Compression and Fast Heating of Liquid Deuterium Targets in FIREX Program

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Abstract. The purpose of the first phase of the FIREX (Fast Ignition Realization Experiment) program is to demonstrate fast heating of a fusion fuel up to the ignition temperature of 5-10 keV. Such high temperature is difficult to be achieved with deuterated plastic targets used in the previous experiments because of the high radiation loss associated with high concentration of carbon ions. Using liquid deuterium targets is the obvious solution to significantly lower the radiation loss. Compression and heating characteristics of deuterium targets are under active investigation. Preheating temperature of the deuterium target was found to be about Fermi temperature, implying that the energy required for the compression is close to the lowest energy required for compressing a perfectly degenerated Fermi gas. We have also performed fast heating of planar deuterium targets for the first time. It has been found that hot electrons are transported through a plastic barrier layer and deposited their energy in the deuterium target, generating a significant amount of DD neutrons.

1. Introduction

In standard laser fusion scenario, a hot-spark triggering thermonuclear burn is created at the center of the main fuel. If the central hot-spark is larger than the range of the fusion generated alpha-particles, ignition will take place. In thirty years ago, we naively thought that the hot-spark can be created with a density as high as the surrounding main fuel. But in reality, pressure balance decreases the hot-spark density significantly, thereby increasing the core size by a factor of 2-3 and hence the required laser energy by an order-of-magnitude. Nevertheless, the progress of high-temperature and high-density compression in mid-to-late 80's was large enough to start ignition programs, such as the National Ignition Facility in the US and the Laser Mega Joule in France. Although these projects are anticipated to demonstrate first ignition and burn in a controlled way, there still exists a large jump towards

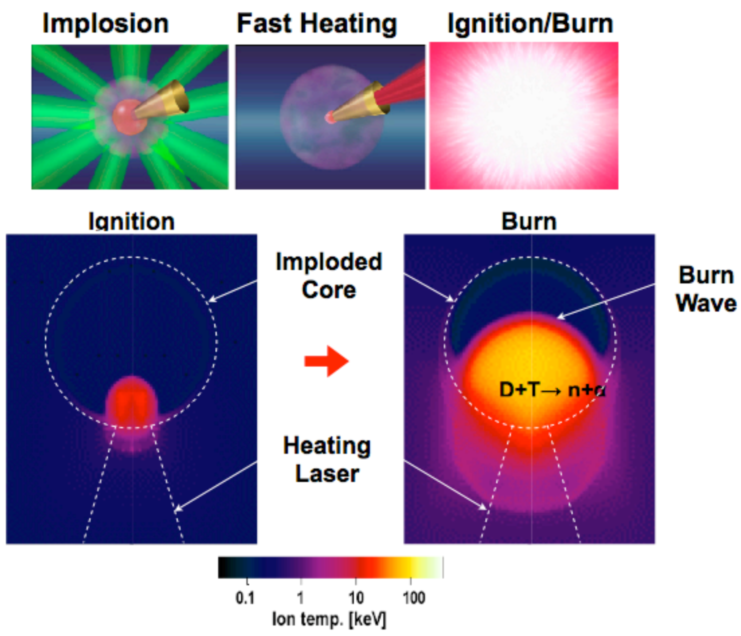

Fig. 1 Fast Ignition concept.

operation of MJ class lasers in high repetition. Compact ignition schemes are therefore desired for energy development. One such approach is the fast ignition (FI) scheme [1-3]. As is illustrated in Fig. 1, the fusion fuel is first imploded by irradiating laser light just like the standard fashion except for the insertion of a cone in some cases. At the maximum compression timing, a high-intensity short-pulse laser is injected through the cone. Since the fuel is heated much faster than pressure equilibrium, a high-density hot-spark can be created before significant hydrodynamic disassembly. The most distinct advantage of FI is that it can ignite at the laser energy of only about 1/10 of that required for the central ignition. If FI is demonstrated, inertial fusion development will be much more accelerated.

2. FIREX Program

In order to achieve fast ignition with remarkably small-size lasers with several tens to a hundred kJ, one needs 1) high density compression of more than1000 times liquid density, and 2) good coupling from lasers to thermal energy of the fuel with an efficiency of 20-30%. We have demonstrated both the high-density compression up to 600 times liquid density [4] and the fast heating with an efficiency of 20% [5]. In the latter experiment the compressed fuel has been heated to 0.8–1-keV temperature. These two major achievements have provided scientific basis to start a new program called FIREX to demonstrate ignition-and-burn by the fast ignition scheme. The scientific feasibility of fast ignition as a pathway producing reactor plasmas will be fully examined in the FIREX program.

In order for the program to be flexible, it is divided into two phases. The purpose of the first phase (FIREX-I) is to demonstrate fast heating of a fusion fuel up to the ignition temperature of 5-10 keV. The heating laser for this program is a high-energy peta-watt (10 kJ/10 ps) laser [6] that is currently under construction. The first experiment of FIREX-I will start in FY2007, followed by fully integrated experiments until the end of FY2010. If subsequent FIREX-II will start as proposed, the ignition-and-burn will be demonstrated only slightly after that at the National Ignition Facility and at the Laser Mega Joule, providing a scientific database of both central- and fast-ignition.

Since the burning wave travels through the entire fuel at a velocity much faster than any other hydrodynamic velocity, the burning proceeds no matter what the fuel size is. The energy gain increases simply with increasing the size of the compressed core, that is, by increasing the confinement time. Indeed, our two-dimensional hydro-code simulation predicts that energy gain increases monotonically from 5-10 at FIREX-II to more than 100 at reactors. There is no essential difference between the FIREX-II plasma and the reactor plasma except for the size. This is why ignition and burn in FIREX is so important. In the FIREX-II program, the implosion laser is planned to be a 50 kJ/3ns blue lasers, whereas the heating laser to be a 50 kJ/10ps red laser. The physical size of the whole laser system will be relatively small to barely fit the existing GEKKO building.

The heating laser is under construction. The laser has a 4-beam and 4-pass regeneration amplifier system. The high energy of 3.6 kJ/ beam has been demonstrated on May 2006. The full beam equivalent of 14.4 kJ is over the design value of 12 kJ. The pulse compressor and focusing infrastructure are now completed. One beam will be activated by March 2007, followed by full beam operation by March 2008. The most challenging technology development in this program is segmentation of the grating for pulse compression. A feedback control for the segmentation has demonstrated the extremely high stability of phase matching within ±1/40 of light wavelength.

We will use a foam cryogenic DT target with cone as a target for FIREX program. The fuel gas is fed through a thin capillary into the foam layer and cooled down to be liquid and solid. The following three major efforts are underway: 1) Low density foam targets with good uniformity. Faom targets are made from oil globules surrounded by water solutions in oil. This is called O/W/O emulsion technique. For target uniformity, density matching between Oil and Water is critical. However, polymerization requires high temperature that degrades the density matching due to unmatched thermal expansion. We have developed a catalysis that accelerates the polymerization even at room temperature. Reasonably good uniformity was obtained by this technique. 2) As for hole boring, laser etching with the second harmonics of YAG laser has demonstrated a sufficient quality for the hole. 3) Liquefaction and solidification. We have demonstrated hydrogen liquefaction and solidification in a cone target through a thin 10-micron capillary.

3. Liquid Deuterium Target Experiments

3.1 Necessity of Deuterium Targets for FIREX Program

In the previous experiments [4, 5], we have used deuterated plastic shells as surrogate targets for fusion fuel. However, since high radiation losses from these targets is expected to prevent heating up to the ignition temperature, we will use a foam cryogenic D2 and DT target with a cone as a target for FIREX program. The suitable foam density can be estimated by simple energy balance in the core. The increase of the thermal energy is determined by the balance of the heating power (external heating P_h and alpha heating P_α) and the power loss (expansion loss P_w, Conduction loss P_e, radiation loss P_r):

$$\frac{3\left(1+\langle Z\rangle\right)}{2}\frac{\rho(t)}{m_i}\frac{\mathrm{d}T(t)}{\mathrm{d}t} = P_h(t) + P_\alpha(t) f_\alpha - [P_w(t) + P_e(t) + P_r(t)], \qquad (1)$$

where <Z> stands for the average atomic number, T is the temperature, ρ is the mass density of the compressed core, m_i is the ion mass, and f_α is the fraction of alpha energy that is absorbed by the core, and f_α =1 is assumed for simplicity. The powers in right hand side are given by [7]

$$P_\alpha(t) = A_\alpha \rho_{DT}(t)^2 \langle \sigma v\rangle, \quad A_\alpha = 8.04\times 10^{40}, \qquad (2)$$

$$P_r(t) = A_r \rho(t)^2 T(t)^{1/2}\langle Z\rangle\langle Z^2\rangle, \quad A_r = 3.05\times 10^{23}, \qquad (3)$$

$$P_w(t) = A_w \frac{\rho(t)T(t)\frac{\left(1+\langle Z\rangle\right)}{2} v_{ex}(t)}{R(t)}, \quad A_w = 2.3\times 10^{15}, \qquad (4)$$

$$P_e(t) \approx A_e \frac{f_{SH}\left(\langle Z\rangle\right)}{\langle Z\rangle}\frac{T(t)^{7/2}}{R(t)^2}, \quad A_e = 4.1\times 10^{19}, \qquad (5)$$

in cgs units except for the temperature in keV. Here ρ_{DT} is the mass density of the fuel part, <σv> is the fusion reaction rate, R is the radius of the core, v_{ex}=dR/dt is the expansion velocity, and f_{SH} is the Spitzer-Härm's $\varepsilon\delta_T$-coefficient normalized at Z=1. Assuming the expansion velocity to be a fluid velocity behind a strong shock, we may solve the Eq. (1) numerically.

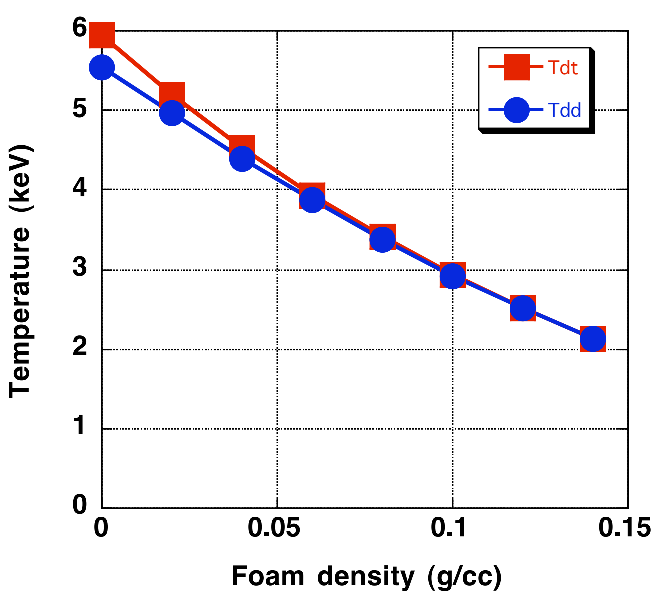

Fig. 2 Expected core temperature vs. foam density for the FIREX condition.

Figure 2 shows the temperature calculated by this simple model as a function of foam density for the case of the fixed fuel density of 200 g/cc, the initial radius of 15 micron, the initial temperature of 0.4 keV, the heating power of 1 PW, and the coupling efficiency from the heating laser to the thermal energy of 25%. Two curves correspond to DT and D2 fuels. Due to the alpha heating, the temperature of the DT fuel is slightly higher than that of the D2 fuel. In both cases, the temperature decreases with

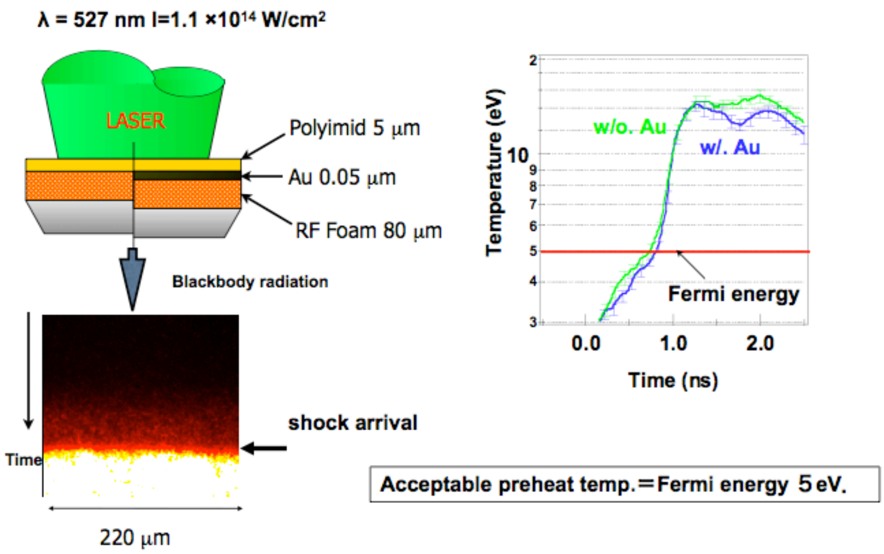

Fig. 3. Temperature on the rear target surface.

increasing foam density because of the increasing radiation loss. It appears that to get a significant heating we need a foam density much lower than 0.1 g/cc.

3.2 Hydrodynamics of Deuterium Targets

Obviously there is a concern that if deuterium targets are seriously preheated by hot electrons, high-density compression will be failed as was suggested in the previous experiments [8]. Also, if energy coupling from the heating laser to the compressed core energy is seriously degraded in deuterium targets, high-temperature heating will also be failed. In order to address these issues, we have performed experiments using cryogenically cooled liquid deuterium targets.

As for the preheating issue, several critical quantities of liquid deuterium targets, such as preheat temperature, target density profile, and target acceleration were compared with our hydrodynamic simulation. We used a low-density (0.34 g/cc) plastic foam with 80-micron thickness as a sustainer of liquid deuterium. (The foam density was designed to be equal to the foam+D2 density used in the density and trajectory measurements.) The foam layer is attached with a solid density (1 g/cc) plastic with 5-micron thickness as an ablator. The target was irradiated with a 0.5-micron laser light at an irradiance of 10^{14} W/cm^2. To suppress the preheating, we also used the same target but with a thin gold layer between the plastic ablator

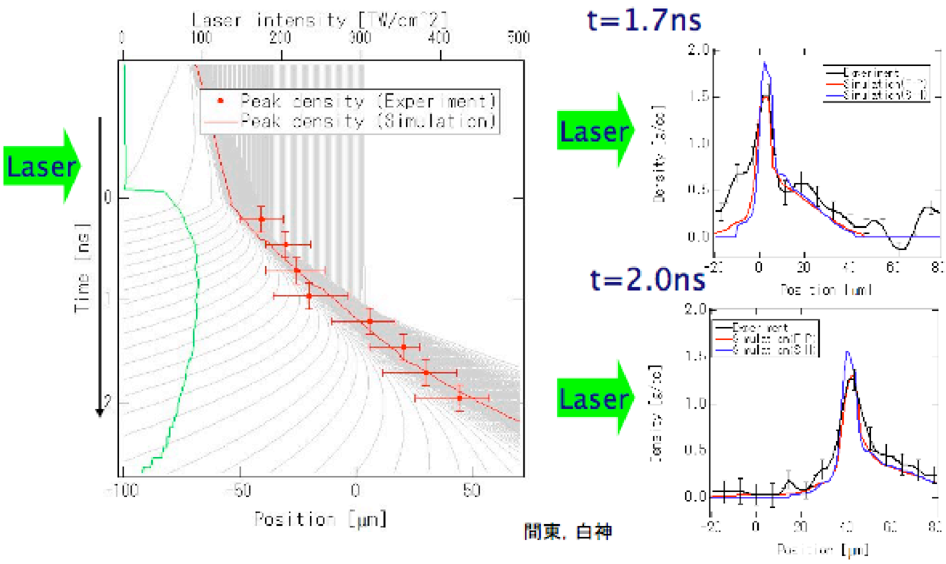

Fig. 4. Target trajectory and in-flight density distribution.

and the foam layer. The gold layer was designed to be thin enough (0.05 micron) to prevent potential hydrodynamic instabilities between two layers.

The preheat temperature shown in Fig. 3 was conventionally measured from blackbody radiation in a UV-visible light region. The sudden temperature increase at around 1 ns is due to the shock arrival on the rear surface of the target. Since the shock heated temperature can be controlled by laser pulse shape, the primary concern is the preheat temperature just before the shock arrival. It has been found that the target preheat level is about the Fermi temperature (5 eV) corresponding to liquid density deuterium. This preheating level may further be reduced by the insertion of the gold layer. The insufficient reduction of the preheat temperature is probably due to the insufficient gold thickness. In any case, the moderate preheat implies that the energy required for compression is close to that of perfectly degenerated Fermi gas. Due to the moderate preheat level, the target density profile shown in Fig. 4 and the target trajectory were in good agreement with that predicted by the hydrodynamic simulation. It appears therefore that the concern of preheat in deuterium targets was somewhat groundless.

The second concern about heating efficiency in deuterium targets will be addressed in the coming experimental campaign. In recent preliminary experiments, we have injected the peta-watt laser onto a liquid deuterium target with 100-micron thickness sandwiched by two plastic layers with 7-micron thickness. This is illustrated in Fig. 5. To study hot electrons transported in the target, we have observed Kα line emission generated by hot electron bombardment with Cl atoms that were doped into the plastic foam. We have also observed a clear DD neutron signal from the liquid deuterium target. These observations indicate that hot electrons are indeed transported through the plastic layer and deposited their energy in the deuterium target.

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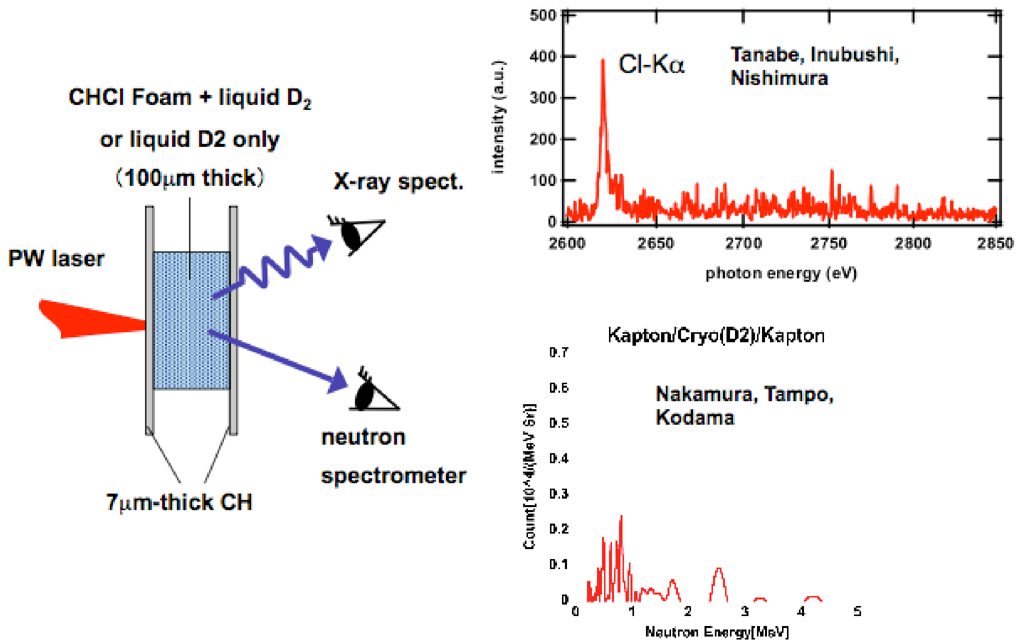

Fig. 5 Fast heating of a liquid deuterium target.

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