X-ray monochromatic high-speed imager for FIREX fast ignition research

Hiroaki Nishimura, Minoru Tanabe, Takashi Fujiwara, Shinsuke Fujioka, Hiroyuki Shiraga, and Hiroshi Azechi

Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka 565-0871 Japan

nishimu@ile.osaka-u.ac.jp

Abstract. A novel x-ray imager, consisting of two toroidally bent Bragg crystals and a 2D image sampler using a conventional x-ray streak camera, has been demonstrated for use in fast ignition research. Sequential and 2D monochromatic x-ray images of laser-imploded core plasma were successfully obtained with a temporal resolution of 20 ps, a spatial resolution of 31 µm, and a spectral resolution of over 200, simultaneously.

1. Introduction

Fast ignition has been recognized as a pathway to efficient thermonuclear burn in laser-driven inertially confined fusion (ICF) plasmas [1]. This scheme differs from central ignition by using separate lasers for core plasma formation and additional heating processes with a large energy peta-watt laser. Only when the heating laser is injected within a plasma confinement time (typically less than 100 ps) [2], adequate energy transfer can be achieved. The scale of the core plasma is several tens of micrometers. Thus, high spatial and temporal resolutions, typically 10 µm and 10 ps, and seamless data acquisition are simultaneously required to investigate phenomena occurring in these short-lived dense plasmas. In addition, x-ray spectroscopy in the keV range can apply to diagnose plasma parameters such as electron temperature and density of the ICF plasmas.

Various x-ray spectroscopic and imaging methods have been used to measure electron temperature and density profiles of ICF plasmas [3-5]. Spatially, temporally, and spectrally resolved two-dimensional 2D images have been obtained by using a monochromatic x-ray framing camera [3]. However, its temporal resolution of 35 ps and frame interval of 50 ps do not allow for detailed observation of fast-ignitor plasmas.

We report a new type of monochromatic x-ray camera, called a monochromatic sampling image x-ray streak camera: M-SIXS. This method achieves high spatial, temporal, and spectral resolutions providing temporally continuous x-ray images of the core plasma.

Fig. 1 Schematic view of M-SIXS camera.
2. Monochromatic sampling image x-ray streak camera

A basic M-SIXS consists of a toroidally bent Bragg crystal and a 2D sampling image x-ray streak camera SIXS [6]. Figure 1 shows a schematic view of a M-SIXS system. The use of a bent-crystal imaging device has several advantages in the keV x-ray region, such as high photon collection efficiency and high spectral and spatial resolutions, compared to an x-ray pinhole imager. Because of reflection optics, system geometry blocks energetic x rays and γ rays emitted from the fast-ignitor plasma with a thick direct shield. The toroidally bent crystal is bent to two different bend radii [7]. In order to avoid spherical aberration in the output image, toroidally bent crystals of two different radii are adopted. For a toroidal surface, the focal lengths $f_m$ for the meridional plate and $f_i$ for the sagittal plate are given by their respective direction radius $R_m$ or $R_i$: $f_m=R_m \sin \theta_i/2$ and $f_i=R_i/2\sin \theta_i$. Here $\theta_i$ is the Bragg angle for the wavelength of the x ray. These focal lengths must be equal, providing the relation $R_m/R_i=\sin^2 \theta_i$. When the image magnification is larger than 1, the spectral range covered by the crystal is primarily determined by the variation of the Bragg angle compared with the rocking-curve width [8]. In practice, a spatial resolution of less than 10 μm has been attained [3].

SIXS applies a 2D image sampling technique to an x-ray streak camera (XSC). This is suitable for observation of rapidly changing small x-ray sources. As shown in Fig. 1, an image of the object is focused on the photocathode, and then sampled by placing a periodic pinhole-array set in front of the photocathode. Figure 2 shows the image sampling and reconstruction processes. A static image, obtained without supplying a sweep voltage to the streak tube, is shown in Fig. 2(a), providing the absolute position of each sampling point. A streaked image of sampling points is shown in Fig. 2(b). Time-resolved 2D images can be reconstructed in such that the sampled images for a specific time are re-arranged as shown in Fig. 2(c). Spatial non-uniformity of photocathode sensitivity and dispersion of pinhole size are considered in the reconstruction process.

According to sampling theory, the sampling distances for image sampling $S_x$, $S_y$ should be $S_x$, $S_y \leq (1/2)MAR_{major}$ in order to cover all of spatial frequencies in the original image information, where $M$ and $Δr_{major}$ are the image magnification and the spatial resolution of the imager. If the sampling distance is larger than $(1/2)MAR_{major}$, some of the original image information between the sampling points is lost. Spatial resolution of the system, as determined by the sampling distances, is defined as $Δr_{image}=2S_y/M$ or $Δr_{image}=2S_x/M$. The size of the sampling pinhole does not affect the spatial resolution, because the sampling distance is much larger than the pinhole diameter. Temporal resolution is determined by both pinhole size and XSC sweep speed, and the window of available time is determined by the pinhole spacing in the sweep direction [6].

3. Experiment

Two x-ray photon energies, 3.27 keV corresponding to Cl$^{15s}$Heβ and 3.51 keV corresponding to Cl$^{16s}$Lyβ, were chosen to derive an electron temperature profile of the laser imploed-core plasma, supposing a case that chlorine is doped as a seed material in the fusion capsules. Specifications of the toroidally bent crystals dedicated to these two lines are listed in Table I. A100-μm-thick beryllium (Be) filter was set in front of each crystal to shield them from plasma debris. The crystals were mounted on miniature goniometers and x-y-z-translation stages to allow alignment to the correct tilts and distances. The initial alignment of the system was made optically, and then the final confirmations were made using the x-ray from laser-produced plasma. Small angular deviations between the optical and x-ray images have been investigated separately with an x-ray tube [9]. The measured angular
 discrepencies were less than 1 mrad.

A sampling pinhole array was placed in front of the photocathode (13.2x17.3 mm²) with a separation distance of 5 mm. The 55x34 pinholes were fabricated on a 25-µm-thick nickel substrate by a photolithographic method. The diameter of the pinholes was 30 ± 3 µm. The x and y sampling distances between the pinholes were 400 µm. Although the spatial resolutions of the both toroidally bent crystals were 10 µm, the sampling distance was three times larger than (1/2)MΔr, so some of original image information between the sampling points was lost. For the setup adopted in this experiment, the resultant spatial resolution was 31 µm and the temporal resolution was 20 ps. In addition, the pinhole separation along the sweep direction was 800 µm, creating an observable time-window of 600 ps. The photocathode was made of a 0.03-µm-thick gold, coated on a 3-µm-thick plastic film. A 100-µm-thick Be filter was placed in front of the photocathode in order to absorb scattered visible light and soft x rays.

A proof-of-principle experiment was performed at the GEKKO XII laser facility. A deuterated plastic CD shell target was irradiated with 12 beams of 527 nm in wavelength, totaling 4 kJ of energy in a Gaussian pulse with a 1.3 ns full width at half maximum. To smoothen the laser intensity profile on the shell surface, random phase plates were installed for each laser beam. The laser beams were focused at d/R=-5, where R is the shell radius and d is the distance from the shell center to the laser focus point. d is defined as negative when the focus point is beyond the shell center. The CD plastic shell target was 481 µm in diameter and 5.23 µm in wall thickness.

Figure 3 shows a streaked monochromatic x-ray image of the laser-imploded-core plasma at 3.27 keV. Figure 4(a) shows the reconstructed 2D x-ray images of the core plasma at 3.27 keV. The outer frame sizes of the 2D images are 120x120 µm² and the frame interval is 20 ps. The time origin was defined as the time corresponding to half of the x-ray intensity peak in the streaked image shown in Fig. 3. Similarly, the reconstructed images for 3.51 keV were obtained, as shown in Fig. 4 (b). The two images, for 3.27 and 3.51 keV, were simultaneously recorded on the same photocathode for the same shot. The time origin for 3.51 keV corresponds to that of 3.27 keV. X-ray intensities for the two images gradually increase in time and reach their peak at 160 ps. The imploded core is about 50 µm in diameter.

---

**TABLE I. Specifications of two crystals.**

| X-ray energy (keV) | 3.27   | 3.51   |
|--------------------|--------|--------|
| Bragg crystal      | Silicon (220) | Quartz (11.2) |
| Bragg angle (deg)  | 80.7   | 76.4   |
| Bent radii (mm)    | 200/195.8 | 200/189.5 |
| Spectral window (eV) | 11.7   | 26.2   |
| Image magnification | 25.8   | 26.2   |
| Target-crystal (mm) | 102.5  | 100.9  |
| Crystal-detector (mm) | 2648.2 | 2640.7 |

---

Fig. 3 Streaked monochromatic x-ray image of the laser imploded core plasma at 3.27 keV.
4. Summary
A new monochromatic x-ray imager has been proposed, and its feasibility was successfully demonstrated with a temporal resolution of 20 ps, a spatial resolution of 31 µm, and a spectral resolution over 200, simultaneously. The system provided seamless images with high temporal resolution. The spatial resolution has not yet been sufficiently optimized for practical use in implosion experiments. A combination of higher sweep-speed, larger image magnification, and narrower sampling distances should lead to a temporal resolution better than 10 ps and a spatial resolution better than 10 µm. By using a chlorine-doped shell target, we plan to obtain temporal evolution of electron temperature profiles of fast-ignitor plasmas created with Gekko-XII and LFEX laser facilities.

 References
[1] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason, Phys. Plasmas 1, 1626 (1994).
[2] R. Kodama, H. Shiraga, K. Shigemori, Y. Toyama, S. Fujioka, H. Azechi, H. Fujita, H. Habara, T. Hall, Y. Izawa et al., Nature London 418, 933 (2002).
[3] K. Fujita, H. Nishimura, I. Niki, J. Funakura, I. Uschmann, R. Butzbach, E. Förster, M. Nakai, M. Fukao, A. Sunahara et al., Rev. Sci. Instrum. 72, 744 (2001).
[4] J. A. Koch, J. T. W. Barbee, N. Izumi, R. Tommasini, R. C. Mancini, L. A. Welser, and F. J. Marshall, Rev. Sci. Instrum. 76, 073708 (2005).
[5] N. Miyanaga, Y. Aoki, H. Shiraga, K. Shimada, K. Fujimoto, M. Heya, and M. Nakasuji, Rev. Sci. Instrum. 68, 817 (1997).
[6] H. Shiraga, M. Nakasuji, M. Heya, and N. Miyanaga, Rev. Sci. Instrum. 70, 620 (1999).
[7] E. Förster, K. Gäbel, and I. Uschmann, Laser Part. Beams 9, 135 (1991).
[8] I. Uschmann, E. Förster, K. Gäbel, G. Hölder, and M. Ensslen, J. Appl. Crystallogr. 26, 405 (1993).
[9] M. Vollbrecht, I. Uschmann, E. Förster, K. Fujita, Y. Ochi, H. Nishimura, and K. Mima, J. Quant. Spectrosc. Radiat. Transf. 58, 965 (1997).

Fig. 4 Reconstructed monochromatic x-ray images of the core plasma for (a) 3.27 keV and for (b) 3.51 keV x ray. Frame interval is 20 ps.