Attenuation Correction for X-ray Emission Computed Tomography of Laser-Prouduced Plasma

Attenuation Correction for X-ray Emission Computed Tomography of Laser-Prouduced Plasma

Yen-Wei CHEN*, Zensho NAKAO* and Shinichi TAMURA**

Abstract

An attenuation correction method was proposed for laser-produced plasma emission computed tomography (ECT), which is based on relation of attenuation coefficient and emission coefficient in plasma. Simulation results show that the reconstructed images are dramatically improved in comparison to reconstructions without attenuation correction.

Key Wards : Emission computed tomography (ECT), Attenuation correction, Projection, Reconstruction, Algebraic reconstruction technique (ART)

1. Introduction

In inertial confinement fusion (ICF) research, the implosion symmetry is one of the most important issues to achieve high density compression. The x-ray images obtained by pinhole camera and coded aperture imaging have provided direct information on uniformity of the compressed core. However, because these images are two-dimensional projections of the three-dimensional spherical implosion targets, these may not be enough to evaluate the implosion symmetry. If attenuation of x-ray within plasma is neglected, the intensity of the obtained two-dimensional x-ray image is approximately proportional to a line integral of the three-dimensional x-ray distribution emitted from imploded target. The reconstruction of three-dimensional x-ray distribution from its projections is just a linear inversion problem. In order to obtain tomographic pictures of the imploded target, we have successfully developed an x-ray emission computed tomographic (ECT) technique to reconstruct three-dimensional compressed core from pinhole camera images [1] or uniformly redundant arrays (URA) coded aperture images [2].

On the other hand, in recent laser fusion experiments, high density compressions have been achieved [3]. Thus, neglecting attenuation of x-ray within the plasma is not a valid approximation. It is necessary to develop a new ECT technique with attenuation correction. In recent medical ECT, there have been several methods [4], [5], [6] proposed for attenuation correction. Most correction or compensation methods proposed have assumed, for simplicity, a uniform attenuation coefficient distribution. In laser plasma ECT, the attenuation coefficient distribution is dependent on plasma density and plasma temperature, which are unknown parameters and non-uniform. In this paper we will present a new attenuation

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correction for laser plasma ECT based on the relation between the attenuation coefficient and emission coefficient in plasma.

2. Method

For simplicity, we consider a two-dimensional case here. The projection geometry is shown in Fig. 1. Let $f(x,y)$ and $\mu(x,y)$ represent a two-dimensional activity distribution and the attenuation coefficient distribution of the plasma, respectively. The attenuated projection $P_\phi(r)$ with the projection angle ϕ is given as

$$P_\phi(r) = \int_{-\infty}^{\infty} f(r,s) \cdot \exp\left[-\int_{-G_\phi(r)}^{s} \mu(r,s')\,ds'\right]ds, \tag{1}$$

where

$$r = x\cos\phi + y\sin\phi \tag{2a}$$
$$s = -x\sin\phi + y\cos\phi \tag{2b}$$

and $G_\phi(r)$ is the distance from the center of rotation to body contour. Computed tomography (CT) is one of the inversion techniques to estimate the activity distribution $f(x,y)$ from its several projections $P_\phi(r)$. In conventional ECT, the attenuation is neglected ($\mu(x,y) = 0$). The activity distribution $f(x,y)$ can be easily obtained by Radon transform or other methods [7]. In recent medical ECT with attenuation correction, the attenuation distribution was assumed to be known. Thus the unknown parameter in Eq. (1) is only $f(x,y)$ and it is possible to obtain $f(x,y)$ from the projection data. If $\mu(x,y)$ is unknown, there are two unknown parameters in Eq. (1); it is impossible to obtain the solution $f(x,y)$ from only the projection data. Hence, it is necessaryto know another information on $f(x,y)$ or $\mu(x,y)$ in order to solve for activity distribution $f(x,y)$.

In laser plasma, when the x-ray photon

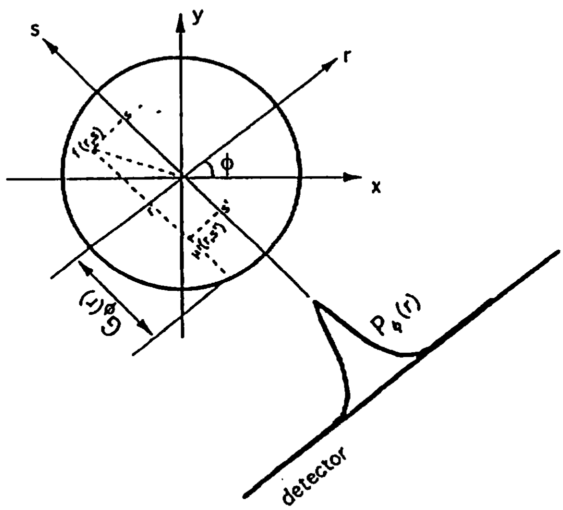

Fig. 1 Y.-W. Chen et al.
Fig. 1 Projection geometry.

energy $h\nu$ in the observed region is higher than the ionization energy of the plasma, the dominant radiation attenuation (absorption) process is inverse-bremsstrahlung. The attenuation (absorption) coefficient $\mu(x,y)$ [8] is given as

$$\mu(x,y) \propto \rho(x,y)^2 \cdot T(x,y)^{-1/2} \cdot (h\nu)^{-3}, \tag{3}$$

where $\rho(x,y)$ and $T(x,y)$ are plasma density and temperature distribution, respectively, which are unknown and non-uniform. The dependances of attenuation coefficient (μ) on plasma density (ρ) and temperature (T) in a CD plasma are shown in Fig. 2(a) and the attenuation of x-ray is shown in Fig. 2(b) as a function of area density ρR.

In such plasma, the dominant of radiation process is bremsstrahlung. By assuming a Maxwellian electron-energy distribution, the radiation emission intensity $f(x,y)$ [8] is given as

$$f(x,y) \propto \rho(x,y)^2 \cdot T(x,y)^{-1/2} \cdot \exp\left[-\frac{h\nu}{kT(x,y)}\right], \tag{4}$$

where k is the Boltzmann constant. From

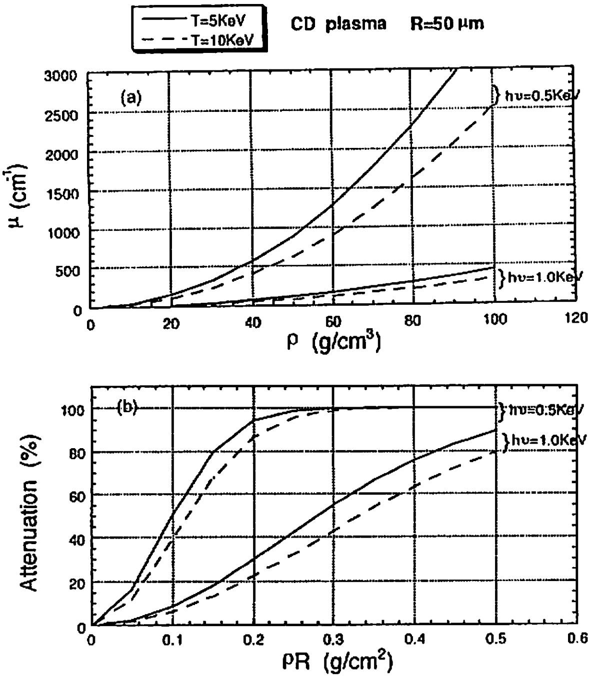

Fig. 2 Y.-W. Chen et al.

Fig. 2 The attenuation coefficient (a) and the attenuation (b) in a CD plasuma.

Eqs. (3) and (4), it is easy to get the relation between $\mu(x,y)$ and $f(x,y)$ as

$$\mu(x,y) \propto f(x,y)\cdot\exp\left[-\frac{h\upsilon}{kT(x,y)}\right]. \quad (5)$$

Assuming the temperature T is much larger than x-ray photon energy $h\upsilon$ (typical values of T and $h\upsilon$ are 10keV and 1 keV), $\exp[-h\upsilon/kT(x,y)]$ in Eq. (5) is approximately a uniform constant of 1 . Thus $\mu(x,y)$ is directly proportional to $f(x,y)$ in the space, which can be written as

$$\mu(x,y)=\beta\cdot f(x,y), \quad (6)$$

where β is a constant determined by x-ray photon energy, atomic number Z of plasma and detection efficiency, which are known parameters. Thus the projection $P_\phi(r)$ of Eq. (1) can be rewritten as

$$P_\phi(r)=\int_{-\infty}^{\infty} f(r,s)\cdot\exp\left[-\beta\int_{G_\phi(r)}^{s} f(r,s')\,ds'\right]ds, \quad (7)$$

As shown in Eq. (7), the unknown parameter in projection is just f. It is now possible to obtain the real solution f from the projections.

3. Simulation results and discussion

We carried out the computer simulations to demonstrate the capability of this method. A typical iterative algorithm known as the algebraic reconstruction technique (ART) [1], [7] was used here for reconstruction. The algorithm is shown as follows:

$$f^{k+1}(x,y)=f^{k}(x,y)\cdot P_\phi(r)/R_\phi^{k}(r), \quad (8)$$

where $f^k(x,y)$ is the reconstruction obtained after k th iteration, and $R_\phi^k(r)$ is its attenuated projection. Figure 3 (a) shows the phantom used in the simulation. It consists of 51x51 pixels, which represents a typical implosion target. There is a hot core at the center surrounded by cold plasma. Its profile is shown in Fig. 3 (b) and the projections ($\phi=0$) with and without attenuations are shown in Fig. 3 (c). Figure 4 (a) shows a reconstruction result of low-density plasma (attenuation= 0) after 10 iterations from 10 one-dimensional projections. Figures 4 (b) and 4 (c) show the reconstruction results of high-density plasmas with attenuation of 22.5% and 45.0%, respectively. Figure 4 (d) shows the reconstruction result with attenuation correction for the case of attenuation=45.0% (Fig. 4 (c)). In order to make a quantitative comparison, we show the profiles of reconstruction, which are taken across the center in horizontal directions, in Fig. 4 (a')–(d'). Dashed lines are phantoms and solid lines are reconstructions. Furthermore, we show a normalized rms error ζ (rms of the difference projection/rms of the true projection) in Fig. 6 as function of attenuation.

As shown in Figs. 4 , 5 and 6 , for low-

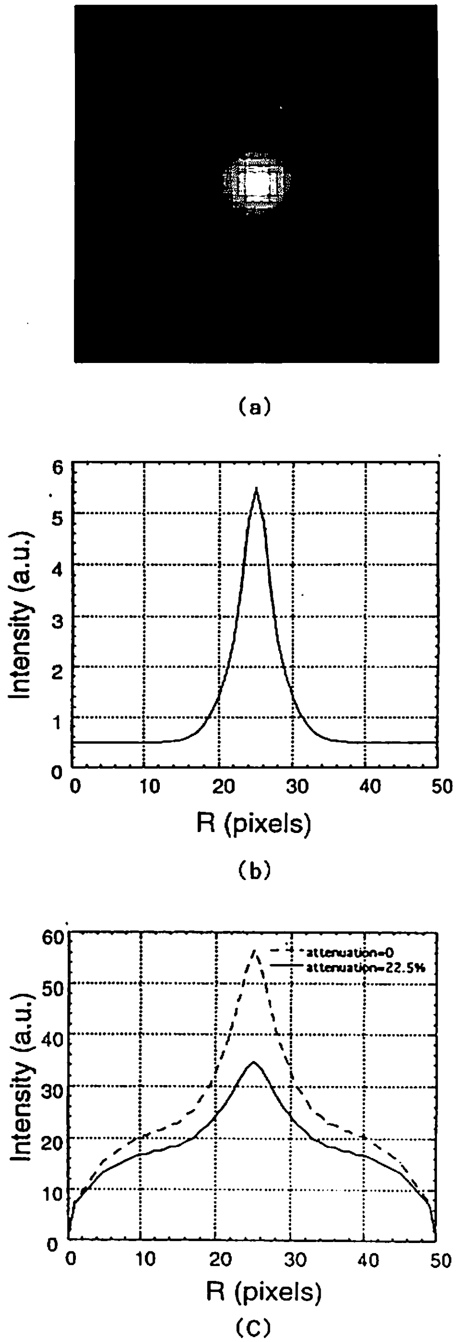

Fig. 3 Y.-W. Chen et al.

Fig. 3 (a) Two-dimensional phantom used in the simulation which consists of 51x51 pixels, (b) its profile taken acr oss the center in horizontal directions and (c) projections ($\phi = 0$).

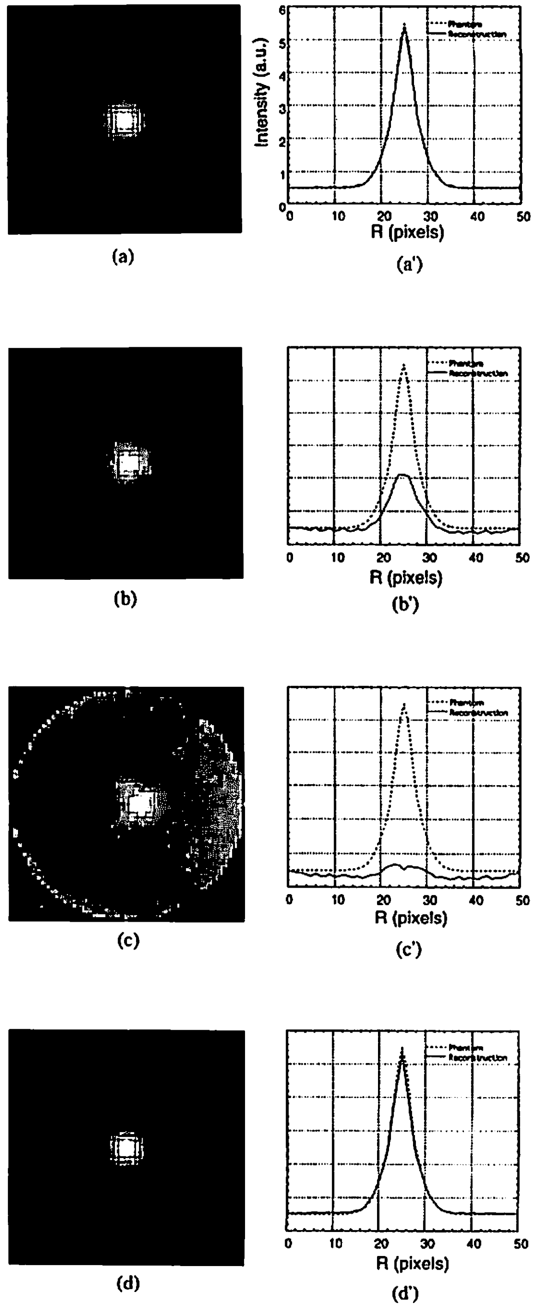

Fig. 4 Y.-W. Chen et al.

Fig. 4 Reconstruction results for defferent attenuations: (a), (a') attenuation = 0; (b), (b') attenuaion = 22.5%; (c), (c') attenuation = 45.0%; and (d), (d') attenuation = 45.0% with attenuation correction.

density plasma (attenuation= 0), ART can provide a good reconstruction with an rms error ζ of 1.5%, which is the accuracy of the conventional ART algorithm. For high-density plasma (with attenuation), if we do not correct or compensate the attenuation, the reconstruction is very poor and the rms error of reconstruction will linearly increase with increasing attenuation, while by using the proposed attenuation correction method it is possible to obtain a good reconstruction with a small rms error which is almost the same as that of low-density plasma (no attenuation) even for higher density plasma.

On the other hand, in real experiments the projection data always contains noise such as film grain and statistical noise. The effect of noise was also checked. We added a Gaussian noise (average= 0 , $\sigma^2 = 10\% \times \langle I \rangle$) to each projection. Figures 5(a), 5(b) and 5(c) show the reconstructions from the noisy projections with attenuation correction for the cases of attenuation= 0 , 22.5% and 45.0%, respectively. The normalized rms error ζ is also shown in Fig. 6 with a solid line. As compared to the case without noise (chain-dotted line), it can be seen that there is a significant reduction of the quality of reconstruction for the noisy data, especially for the case with larger attenuation, because larger attenuation results in poorer signal to noise ratio.

4. Conclusion

We have developed a new attenuation correction method for laser plasma ECT, which is based on relation of attenuation coefficient and emission coefficient in plasma. Simulation results show that the reconstructed images are dramatically improved in comparison to reconstructions without attenuation correction and it is possible to obtain an equally good reconstruction as that of low-density plasma (no attenuation) even for higher density plasma by using the proposed attenuation correction method. This method is expected to be an important diagnostic tool in future high density laser fusion experiment. The further work is to improve the quality of reconstruction for noisy data.

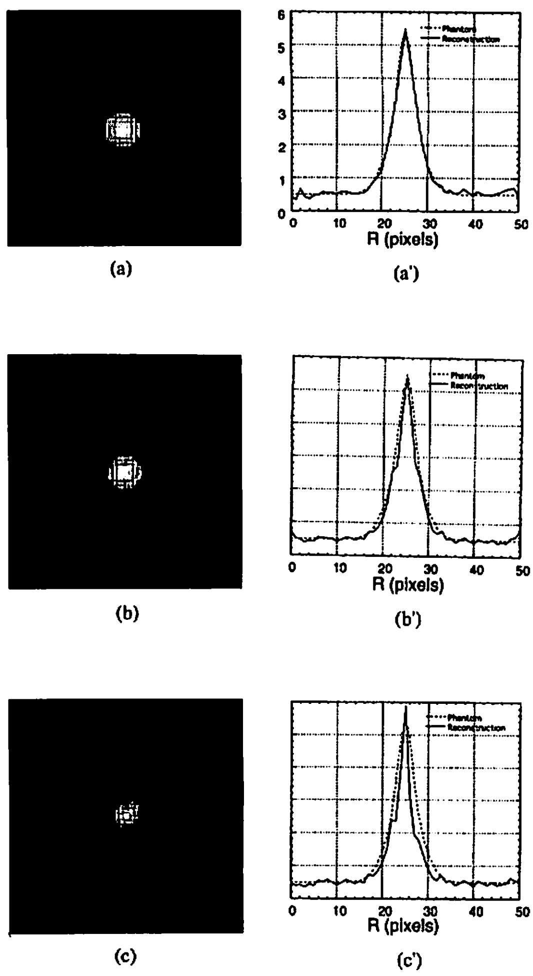

Fig. 5 Y.-W. Chen et al.

Fig 5　Reconstruction results with attenuation correction from noisy data: (a), (a') attenuation= 0 ; (b), (b') attenuaion= 22.5%; and (c), (c') attenuation=45.0 %.

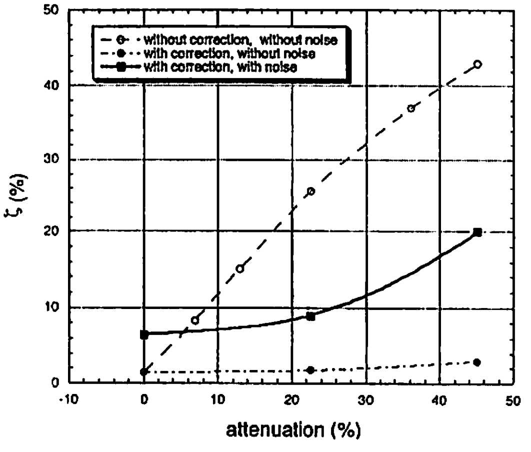

Fig. 6 Y.-W. Chen et al.

Fig. 6 Normalized rms errors ζ of reconstruction as a function of attenuation.

RERFERENCES

1. Chen, Y.-W., Miyanaga, N., Yamanaka, Mr., Nakai, M., Tanaka, K.A., Nishihara, K., Yamanaka, T. and Nakai, S., "Three-dimensional imaging of laser imploded targets," *J. Appl. Phys.*, vol.68, no. 4, pp.1483–1488, 1990.
2. Chen, Y.-W., Yamanaka, M., Miyanaga,, N., Yamanaka, T., Nakai, S., Yamanaka, C. and Tamura, S., "Three-dimensional reconstruction of laserirradiated targets using URA coded aperture cameras," *Opt. Commun.*, vol.71, no. 5, pp.249–255, 1989.
3. Nakai, S., Mima, K., Yamanaka, M., Azechi, H., Miyanaga, N., Nishiguchi, A., Nakaishi, H., Chen, Y.-W., Setsuhara, Y., Norreys, P.A., Yamanaka, T., Nishihara, K., Tanaka, K., Nakai, M., Kodama, R., Katayama, M., Kato, Y., Sasaki, H., Jitsuno, T., Yoshida, T., Kanabe, T., Yokotani, A., Norimatsu, T., Takagi, M., Katayama, H., Izawa, Y. and Yamanaka, C., "High density compression of hollow-shell target by Gekko-XII and laser fusion research at ILE, Osaka University," *Laser Interaction and Related Plasma Phenomena*, vol. 9, pp.25–67, 1989.
4. Tanaka, E., "Quantitative image reconstruction weighted backprojection for single photon emission computed tomography," *J. Comp. Asst. Tomogr.*, vol. 7, pp.692–700, 1981.
5. Chang, L. T., "A method for attenuation correction in radionuclide computed tomography,"*IEEE Trans. Nucl. Sci.*, vol.NS-25, pp.638–643, 1987.
6. Inoue, T., Kose, K. and Hasekawa, A., "Image reconstruction algorithm for single-photon-emission computed tomography with uniform attenuation," *Phys. Med. Biol.*, vol.34, pp.299–304, 1989.
7. Herman, G. T., *Image Reconstruction from Projections*, Academic, New York, 1980.
8. Zel'dovich, Ya. B. and Raizer, Yu. P., *Physics and Shock Waves and High-Temperature Hydrodynamic Phenomena*, Academic, New York, 1966.
9. Nakai, M., Shinohara, S., Katayama, M., Chen, Y.-W., Kobayashi, S., Miyanaga, M., Tanaka, K. A., Nishihara, K., Yamanaka, M., Yamanaka, T. and Nakai, S., "Development of x-ray emission computed tomography for ICF research," *Rev. Sci. Instrum.*, vol.61, pp.2783–2785, 1990.