Penumbral Imaging of Laser-Imploded Targets and Its Blind Reconstruction

Penumbral Imaging of Laser-Imploded Targets and Its Blind Reconstruction*

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Abstract

We describe the use of penumbral imaging technique for hard x-ray imaging of laser-imploded targets. The technique uses the facts that spatial information can be recovered from the shadow or penumbra that an unknown source casts through a simple large circular aperture. The imaging system consists of a large circular aperture (penumbral aperture), filters, and a sensitive x-ray CCD camera as a detector. The x-ray images with photon energies of 5keV and 10keV to 30keV have been obtained. We also propose a new reconstruction method based on power cepstrum of the penumbral image, which does not require exact information about the aperture function.

I . INTRODUCTION

Penumbral imaging [1], one of coded aperture imaging techniques [2], is a technique for imaging objects that emit high-energy photons; such objects arise, for example, in nuclear medicine, x-ray astronomy, and laser fusion studies. For these high-energy photons, classical imaging techniques (e.g., lenses) are not applicable.

The technique uses the facts that spatial information can be recovered from the shadow or penumbra that an unknown source casts through a simple large circular aperture. Since such an aperture can be "drilled" through a substrate of almost any thickness, the technique can be easily applied to very penetrating radiations [3], [4], [5] such as neutrons and γ rays.

In this paper, we describe the use of penumbral imaging technique for hard x-ray imaging of laser-imploded targets. The imaging system consists of a large circular aperture (penumbral aperture), filters, and a sensitive x-ray CCD cemera as a detector. The x-ray images with photon energies of 5keV and 10keV to 30keV have been obtained. We also propose a new reconstruction method based on power cepstrum of the penumbral image, which does not require exact information about the aperture function, since the aperture function is not known or known with some error in many experiments.

The basic concept of penumbral imaging is given in section 2. The blind reconstruction method is presented in section 3 and the imaging system with a sensitive x-ray CCD camera is given in section 4. The experimental results are shown in section 5.

II . PENUMBRAL IMAGING

The basic concept of the penumbral imaging technique is shown in Fig.1. The encoded image consists of a uniformly bright region surrounded by a penumbra (hatched region). Information about the source is encoded in this penumbra. It is easy to show that the encoded image $p(\mathbf{r})$ is given by [6]

$$p(\mathbf{r}) = a(\frac{L_1}{L_1+L_2}\mathbf{r}) * o(-\frac{L_1}{L_2}\mathbf{r}), \qquad (1)$$

where $a(\mathbf{r})$ is the aperture function or point spread function (PSF); $o(\mathbf{r})$ is the function describing the source; L_1 and L_2 are the distances from source to aperture and from aperture to detector, respectively; L_2/L_1 is the magnification of the camera; and * denotes the convolution. If the exact point spread function $a(\mathbf{r})$ is *a priori* known, the source function $o(\mathbf{r})$ may be deconvolved. Usually a Wiener filter is used for deconvolution [3], [4], [5]. But in many experiments, the PSF is not known or known with some error, yielding an erroneous result. Thus it is necessary to deconvolve o from p alone, which is known as a blind deconvolution problem[6].

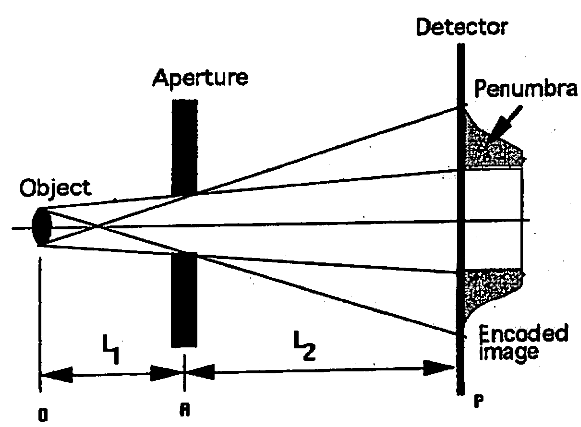

Figure 1: The basic concept of penumbral imaging.

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III. BLIND RECONSTRUCTION

Since the penumbral aperture is a circular aperture, the PSF of the aperture can be approximated by a cylinder as

$$a(\mathbf{r}) = \begin{cases} 0 & ; \ |\mathbf{r}| > R \\ 1/(2R); & |\mathbf{r}| \le R, \end{cases} \tag{2}$$

where R is the radius of the cylinder, which is dependent on the radius (r) of the aperture and the magnification (M) of the camera ($R=r(1+M)$). Estimation of $a(\mathbf{r})$ can be simplified to that of R.

By taking Fourier transform of both sides of Eq.(1), we can rewrite the convolutional relationship of (1) into one of multiplication as

$$P(\mathbf{u}) = A(\mathbf{u}) \cdot O(\mathbf{u}), \tag{3}$$

where P, A, O are the Fourier transforms of p, a, o, respectively, and $\mathbf{u}$ is the spatial frequency. The Fourier transform $A(\mathbf{u})$ of $a(\mathbf{r})$ is given as

$$A(\mathbf{u}) = J_1(Ru)/(Ru), \tag{4}$$

where $u=|\mathbf{u}|$. The first five zeros of $A(\mathbf{u})$ occur at $u=3.83/R$, $7.01/R$, $10.2/R$, $13/3/R$, and $16.5/R$, which are inversely proportional to R. The zeros of A are zeros of P. Thus R can be estimated by searching the zero crossing point of the frequency response of the penumbral image p. But it is usually difficult to search the zero points because the penumbral image is always with noise.

Since the zeros are periodic in $A(\mathbf{u})$, we use a technique[7], [8] to estimate R from the power cepstrum of the penumbral image (p) as a preprocessing of deconvolution. The cepstrum is defined by the Fourier transform of a log Fourier transform as

$$C_p(q) = F\{\log|P(u)|\}. \tag{5}$$

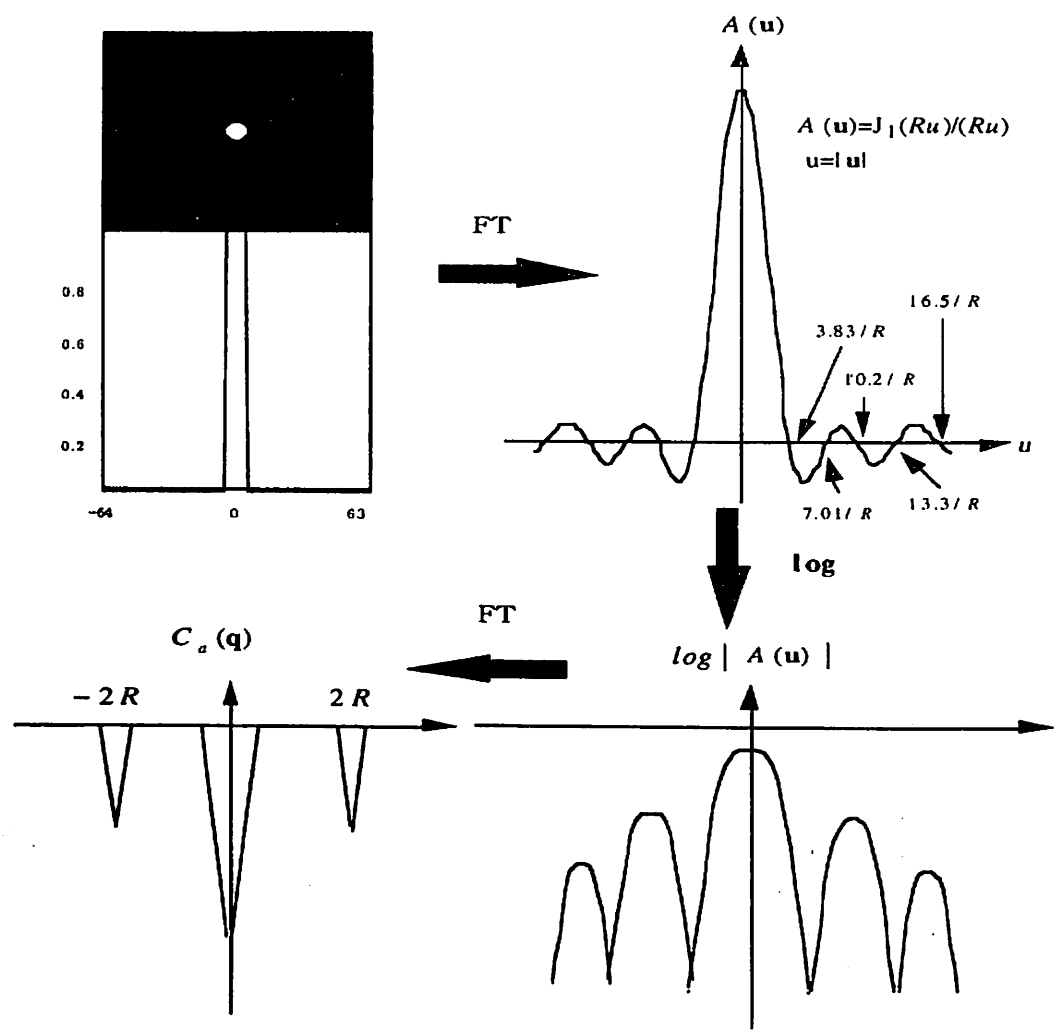

Figure 2: Fourier transform and cepstrum of a circle aperture.

where F{ } denotes the Fourier transform. From Eq.(3), the convolutional relations are additive in the cepstral domain:

$$C_p(q) = C_a(q) + C_o(q). \quad (6)$$

It has been shown that the periodic (nearly periodic) zeros in $A(\mathbf{u})$ lead to large negative spikes in $C_a(\mathbf{q})$ [7], [8], [9]. One example of $C_a(\mathbf{q})$ is shown in Fig.2. We can see that the large negative spikes appear in $\mathbf{q}=\pm 2R$ (in two-dimensional cepstral domain, the spikes are rings of spikes). Since the zeros are usually non-periodic in $O(\mathbf{u})$, the negative ring spikes will not appear in $C_o(\mathbf{q})$. Thus the negative ring spikes in $C_p(\mathbf{q})$ are that of $C_a(\mathbf{q})$. Since the ring radius of the negative spikes in $C_p(\mathbf{q})$ is $2R$, we can estimate R directly from $C_p(\mathbf{q})$.

Ⅳ. CAMERA SYSTEM

The schematic diagram of the penumbral camera used for x-ray imaging of laser-imploded target is shown in Fig.3. The camera system consists of a penumbral aperture (large circle) mounted onto a tapered nose cone, a cylindrical extension tube, a filter holder and a sensitive x-ray CCD camera.

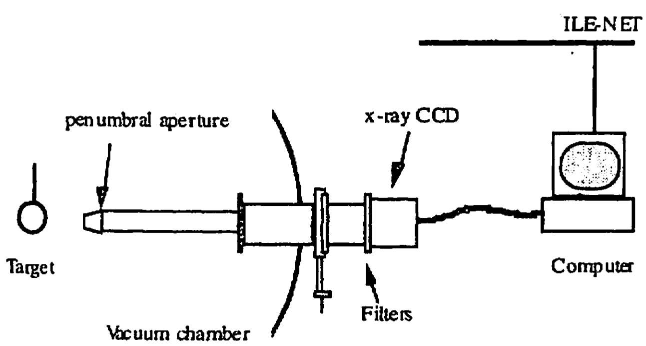

Figure 3: Schematic diagram of penumbral camera for x-ray imaging of laser-imploded target.

The penumbral aperture used a 530μm diameter hole drilled in a 25μm thick tantalum substrate. The hole was a circle with irregularity less than 1%. The distance between the aperture and the target was 11.6cm and the magnification of the camera was ×8.8.

In order to improve the data acquisition process and the detection efficiency, an x-ray charge coupled device (CCD) camera [10], which was developed by Princeton Instruments, is used as a detector. Front illumination CCD devices is with 1242×1242 pixel array, each pixel having $22.5\times22.5\mu m^2$ dimension giving an active area of $28\times28mm^2$. The pixel resolution of the penumbral camera is estimated as about 2.8μm on the target plane. The device has no scintillator and no fiber coupler to avoid degradation of the spatial resolution on the device. The phosphor is directly coated on the CCD array. The spectral response of the CCD mainly depended on Si material of the device and were existed from 0.5 keV to 30keV.

The maximum signal level (saturation level) is 65535 counts and the typical dark current level is about 168 counts, which can be considered as noise level of the camera. Thus, the dynamic range of the CCD camera is from 168 to 65535 counts. The camera response to incident intensity is shown in Fig.4(a), which is dependent on incident photon energy (E). Spectral dependent minimum (detectable) and maximum (saturation) levels for incident light intensity detection are shown in Fig.4(b). In order to make a comparison, the minimum (detectable) and maximum (saturation) levels of a calibrated x-ray film (FUJI MI-FX) [10] are also shown in Fig.4(b). As shown in Fig.4(b), the detectable incident intensity by the CCD (●) is much lower than that by the film (○) and the dynamic range (difference of the maximum and the minimum levels) of the CCD is also larger than that of the film. These advantages will make the CCD camera to succeed the x-ray film as a detector as well as the direct digital data acquisition.

A titanium foil filter with a thickness of 100μm and a beryllium foil filter with a thickness of 40μm were placed in the front of the CCD to obtain the encoded image with photon energies of 5keV and 10keV to 30keV taking account of the spectral response of the CCD camera [Fig.4(b)].

Ⅴ. EXPERIMENTAL RESULTS

The experiments were carried out at the frequency doubled (0.53μm) 12 beams Nd: glass laser facility, GEKKO XII [11] at Osaka University. A CH plastic shell target with a typical thickness of 8μm and a typical diameter of 530μm was irradiated by partially coherent laser lights (PCL) through random phase plates at a wavelength of 0.53-μm. The pulse shape of the laser lights consisted of a 1.6-ns squared pulse as a main pulse and a 200-ps prepulse with a time separation of 400-ps and the total laser energy was about 3kJ.

A typical penumbral image recorded by the CCD camera is shown in Fig.5(a). Figure 5(b) shows its power cepstrum. The diameter of PSF was estimated as 4837.5μm from the cepstrum (Fig.5(b)). The reconstructed image with the estimated PSF is shown in Fig. 6(a). In order to make a comparison, we also show the reconstructed image with an erroneous PSF (ΔR=+5%) in Fig. 6(b). It can be seen that only a small error in PSF will result in an erroneous reconstruction. The size of the compressed core [Fig. 6(a)] was estimated to be 22μm, which was almost the same result as that obtained from a pinhole image [10]. Discussion on the structure of compressed core is outside the scope of this paper and it will be done elsewhere.

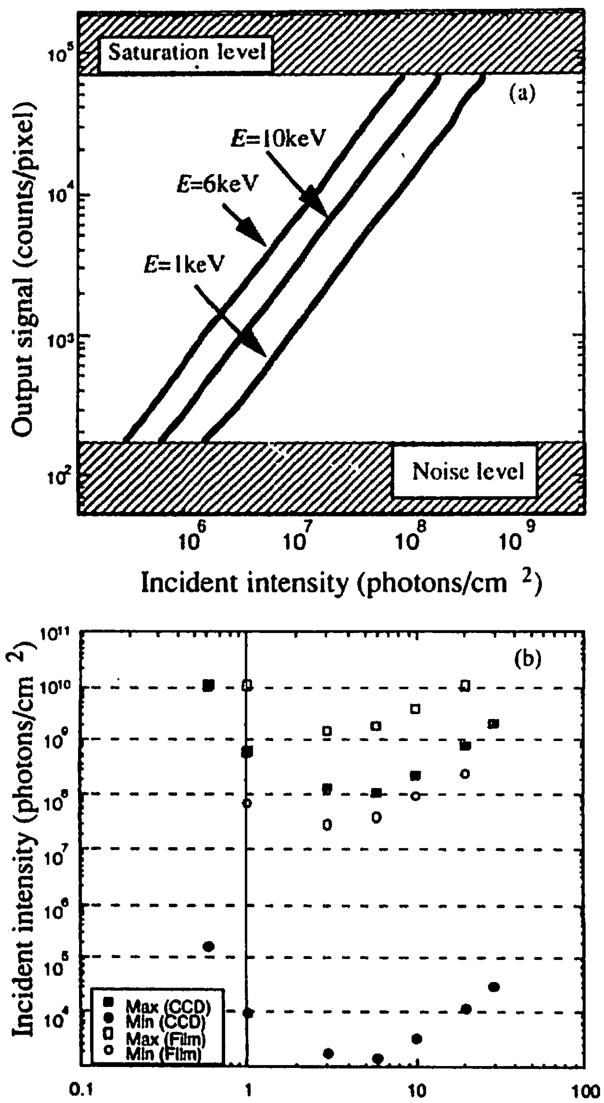

Figure 4: (a) CCD camera response to incident light intensity ; (b) Spectral dependent minimum (detectable) and maximum (saturation) levels

VI. SUMMARY

The penumbral imaging technique has been applied for hard x-ray imaging of laser-imploded targets. The imaging system consists of a large circular aperture (penumbral aperture), filters, and a sensitive x-ray CCD camera as a detector. The x-ray images with photon energies of 5keV and 10keV to 30keV have been obtained. We also proposed a method based on power cepstrum of the penumbral image to estimate the exact information of aperture function (PSF). Experimental results demonstrated the potential of the method for practical uses.

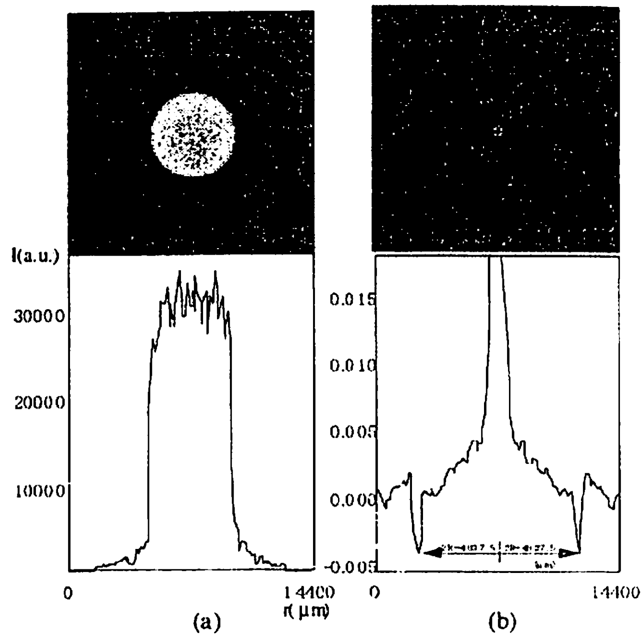

Figure 5: Penumbral image (a) and its power spectrum (b).

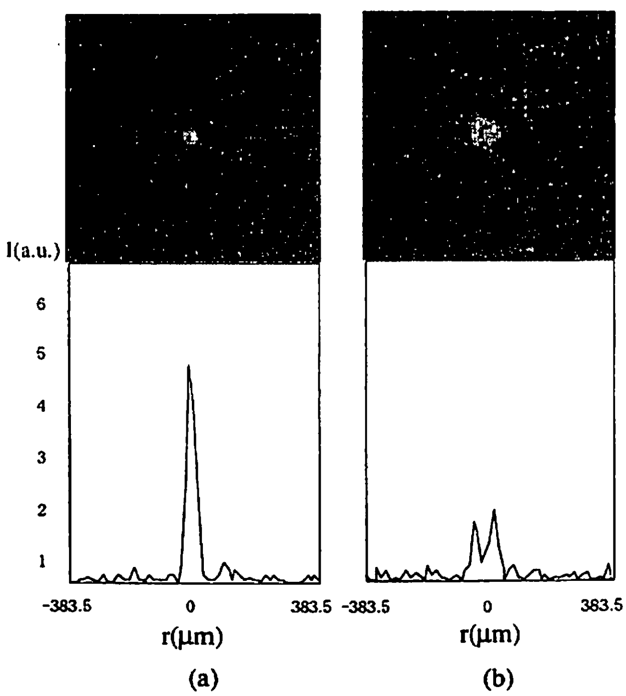

Figure 6: Reconstructed images; (a) with an exactly estimated PSF, (b) with an erroneous PSF (ΔR=+5%).

VII. ACKNOWLEDGEMENTS

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