# The Neutron Imaging Diagnostics and Reconstructing Technique for Fast Ignition*)

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In Fast Ignition (FI) the imaging diagnostics of the fusion neutron is an advanced diagnostic. In this study a neutron or high energy x-ray imaging detector using multi-penumbral array, was developed. The unfolding technique by using Heuristic method was successfully demonstrated in simulation.



Keywords: neutron imaging, penumbra, Heuristic method, image reconstruction, hard Bremsstrahlung x-ray

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## 1. Introduction

The Fast Ignition (FI) project is conducted at GEKKO XII-LFEX laser facility in the Institute of Laser Engineering (ILE), Osaka University. In the FI scheme, the laser compressed fuel by GEKKO XII Laser, is heated by an intense and energetic fast electron beam produced by an ultra-intense laser (LFEX) pulse, initiating the thermonuclear.

In this context diagnosis of the spatial distribution of the temperature of plasma core is extremely important. The shape of the heated plasma can be measured by diagnosing the spatial distribution of neutron or high energy x-ray emitted from the heated core. Furthermore the divergence angle of the hot electrons can also be determined by diagnosing spatial distribution of high energy x-ray in the few MeV range. The penumbral aperture is a well known technique for imaging neutrons or high energy x-ray. The reconstructing process is an essential issue to be properly developed to perform this technique [1]. In recent studies a novel reconstructing technique by using Simulated Annealing Heuristic method was proposed to reconstruct highly spatially resolved images. This method solves weakness for noise that is critical issue in the reconstructing process. In this study the neutron or high energy x-ray imaging detector, using a custom designed multi penumbral aperture array, and the reconstructing technique by Heuristic method was developed. The installation of the imaging diagnostics at the GEKKO XII-LFEX laser facility in the Institute of Laser Engineering, Osaka University was completed. In this paper we present the progress in the development of the penumbra technique.

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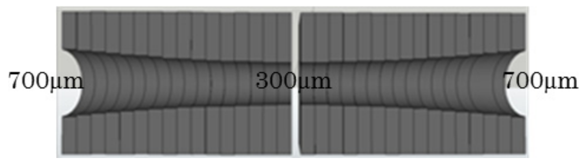


Fig. 1 The schematic view of the penumbral aperture developed.

## 2. Penumbra Aperture Design

Thick apertures are required to properly image neutrons or high energy x-rays. The lead penumbral aperture, 10 cm thick having 1/10 of attenuation length for Deutriun-Deutriun fusion neutron within 2.45 MeV energy range was developed in our previous work [2].

The shape of the inner surface was designed to be toroidal in order to obtain uniform point spread function for large angle. The point spread function (PSF) of the aperture with cylindrical inner surface is distorted at the large angle, on the other hand toroidal one can minimize the distortion at large angle. A 10-cm thick, 32 penumbral apertures array constructed with 100 separate 1-mm thick lead plates was developed as shown in Fig. 1. The entrance, center, and exit diameters were designed to be 700 μm, 300 μm, 700 μm, respectively.

## 3. Reconstructing Technique by using Heuristic Method

A novel technique to reconstruct the penumbral image was developed by Mr. Nozaki [3, 4]. I had applied this method in the new device. In this method, the reconstructed image is iteratively inferred. The advantages of

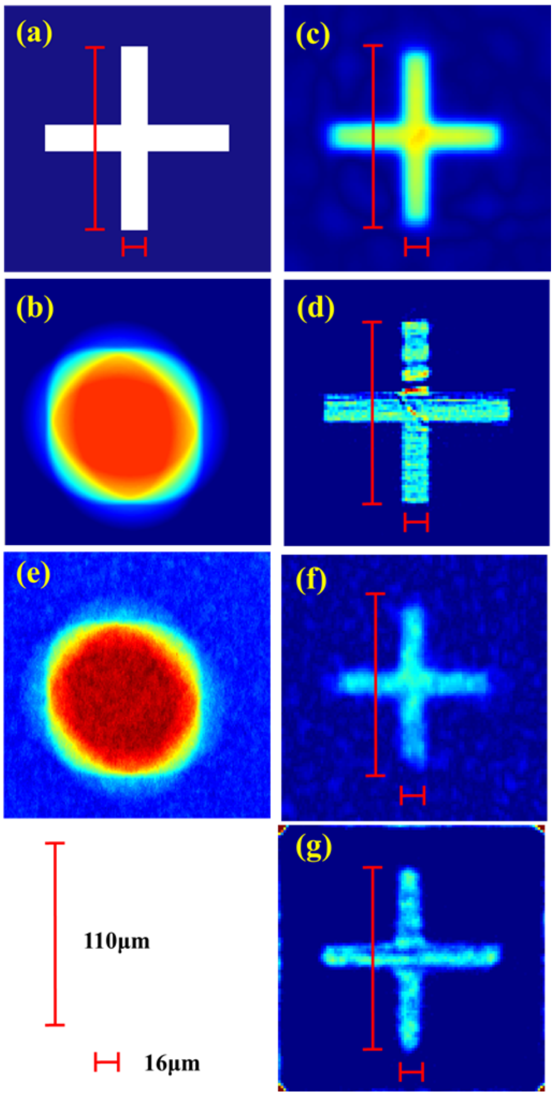


Fig. 2 Images obtained in the test reconstruction. (a) is cross pattern having 110 μm length and 16 μm width, (b) synthesized penumbral image, (c) reconstructed image using wiener filter based deconvolution, and (d) reconstructed image using newly developed method. (e) noise-added penumbral image, (f) reconstructed image from (e) by wiener filter based deconvolution, and (g) reconstructed image from (e) using newly developed method.

this new method are that the noise originated from the artifact is not amplified, not using any inverse calculation in the reconstructing process. More over this method substitutes each point source with PSF.

The Simulated Annealing method [4] is used in order to avoid local solution in this Heuristic method.

Reconstructing techniques were tested by using artificially made samples. The PSF from point source were calculated separately from every point, with 2 μm spatial resolution on the target surface, by analytic calculation and the Monte-Carlo simulation code MCNP5. A small distortion was observed in the PSF from the source 1113 mm far from the central position. The size of image we intend to

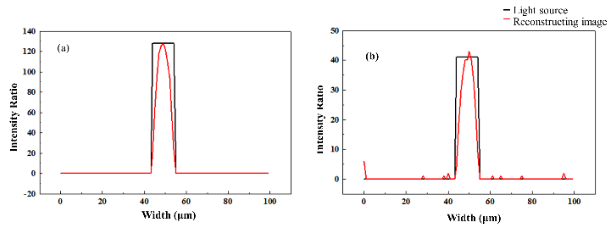


Fig. 3 (a) is a line profile of Fig. 2 (d), Fig. 3 (b) is a line profile of Fig. 2 (g) which reconstructed image of cross pattern added noise.

observe is comparable to the aperture diameter, thus the space-variant PSF should be treated in the reconstructing process. A similar work was reported in Ref. [5]. However in this method non-space variant PSF is used, thus image quality is affected from misalignment of the penumbra. The Heuristic method can be easily applied with the space-variant PSF, being at the same time not sensitively affected by background noise.

Figure 2 shows a reconstruction performance test performed using cross shaped sample. Figure 2 (a) shows the cross pattern light source having 110 μm length and 16 μm width. Figure 2 (b) shows a synthesized penumbral image by using space variant PSF corresponding to each of the 1 μm pixel of the source. Figure 2 (c) is a reconstructed image using a wiener filter based deconvolution and (d) is a reconstructed image using our new method. Figure 2 (e) also shows a penumbral image with in addition a typical experimentally observed background signal. (f) and (g) are reconstructed images using wiener filter based deconvolution and the new method, respectively.

A clear pattern was reconstructed by Heuristic even in presence of typical experimental noise. As in the Figs. 2 (c) and (f), the farther from center point the pixel is, the more influence of space-variance PSF is. So the length of the cross image by deconvolution shortens more than the length of the cross which is original although the width is reconstructed well to some extent. Figure 3 shows the comparisons of line profiles between (a) and (d), and (a) and (g). A 16-μm sized pattern was confirmed to be well reconstructed. Even in presence of some noise in the reconstructed image by deconvolution, which also affects the hard edge resolution.

Next, the spatial resolution for the Heuristic method was estimated by Modulation Transfer Function (MTF) curve. Figure 4 shows MTF curve of this system by using square wave chart, and 1.56 μm was estimated as a spatial resolution defined as 0.1 of the MTF [6].

In this simulation without noise, the causes that limit spatial resolution of this system to 1.56 μm are mainly related to the pixel size of the detector, pixel size of reconstructing image and signal-to-noise ratio (SNR) of penumbral image. The special resolution is be fined as the minimum width that can be distinguished from PSF to image,

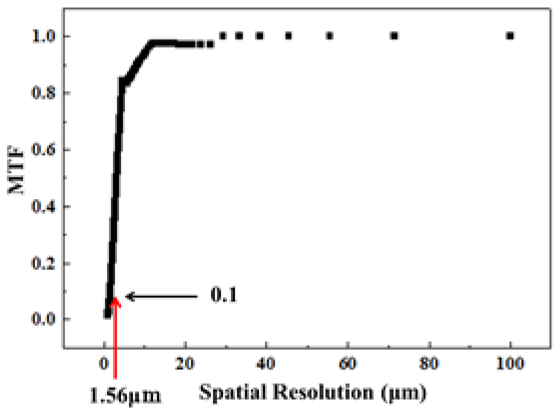


Fig. 4 Modulation transfer function curve obtained in a tested image by using newly developed Heuristic method.

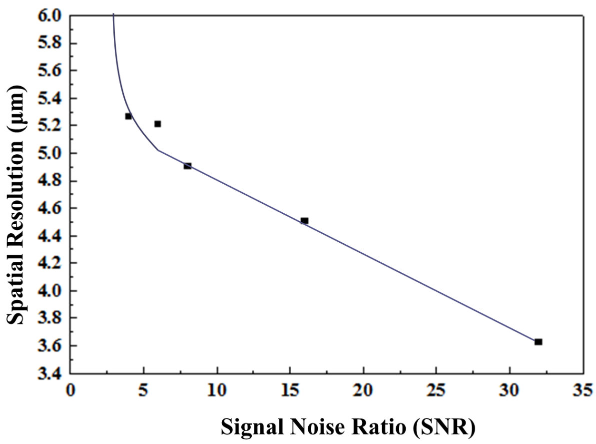


Fig. 5 Correlation between spatial resolution and SNR.

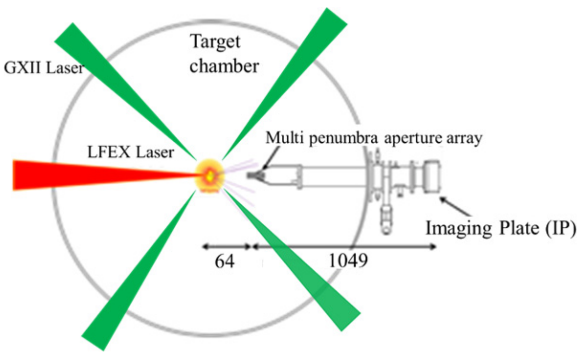


Fig. 6 Installation of multi penumbral diagnostic in the fast ignition experiment in the GEKKO XII and LFEX laser facility in Institute of Laser Engineering, Osaka University.

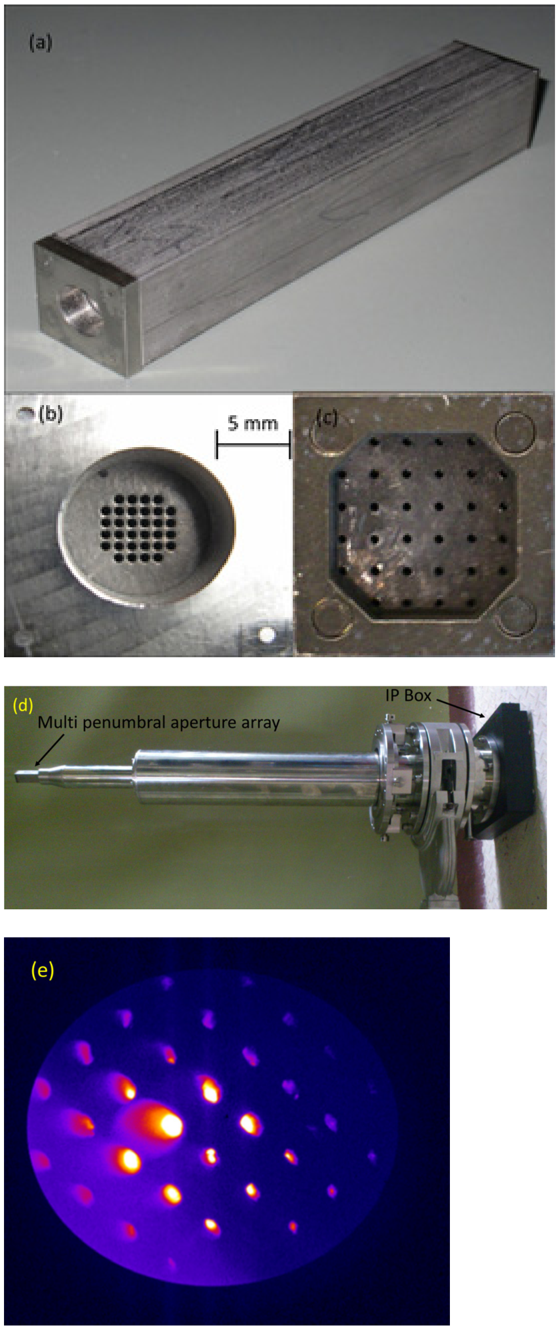


Fig. 7 (a) a picture of the multi penumbral aperture array, (b) front surface and (c) rear surface, (d) picture of the whole detector, (e) typical penumbral image obtained in the experiment.

using the Heuristic method. In MTF curve of Fig. 4, SNR was infinity.

Figure 5 shows correlation of spatial resolution and SNR. For FI application, a spatial resolution of 10-20 μm is necessary to diagnose the fusion reaction region. So it is necessary to develop a device capable to measure more than SNR2-SNR4.

## 4. Installation in Experiment

The experiment was conducted in the GEKKO XII and LFEX laser facility in Institute of Laser Engineering, Osaka University. Figure 6 shows Installation of multi penumbral diagnostic in the fast ignition experiment.

The penumbral detector was implemented in the experiment and the x-ray image from a typical fast-heating shot was clearly observed.

Figures 7 (a), (b), and (c) are pictures of multi penumbral aperture array, (d) shows the testing detector body with a penumbral aperture and inserting manipulator using image plate as a x-ray detector. Figure 7 (e) shows typical experimentally observed image.

This diagnostics will be implemented in upcoming Fast Ignition Realization Experiment which will be conducted in September 2013. The hard x-ray image will provide a much deeper understanding of the physics on hot electron transport.

## 5. Conclusions and Future Prospects

The neutron or high energy x-ray imaging detector by using multi channels penumbral aperture array was developed for FI science. The reconstructing method, implementing Heuristic algorism was developed and successfully demonstrated in the experiment. The performance of the Heuristic method was tested by using pattern sample image, and the accuracy of reconstructed image was then evaluated. Low influence of background noise on the quality of the reconstructed image was demonstrated.

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