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Penumbral imaging with multi-penumbral-apertures and its heuristic reconstruction for nuclear reaction region diagnostics

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Penumbral imaging with multi-penumbral-apertures and its heuristic reconstruction for nuclear reaction region diagnostics

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Abstract. Imaging of nuclear reaction region is important to clarify heating mechanism in a fast-ignition plasma. The nuclear reaction region can be identified by hard x-ray and neutron images, which are emanated from the heated region. We proposed a novel penumbral imaging that is suitable for imaging quanta having strong penetrating power, such as hard x ray and neutron. Using multiple penumbral apertures arranged with *M*-sequence leads to two orders of magnitude higher detection efficiency than that with a single aperture. In addition, a heuristic method was introduced to a image reconstruction procedure for reducing artifacts caused by noise in a penumbral image. A proof-of-principle experiment indicates that the proposed imaging is superior to the conventional one.

1. Introduction

The fast ignition scheme is investigated to achieve fusion ignition and burn with a relatively small laser facility. Institute of Laser Engineering of Osaka University launches FIREX (Fast Ignition Realization Experiment) project[1] to demonstrate fusion ignition with this scheme. A high-intense short-pulse laser must heat locally a fusion fuel for achieving a high gain of fusion energy with the fast ignition scheme. Physical processes dominates the local heating can be understand by identifying the nuclear reaction region in a fast ignition plasma. Advanced penumbral imaging technique has been proposed to obtain two-dimensional images of hard x-rays and/or neutrons emitted from the nuclear reaction region. Penumbral imaging[2] is suitable for imaging quanta having strong penetrating power, such as hard x-rays and neutrons. Penumbral imaging is one of encoded imaging techniques. A reconstruction or decoding process is required for obtaining an objective image from the pneumbral image. In a conventional penumbral imaging, a reconstructed objective image is distorted mainly due to noises and aperture shape uncertainties. A heuristic method is introduced to the image reconstruction procedure for reducing the image distortion. It was found in the previous study that neutron yield of 10^{11} is required for the conventional penumbral imaging.[3] This yield is two orders of magnitude larger than that predicted for the FIREX project. We used multi-apertures for the penumbral imaging. Signal intensity increases with multi-penumbral-apertures arranged in *M*-matrix compared to that with single one, signal increment is proportional to number of the apertures. We carried out a proof-of-principle experiment for the proposed imaging technique, which is a combination of the heuristic reconstruction method and the multi-penumbral-apertures.

2. Heuristic image reconstruction of penumbral image

The penumbral imaging[4, 5, 6] uses aperture, whose diameter is larger than objective size. The penumbral image consists of a uniformly bright region surrounded by a penumbra. Spatial information of the objective is contained in the penumbral region. Deconvolution operation is used for the image reconstruction in the conventional penumbral imaging. Weiner filter is used to reduce amplitude of noise.[6] In the case that the amplitude of noise is much lower than that of signal, the use of Weiner filter is a simple and straightforward technique to reduce noises, however, in the contrary case, noise is difficult to be removed by the Weiner filter. Noise remained in a penumbral image is amplified by the deconvolution process.

Heuristic method[7, 8, 9], which has high tolerance to noise, has been adapted to the reconstruction process. In the heuristic method, the optimal objective image is estimated by minimizing the mean square difference between an obtained penumbral image and an estimated one. The heuristic method was compared with the conventional one. Figure 1(a) is the penumbral image obtained in an experiment. Signal to noise ratio (SNR) of the penumbral image is about 17.7. The objective image reconstructed by the conventional method is shown in Fig. 1(b). Although SNR of the penumbral image is sufficiently high, artifacts are overlapped on the image reconstructed by deconvolution process. The clear image without artifacts was obtained with the heuristic method as shown in Fig. 1(c). The heuristic method clearly excludes artifacts those appear in the conventional reconstructed image.

3. Proof-of-principle experiment of Uniformly redundant array of penumbral aperture

Uniformly redundant array of penumbral aperture (URPA) was proposed to increase image intensity.[10] Penumbral apertures are arrayed in a two-dimensional M-matrix. There is a *G*-matrix corresponding to a *M*-matrix. A convolution of the *M*- and the *G*-matrix generates the perfect delta function. Multiple penumbral images arrayed in a *M*-matrix are unified automatically by convoluting with a G-matrix, and signal intensity is easily enhanced. The concept of the URPA imaging technique is shown in Fig. 2. The multiple penumbral images arrayed in the M-matrix are recorded on a detector as shown in Fig. 2(c). The unified penumbral image (Fig. 2(e)) is obtained by convoluting the multiple penumbral images (Fig. 2(c)) with the G-matrix (Fig. 2(d)) and the object image (Fig. 2(f)) is reconstructed from the unified penumbral image (Fig. 2(e)).

The proposed scheme was applied to imaging 2-3 keV x-rays. A Nd: YAG laser was used in this experiment. Energy, pulse duration, and wavelength of the laser were, respectively, 1.5 J, 3.5 ns, and 1064 nm. Penumbral apertures (400 μm in diameter) were fabricated on a 25 μm-thick tantalum substrate. A separation distance between apertures was 500 μm. The distance between the aperture and the object was 211 mm and the distance between the aperture and the detector was 916 mm, thus camera magnification was 4.3. A 100 μm-thick beryllium was put in front of the aperture as an x-ray

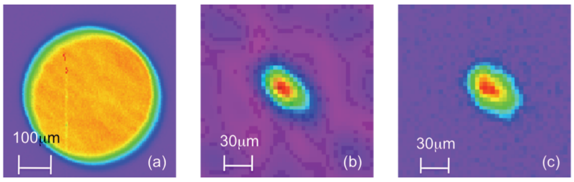


Figure 1. Comparison between the heuristic method and the conventional one. (a) penumbral image for comparison, (b) reconstructed image with the conventional reconstruction, (c) that of with the heuristic reconstruction.

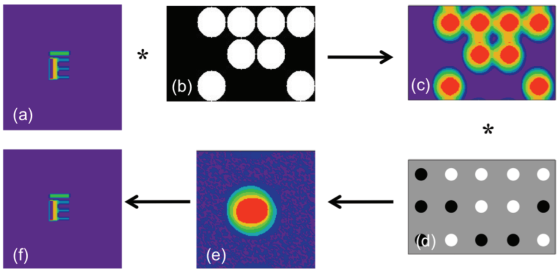


Figure 2. Basic concept of the URPA. (a) the objective image, (b) the multi-penumbral-apertures, (c) the multiple penumbral images arrayed with the M-matrix, (d) the G-matrix corresponding to the M-matrix, (e) the unified penumbral image, (f) the objective image reconstructed from the unified penumbral image.

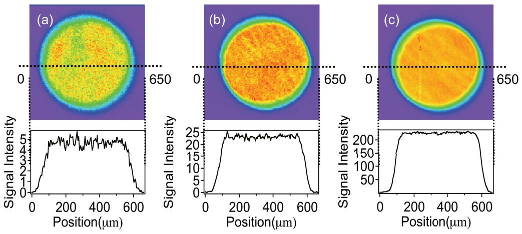


Figure 3. Comparison between the single aperture and URPA.
(a) the penumbral image of the single aperture and that of line profile, (b) the unified penumbral image with 3 x 5 URPA and that of line profile, (c) the unified penumbral image with 7 x 9 URPA and that of line profile.

filter to exclude low energy photons whose energy is less than 2 keV. A planar gold foil was irradiated by a laser pulse, and x-ray images from laser-produced plasma were imaged with the URPA. Three kinds of apertures were used in the experiment; (1) single penumbral aperture, (2) 3×5 URPA and (3) 7×9 URPA. The penumbral image with single aperture is shown in Fig. 3(a). Unified penumbral images obtained with 3×5 URPA or 7×9 URPA are shown in Figs. 3(b) and (c) and, corresponding line profiles are shown below them. SNRs of the unified penumbral images were evaluated to be 2.7, 6.3 and 17.7 for single, 3 x 5, 7 x 9 URPA, respectively. SNRs of unified penumbral images increased in proportion to square root of the number of apertures.

4. Combination of heuristic image reconstruction and URPA imaging

The proposed imaging technique was compared with the conventional penumbral one. The reconstructed image of the conventional penumbral imaging is shown in Fig. 4(a). A single aperture and the reconstruction procedure based on decombolution and a Wiener filter were used for Fig 4(a). The reconstructed image is strongly distroted by artifacts because of low SNR. The reconstructed image of the proposed imaging technique is shown in Fig. 4(b). The high quality reconstructed image was obtained by using the proposed imaging technique from an object whose signal intensity is not sufficient.

We evaluate spatial resolution of the proposed imaging technique. For this evaluation, an experiment was performed on Gekko-XII laser facility, Osaka University. Configurations of the imaging system were the same as that in the proof-of-principle experiment. A cross slit (slit width 100 μm) was backlit by x rays, and backlit slit was imaged with URPA. Chlorided plastic was irradiated by Gekko-XII laser beams to produce a backlight x-ray source, which emits 2.7 keV x rays. The reconstructed image is shown in Fig. 5(a). Modulation transfer function (MTF) of the imaging system was evaluated from the slit image as shown in Fig 5(b). Spatial resolution was 25 μm in the present system, here spatial resolution was defined as the wavelength corresponds to 0.1 of MTF.

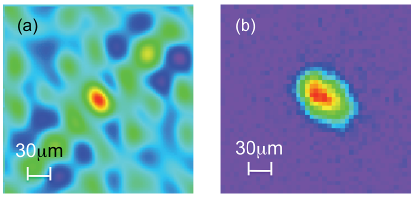
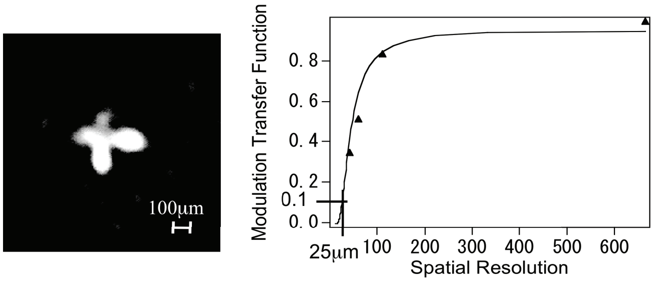


Figure 4. Comparison between the proposed penumbral imaging and the conventional penumbral imaging. (a) the reconstructed image with the single aperture and the deconvolution reconstruction, (b) that with the 7 x 9 URPA and the heuristic one.



(a) (b)

Figure 5. Spatial resolution was evaluated by Modulation Transfer Function.
(a) the reconstructed image of backlight cross slit, (b) the relationship between Modulation Transfer Function and spatial resolution.

Spatial resolution is limited by several factors, i.e. x-ray diffraction, unroundness of the apertures, error of aperture positions, detector resolution and SNR of the penumbral image. Diffraction Spread (Δx) on the detector caused by x-ray diffraction is given by

$$\Delta x = 2.4\frac{\lambda}{D}d, \tag{1}$$

here λ is the wavelength of the backlight x-ray source, D the aperture diameter, d the distance between the target and the aperture. Unroundness of the aperture distorts a reconstructed image, and error of the aperture position blurs a reconstructed image. Spatial resolution limited by x-ray diffraction was only 0.6 μm in the present system. Standard deviation of the aperture unroundness was 1.47 μm, by which spatial resolution was limited to 1.8 μm. Standard deviation of the aperture position errors was 2.6 μm, by which the spatial resolution is limited to 1.8 μm. Spatial resolution of the detector was 10.5 μm. As the result of the above evaluation, SNR of the penumbral image limits dominantly the spatial resolution in the present experiment.

Acknowledge

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