Temperature Measurement of Preheated Planar-Cryogenic Targets

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Abstract. The temperature measurement of preheated target is reported. Inertial confinement fusion (ICF) targets should be imploded with a low adiabat for achievement of high density compression. The high energy photons and electrons from ablation plasma can preheat the uncompressed fuel and disturb the low adiabat compression. Preheat has to be evaluated and suppressed for ICF targets. The planar target of cryogenic deuterium was developed for measurement of the self emission from the rear surface. Experiment indicated that the x-ray preheating is more effective than that of non-local electron heat transport at the laser intensity of $10^{14}$ W/cm².

1. Introduction

In laser-driven inertial confinement fusion (ICF) targets, the deuterium-tritium fuel enclosed by plastic shell forms a spherical target [1]. The ablative of laser irradiated target is blown off and becomes corona plasma and the inner fuel is compressed to a few thousand times of solid density due to the rocket effect. The hydrodynamic instabilities and fuel preheating disturb the high density compression. Previous investigations proposed some schemes for the repression of Rayleigh-Taylor instability (RTI) growth [2], but the preheating has not been researched enough.

The temperature of this corona plasma is up to keV (1 eV = 11605 Kelvin). The photon and electron at such temperature potentially preheats the fuel. In the preheated fuel, the entropy can be increased and the compressibility can be decreased. The index of preheating is described as the isentrope parameter [3], $\alpha = p(n,T) / p_F(n)$, where $p_F$ is the Fermi pressure, $p_F = n_e \hbar^2 (3\pi^2 n_e)^{2/3}/5m_e$, where $n_e$ is the electron number density, $\hbar$ is the Planck radius, $m_e$ is the electron mass, respectively. The Fermi temperature, $T_F$, which is defined as $T_F = 5p_F / 2n_e k_B$, where $k_B$ is the Boltzmann constant, is 5 eV for the deuterium-tritium (DT) fuel compressed to thousand times of solid density. The limit of acceptable preheated temperature is calculated to 2 eV, when $\alpha \leq 2$. Figure 1 shows the range of electron and x-ray in the liquid deuterium (LD₂) under the condition of the liquid density (0.25 g/cm³) at room temperature. The x-rays with the energy of several hundred eV or the electrons with the energy of some decade keV electrons can preheat the LD₂ with the thickness of 20 μm, which is the thickness of the main-fuel layer proposed in FIREX. At the long wavelength laser irradiation condition, the non-local electron heat transport arises at relatively low intensities. On the other hand, the x-ray emission at short wavelength laser irradiation condition is much more than long wavelength laser irradiation. This paper reports the experimental measurement of temperature due to the preheating.
under the non-local electron or x ray heat transport dominant condition. To compare the difference of preheat source, experiment was executed under two different laser wavelengths.

2. Experimental setup

Experiment has been conducted on GEKKO-XII, HIPER (High Intensity Plasma Experimental Research) facility [4], in Institute of Laser Engineering. The HIPER irradiation facility was constructed with twelve laser beams, which were aligned to one direction. Each beam irradiates 2.5 ns duration light with smoothing by two dimensional smoothing by spectral dispersion (2D-SSD) technique [5]. The laser light was converted to second ($2\omega$, $\lambda = 0.53 \, \mu m$) or third ($3\omega$, $\lambda = 0.35 \, \mu m$) harmonics by rotating the KDP crystals. The $2\omega$ irradiation enhances the non-local electron heat transport because of its high electron temperature at the critical density. In the $3\omega$ irradiation, the critical temperature was lower, but the x ray emission of Bremsstrahlung is much higher than $2\omega$ irradiation. The comparison of the effectiveness of x ray and electron heat transport without laser plasma instabilities was studied in this experiment. We employed five beams for the $2\omega$ irradiation at the intensity of $1.5 \times 10^{14} \, W/cm^2$, or the $3\omega$ irradiation at the intensity of $1.2 \times 10^{14} \, W/cm^2$.

Figure 2 shows the schematic view of components of the target cell [6]. The target cell was composed 100 $\mu$m gap sandwiched by 4 $\mu$m thick polyimide foils. The liquid deuterium was filled into the gap when the target cell was cooled to $\approx 15 \, K$. To reduce the expansion of polyimide foils, we applied “double flange” structure, which is constructed by “extension flange” and “sealing flange”. The target cell was sealed by the polyimide foils and the sealing flanges. Additionally, the extension flange was attached on the sealing flange, and pushed the polyimide foil. Thus, the expansion of the target thickness was reduced to 200 $\mu$m.

The rear surface of the target radiated photons depending on its temperature. If the laser-irradiated target is assumed as the blackbody, its emission behaves as Planck distribution. Therefore, the temperature at the witness point of the rear surface of the target was able to be detected from its spectrum and intensity [7]. The optical streak camera coupled with S-20 cathode was applied to observe the self-emitting light from the witness point. The streak camera was coupled with spectrometer, and then it measured spectrally resolved self emission. The self-emitting light was collected by a condenser lens into the optical fibre. The wavelength was calibrated by using the Hg lamp (HAMAMATSU, L537-02) and the sensitivity was also calibrated by using the xenon lamp (HAMAMATSU, L2175). The spectral and temporal resolution was 20 nm and 200 ps, respectively. The detector observed the witness point 137.5° from the drive laser. Since the self emission was spatially restricted and integrated for the area of 200 $\mu$m in diameter at the centre of the target chamber, the centre of rear surface of the target cell should to be aligned to the centre of the witness point. However, the target cell was expanded about 100 $\mu$m after filling the LD2, thus another visible streak camera with S-20 cathode employed to monitor the imaged self emission from the rear surface of the target. This detector observed the witness point 150° from the drive laser. The distribution of shock wave arrival time gives the position of target centre and uniformity of shock wave, and the intensity gives the luminosity temperature of the witness point. The spatial and temporal resolutions were 17 $\mu$m and 200 ps, respectively.

3. Experimental results

Figure 3-(a) shows the spectral evolution of self emission at the rear surface of the target. The short wavelength light was delayed in optical fibre. The bright line of 527 nm was the $2\omega$ light of drive laser. Obtained data was lower than detection limit, about 0.5 eV. Figure 3-(b) shows the spatial distribution of the self emission. The expansion of rear surface of the target was negligible in this result. The dashed-line area was integrated in spectral measurement. The temperature of the centre of the witness points were derived as Fig. 3-(c) for each detector. The time origin is the timing of half of maximum of the rising of the laser irradiation. The temperature of the target before shockwave arrival was lower than 0.6 eV with the $2\omega$ irradiation at the intensity of $1.5 \times 10^{14} \, W/cm^2$.
Figure 4 shows the temperature evolution in the $3\omega$ irradiation at the intensity of $1.2 \times 10^{14}$ W/cm$^2$. It clearly shows that the target was preheated to 2 eV until the time of 1.5 ns and the temperature was saturated between 1.5 ns and shock arrival.

4. Discussion
In the case of $2\omega$ irradiation, preheat was not crucial problem. Since the most effective energy for non-local electron heat transport is 6.9 times of electron temperature [8], its energy is estimated to $\approx 12$ keV by ILESTA-1D simulation code [9]. Since the mean free path of 12 keV electrons in solid plastic is about 1 $\mu$m, the non-local electron heat transport only affected in the polyimide ablator.

In the case of $3\omega$ irradiation, preheat was much effective than $2\omega$ irradiation case. It suggests that the x-ray preheating is more effective under the experimental conditions. Figure 5-(a) shows the raw image of x-ray streak camera detected the self emission of the target from lateral side of the target. It shows that the x-ray self emission disappeared at 1.5 ns. It can explain that the preheat was due to the x ray from ablator, and preheat temperature saturated because the x ray emission ended. Figure 5-(b) is the flow diagram calculated by ILESTA-1D simulation. It shows that the polyimide ablator was blown off at the 1.5 ns, and the LD$^2$ was directly ablated after disappearing of polyimide. Therefore the preheat source in this experimental condition was x ray from polyimide ablator.

5. Summary
The temperature of preheated target was measured. The experimental results show that the non-local electron heat transport is not a crucial problem at the intensity of $10^{14}$ W/cm$^2$. The x-ray preheating is much effective at similar intensities, however the preheated temperature is moderate. After blown off of the polyimide ablator, increase of the preheat temperature was saturated. It suggests the x-ray preheating from carbon, nitrogen, or oxygen was preheated the witness point.

As prospect, the variation of preheating in much higher intensities should be measured. Especially the arising of the effect of the non-local electron heat transport in preheat is important.

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Figures

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Figure 1. Range of x-ray and electron in liquid deuterium.
Figure 2. (a) Exploded view of planar-cryogenic target cell. (b) Top view of the cross section at the target cell.

Figure 3. (a) The spectrally resolved streak image with 3ω irradiation. (b) The spatial distribution of self emission with 3ω irradiation. The integrating area in spectral measurement is surrounded in dashed line. (c) The obtained temperature evolution with 3ω irradiation at the intensity of $1.5 \times 10^{14} \text{ W/cm}^2$. (d) The obtained temperature evolution with 2ω irradiation at the intensity of $1.2 \times 10^{14} \text{ W/cm}^2$.

Figure 4. (a) The flow diagram calculated ILESTA-1D simulation with FP equation for the electron heat transport. (b) The x-ray emission monitored by side-on x-ray streak camera.