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High-speed monochromatic x-ray imager for electron temperature mapping of fast igniter plasmas

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Abstract. We report on experiments aimed at obtaining laser-imploded core plasma temperature maps using two color, monochromatic x-ray imager. This instrument uses two toroidally bent Bragg crystals and a high-speed sampling imager to provide spatial resolution of 25 $\mu$m, temporal resolution of 20 ps, and spectral resolution over 200, simultaneously. Using a deuterated plastic shell target filled with CHClF$_2$ gas, time-resolved monochromatic x-ray images in the Cl-He $\beta$ and Cl-Ly $\beta$ were successfully obtained.

1. Introduction

In fast ignition scheme [1], high-density fuel compression and additional heating with a high intensity ultrashort pulse laser are very important. Dynamics of laser-imploded core plasma and energy deposition by fast particles must be studied in order to achieve efficient fusion burn. The fuel is compressed to several tens of micrometers, and the heating process is found to occur in a temporal window less than 100 ps [2]. Highly spatial and temporal resolutions, typically 10 $\mu$m and 10 ps, and seamless data acquisition are simultaneously required to diagnose the core plasma. In addition, spectral information in the keV range can be used as a diagnostic of plasma parameters such as electron temperature and density.

Monochromatic x-ray imaging with a bent crystal [3] represents an indispensable tool for obtaining narrowband x-ray images covering x-ray line emissions from dopant in a target. Moreover, this monochromatic imaging geometry blocks energetic x rays emitted from fast-ignitor plasma with a thick high Z substrate direct shield. In previous researches, time-resolved monochromatic images have been obtained with monochromatic x-ray framing camera [4], and electron temperature and density profiles of the core plasma were derived [5]. In order to obtain higher temporal resolution in continuous x-ray images, a monochromatic x-ray sampling image x-ray streak camera (M-SIXS) has been developed [6]. In this paper, the feasibility of the M-SIXS in implosion experiments is reported.

2. Experimental arrangements

The M-SIXS consists of a bent Bragg crystal and a two-dimensional (2D) sampling image x-ray streak camera (SIXS) [7]. The instrument geometry of the M-SIXS for this research is schematically shown in Fig. 1. To minimize astigmatism and obtain high photon-collection
efficiency, toroidally bent crystal [3] was used. In the separate experiments, a spatial resolution better than 10 $\mu$m has been confirmed with the toroidally bent crystal [4]. CHClF$_2$ gas was chosen as a dopant, and Cl$^{15+}$ He$\beta$ and Cl$^{16+}$ Ly$\beta$ lines were observed to derive electron temperatures. Specifications of two toroidally bent crystals in this research are listed in Table 1. A 100-$\mu$m-thick beryllium shield was set in front of each crystal.

### Table 1. Specifications of two toroidally bent crystals.

|                         | X-ray energy (keV) | 3.27 | 3.51 |
|-------------------------|--------------------|------|------|
| Bragg crystal           | Silicon (220)      | 200/195.8 |      |
|                         | Quartz (11.2)      | 200/189.5 |      |
| Bent radii (mm)         | 11.7               | 26.0 | 26.3 |
| Spectral window (eV)    | 102.5              | 2667 | 2659 |
| Image magnification     |                    |      |      |
| Target-Crystal (mm)     |                    |      |      |
| Crystal-Detector (mm)   |                    |      |      |

SIXS is a 2D sampling image technique with an x-ray streak camera (XSC) [7]. Two monochromatic x-ray images of the core plasma are focused on a gold photocathode which is 13.2 mm in height and 17.3 mm in width, and then the images are sampled by placing a periodic pinhole-array in front of the photocathode. A separation distance between the pinhole-array and the photocathode was 5 mm. The 41 × 67 pinholes were fabricated on 25-$\mu$m-thick nickel substrate. The pinhole size was 30±3 $\mu$m. The sampled pinhole images are swept with high voltage in the streak tube, and the streaked image of sampling points can be obtained on a phosphor screen, as illustrated in Fig. 1. The spatial resolution of the system $\Delta r_s$, as determined by the sampling distances $S_x, S_y$, is defined as $\Delta r_s = 2S_x/M$ or $\Delta r_s = 2S_y/M$ [6; 7], where $M$ is the image magnification. As the $x$ and $y$ sampling distances were set to 330 $\mu$m, the spatial resolution in this study was 25 $\mu$m. However, according to the sampling theory, the sampling distances for image sampling $S_x, S_y$ should be $S_x, S_y \leq (1/2)M\Delta r_{imager}$ to cover all of the spatial frequencies in the original image information, where $\Delta r_{imager}$ is the spatial resolution of the imager. As the spatial resolutions for two crystals were 10 $\mu$m, the sampling distances are 2.5 times larger than $(1/2)M\Delta r_{imager}$, thus some of the original image information between the sampling points was lost. Temporal resolution is determined by both the pinhole diameter and the sweep speed, and the observable time-window is determined by both the pinhole space in the
sweep direction and the sweep speed. For the set-up adopted in this experiment, the temporal resolution and the observable time-window were estimated to be 20 ps and 500 ps, respectively.

A 6.2 µm in thickness, 490 µm in diameter deuterated plastic shell was used. As a tracer, CHClF₂ gas of 0.2 atm was filled in the shell. It was supported with as 20-µm-outer-diameter and 15-µm-inner-diameter glass capillary through which the tracer gas was filled. The capillary is struck on the shell, glued with a paste to avoid the leakage of the fill gas. The gas fill procedure is described as follows. First, the inside of the shell was evacuated. Second, a buffer gas tank of approximately 200 cm³ in volume located outside a target chamber was filled with CHClF₂ gas. Pressure in the buffer tank was measured with a diaphragm pressure gauge directly installed in the buffer tank. After suitable gas pressure was attained, a valve between the buffer tank and the gas cylinder was closed, then a valve between the buffer tank and the shell was opened slowly. The CHClF₂ gas was flowed to the shell inside through the capillary. Finally, the valve between the shell and the buffer tank was kept open at least 1 hour before the laser shot to equalize the pressures in the buffer tank and the shell inside.

Implosion experiment was performed at the GEKKO XII laser facility. The shell target was irradiated with 12 beams of 526 nm in wavelength and 3.7 kJ in total energy at a Gaussian pulse with 1.3 ns full width half maximum. To homogenize laser intensity distribution on the shell surface, random phase plates for each beam were used.

3. Experimental results

Figure 2 shows typical data from the two color M-SIXS. The two color x-ray images at 3.27 keV and 3.51 keV were simultaneously recorded on the same photocathode of the XSC. The absolute position, namely the center of the shell, was recorded in a separate laser shot. Moreover, the absolute position of each sampling point, spatial non-uniformity of the photocathode sensitivity, and dispersion of the pinhole size were provided with a static image, which obtained without supplying a sweep voltage to the streak tube. Using these experimental data, the 2D images for two color x rays were reconstructed from the streaked monochromatic images shown in Fig. 2.

Figure 2. Streaked monochromatic x-ray images of the chorine doped core plasma at 3.27 keV (left) and 3.51 keV (right). The two color images were recorded on the photocathode of the XSC for the same laser shot.

Figure 3(a) shows reconstructed monochromatic x-ray images at 3.27 keV. The reconstructed images for 3.51 keV is also shown in Fig. 3(b). They are shown with same color scale corrected for the x-ray filter transmission and crystal reflectivity. The time interval is 20 ps and the overall time duration of x-ray emissions is about 400 ps. First frame images were defined as the onset of the line emission. Each frame image at 3.27 keV and 3.51 keV corresponds to the same time. The emission intensity gradually increases as time advances, and reached the peak at 360 ps.
after the onset of the emission. One can clearly see that the x-ray image for 3.27 keV has once a weak peak at 200 ps and a strong peak at 360 ps from the onset of the emission. The similar phenomenon is obtained with a time-resolved x-ray spectrograph. It is of great interest to study such plasma dynamics in detail for fast ignitor research.

Figure 3.  Reconstructed monochromatic x-ray images of the chlorine doped core plasma for 3.27 keV x ray (a) and for 3.51 keV x ray (b). Frame interval is 20 ps. Two color x-ray images are shown with same color scale.

4. Summary
Feasibility of the M-SIXS for deriving electron temperature mapping of the core plasma has been demonstrated with a temporal resolution of 20 ps, a spatial resolution of 25 µm, and an energy resolution over 200 using a deuterated plastic shell target containing CHClF₂ gas. The two color monochromatic images at 3.27 and 3.51 keV have been successfully recorded for the same shot. Temporal evolution of electron temperature profiles is undertaken, and will be obtained in the near future.

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