t=1.5 ps) and shows that Eq. (2) is satisfied (black point) and therefore the temperature can increase and fuel will ignite.

![Figure 3: Ion temperature evolution of deuterium fuel as a function of burning time. The density of the initial pellet is $\rho_0 = 5000$ gcm$^{-3}$. The areal density is $\rho_0R_0 = 15$ gcm$^{-2}$, and the initial temperature is $T_0 = 29$ keV.](image)

3 Discussions

Despite advantages of the use of deuterium such as stability and natural availability, the pure deuterium fuel can not ignite easily. A rough estimate of the energy required for ignition indicates that the ignition of pure deuterium requires about $10^4$ times more
Figure 4: Density changes during 1.5 ps.

Figure 5: Contents of tritium and helium-3 during 1.5 ps.
Figure 6: Self-heating conditions, Eq (2), in the $\rho$ R-T plane for fuel $\text{DT}_{x=0.0025} \text{He}_y^{3}$ with density $\rho = 4984 \text{ gcm}^{-3}$, areal density $\rho R = 14.9 \text{ gcm}^{-2}$ and temperature $T_i = 25.35 \text{ keV}$ for time $t=1.5 \text{ ps}$.
Figure 7: Ion temperature evolution of deuterium fuel as a function of burning time for different initial temperature. The density and areal density of initial fuel pellet is \( \rho_0 = 500 \text{ gcm}^{-3} \), \( \rho_0R_0 = 1.5 \text{ gcm}^{-2} \), respectively.
energy than ignition of DT, compressed to the same density. In this paper, it have been mentioned that the ignition can be occurred even blow the predicted temperature by self-heating condition.

The similar results may be found in previous works that can be explained as follows: charged particles and electron conduction heat a thin layer of the surrounding cold matter, which heats up and ablates. The mass of the hot spot therefore increases in time, and part of the energy lost by the hot spot is recovered. It may then happen that a hot spot initially cools, while its mass and $\rho R$ increase. In such a way, the hot spot captures a larger fraction of the charged particles, and may eventually heat up again and ignite $^{24,25}$. However, corresponding this paper, the early ignition at time evolution of the hot spot is occurred in a different manner. In fact the deuterium reactions (D(D,p)T and D(D,n) $^3$He) produce tritium and helium-3 and these ions play a catalyzer$^{26}$ role via secondary reactions (T(D,n) $^4$He and $^3$He(D,p) $^4$He)$^{27}$. These reactions have large reaction rate that can raise the temperature fast enough to cause ignition. Since the reaction rate of T(D,n) $^4$He reaction is larger than $^3$He(D,p) $^4$He reaction and then the final content of tritium is smaller than helium-3, (fig. 5). However, pure deuterium can be used as breeder fuel in concept of fusion plasma that ignited by lower temperatures are predicted by the static equations.

The initial density $\rho = 5000 \text{ gcm}^{-3}$ has been selected in accordance with previous theoretical studies$^{27-30}$. It seems this density is impossible to achieve by present technology. The standard scheme uses densities up to 1000 gcm$^{-3}$ in the (cold) main fuel while fast ignition should work with 300-500 gcm$^{-3}$ and $\rho R \leq 1.5 \text{ gcm}^{-2}$. In the Fig. 7, ion temperature evolution of deuterium fuel is shown as a function of burning time for different initial temperatures and density $\rho = 500 \text{ gcm}^{-3}$. It can be seen that the fuel pellet with $T_0 \geq 28 \text{ (keV)}$ can be ignited with the same behavior described above. By assuming the fuel plasma as a uniform sphere with Maxwellian velocity distribution and
initial conditions as, $\rho = 500 \text{ g cm}^{-3}$, $T_0 = 28 \text{ (keV)}$ and $\rho R = 1.5 \text{ g cm}^{-2}$, the internal energy $E_i = 3/2NT \simeq 227 \text{ (keV)}$ should be provided by driver beams. These calculations have been made as simple as possible to show the breeding effect of pure deuterium fuel. More precise calculations are needed containing hydrodynamic simulations. These more detailed calculations will be the subject of further studies by the author.

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