Implosion hydrodynamics and heating synchronization measurement using X-ray framing cameras

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Abstract. In fast ignition laser fusion experiments, it is important to know the implosion hydrodynamics and the heating mechanism of imploded core. However, it is difficult to measure the imploded core and heating laser injection at the same time because of their large spectral differences. In this paper, we propose a simultaneous measurement of an implosion process and an injection time of heating laser by using X-ray framing camera (XFC).

1. Introduction

Fast ignition [1-4] is one of the proposed ways to generate fusion plasmas. This scheme separates the compression and heating phases. Nano second pulse lasers are irradiated to a fuel target and generated imploded core plasma. Then, pico second short pulse laser is injected into the tip of the gold cone. When the laser interacts with the gold, energetic electrons are produced. These electrons deposit their energy and raise the fuel to fusion temperatures. Fast ignition scheme is considered as a powerful method for generating laser fusion plasma because the laser energy required for implosion in fast ignition scheme is expected to be much smaller than that in the central ignition scheme.

In Fast ignition fusion experiment, it is important to know the implosion hydrodynamics and the heating mechanism of the imploded core plasma. Especially, to measure a heating laser injection time and observe a core plasma heating process is necessary for efficient heating of the imploded core plasma. However, the large spectral difference between thermal X-ray from the imploded core plasma and high energy X-ray from hot electrons generated by the heating laser causes difficulty in measuring both X-rays at the same time. In this study, we report a simultaneous measurement of both X-rays and discuss the possibility of heating laser injection time measurement with an X-ray framing camera (XFC).

2. Experiment

X-ray framing cameras have been widely used for diagnosing laser-driven implosions [5-8]. Figure 1 (a) shows the schematic diagram of our X-ray framing camera system made by Hamamatsu photonics, Model C5896. The X-ray framing camera has two micro channel plates (MCP) which size is 40 mm × 50 mm. The first MCP is for gating and the second MCP is for amplification of a signal. Four Au striplines are deposited on the first MCP. Four electric pulses propagate through each stripline with arbitrary delay. The first MCP becomes sensitive only when electric pulse exist, therefore time evolution of 2D X-ray images are recorded by using a pinhole imager array with very
high-speed time resolution (about 80 ps). Electrons through tandem MCP hit the fluorescence plate and the visible fluorescent lights are recorded with a CCD camera.

The experiments were performed using Gekko XII laser system and LFEX laser system at the Institute of Laser Engineering, Osaka University. 9 beams of Gekko XII irradiated the plastic shell target to create the imploded core plasma and after that LFEX laser were injected to heat the core plasma. The pulse width of LFEX laser is about 4 ps. The targets were about 500 µm in diameter and 7 µm in thickness with gold cones, which had a 30° opening angle. Observation direction of XFC is shown in Fig. 1 (b).

3. Results and discussion

Figure 2 shows the time- and space-resolved images obtained by X-ray framing camera. As shown in Fig. 2, bright zones are observed in third stripline. The bright zones were observed only when additional heating laser was injected. In fast ignition experiments, hot electrons generated by the heating laser and MeV class high energy electron emit sub MeV ~ MeV class X-ray through bremsstrahlung. These high energy X-rays pass through pinhole array base materials and form a bright zone on the image data. Thus, it is considered that the peak position of these bright zones become indicators of the injection time of additional heating laser.

The temporal evolution of X-ray intensity profile reconstructed from the X-ray image is shown in Fig. 3. Two experimental data are shown as a black line and a gray line. The X-ray intensity peak is consistent with the above mentioned most bright zone in the X-ray image. Although this peak does not show the heating laser injection time directly, but as we said before, it is related to the heating laser injection time. For example, in the experiment shown as a gray line, the injection time of LFEX laser was set to be delayed 160 ps compared to the experiment shown as a black line. As shown in Fig. 3, it is found that the X-ray peak position of gray line is about 1000 ps, which is delayed for 250 ps.
Figure 3. The temporal evolution of X-ray intensity. 1.2 mm thickness Pb filter was used to shield high energy X-ray under the detectable intensity. The LFEX laser injection time is different in the two experiment. The other experimental conditions were same. The target was plastic shell with 45 degree gold cone. GXII laser energy was about 200J/beam and LFEX laser energy was about 550J.

compared with that of black line, about 750 ps. The laser injection time is considered to have an error bar less than 100 ps due to jitter. Therefore, we consider this result is reasonable and we can estimate the heating laser injection time from the peak position of high energy X-ray intensity profile.

The FWHM of MCP gain is considered to be about 80ps in our X-ray framing camera system. However, as shown in Fig. 3, the intensity of high energy X-ray shows broad profile over 200 ps. This broadening cannot be explained by the simple dynode model used in usual MCP gain calculation. Therefore, we are trying to build the new model which explains this broadening. The concept of dynode model is as follows. One dynode is defined by electrons travelling one side wall to the other side wall of the channel. One dynode gain $\delta$ is defined as follows [9]:

$$\delta = \left( \frac{V_z}{V_c} \right) \cdot k$$  \hspace{1cm} (1)

Here, $V_z$ is the voltage between one dynode, $V_c$ is the first crossover potential (i.e., the minimum potential for unity secondary emission ratio) and $k$ is a secondary emission curvature coefficient assumed based on experimental measurements. The total MCP gain $G$ of n dynodes is the multiplication of all dynode’s gain.

$$G = \delta_1 \cdot \delta^{n-1}$$  \hspace{1cm} (2)

Here $\delta_1$ is gain of the first input electron.

In thermal X-ray measurement, $n$ is typically fixed at about 9.8 and $\delta$ is considered to be proportional to the applied electric pulse voltage. Therefore, FWHM of MCP gain becomes about 105 ps when FWHM of electric pulses is 330 ps. This nonlinear gain response makes the high temporal resolution measurement possible. However, in this experiment, high energy X-ray may penetrate both Pt pinhole imager plate and MCP and generate electrons throughout the MCP channel. Electrons generated in mid MCP channel have smaller $n$ compared to that of electrons generated on MCP channel surface. This decrease of $n$ may broaden FWHM of MCP gain. In previous paper [10,11], we confirmed this concept by calculation. We calculated gain profiles by using various $n$ values and found that the FWHM of the gain in the case of small $n$ value is wider than that in the case of large $n$ value. This means that the gain profile of electrons generated in mid MCP channel are broadened compared with that of electrons generated on MCP surface. Therefore, in the case of high X-ray incidence, total gain profile is sum of these various $n$ gain profiles and it is broadened compared with the case of thermal X-ray incidence. This theory is considered to explain the broad high energy X-ray profile qualitatively. Thus, it is considered that we can estimate the heating laser injection time from the peak position of X-ray intensity by using this model calculation. For more precise modelling, it is necessary to know the incident energy of X-rays.

Therefore, we tried to estimate the incident X-ray energy by using metal filter. First, we found that the aluminium filter base material (2 mm thickness) has no effect to shield the incident X-ray. The
transmission rate of 2 mm thickness aluminium is 0.9 for 80 keV X-ray. Therefore, the incident X-ray energy is considered to be above 80 keV. Second, we used Pb filter with 1.2mm thickness. It is found that the incident X-ray intensity was decayed into about 10%~40%, although the decay rates are slightly changed shot by shot. Figure 4 shows the transmission rate of 1.2mm thickness Pb filter. 10%~40% transmission rate correspond to the case of 150~250 keV X-ray. From these results, it is considered that the incident X-ray energy is about 150~250 keV. We are now improving the fitting model considering this result.

![Image of Figure 4](image)

Figure 4. The transmission rate of 1.2mm thickness Pb filter.

4. Summary
We succeeded in measuring heating laser injection time and the imploded core plasma simultaneously by using X-ray framing camera. LFEX laser injection time was observed as bright zones on striplines. The peak position is found to delay corresponding to the delayed setting of LFEX injection time. MCP gain of high energy X-ray calculated by using dynode model explains the broadening of high energy X-ray intensity profile qualitatively. The incident X-ray energy is measured by metal filters and found to be 150 keV~200keV. The more precise model based on this result will be build in near future and XFC will become powerful tools in fast ignition experiments to observe the implosion hydrodynamics and the heating synchronization simultaneously.

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