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Soft X-ray Spectroscopic Imager Using a Micro-channel Plate for Plasma Studies and its Calibration

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We developed a soft x-ray spectroscopic imager using a pin-hole collimator, a changeable aluminum filter array, an MCP and a CCD camera. It can show not only the dynamic x-ray image from plasma but also a stationary image of x-ray with an energy band selected by using a pair of consecutive filters. Before installing the imager in the Hanbit plasma device in Korea Basic Science Institute, Daejeon, Korea, we suggested a simple method of conversion of pixel brightness values into the absolute x-ray photon flux density of the selected energy band by using the central pixel values. The conversion coefficients were obtained by using the measured x-ray spectra from a conventional x-ray generator. Also we did a simple calculation to produce a look-up table of the non-uniformity of pixel responses, for correction of the image distortion due to the MCP bias angle and the pin-hole geometry.
KEY WORDS: Plasma, micro-channel plate, soft x-ray, spectroscopic image, photon flux density

I. Introduction

Various active diagnostic tools, such as Langmuir probe, Thompson scattering analyzer and so on, are used to diagnose the plasma parameters, such as the temperature and densities of the electron and ions, and their temporal behavior. [1] However, since all these active methods use the interaction of a physical probe or an external radiation beam with the plasma, they inevitably disturb the physical state of the plasma under study. So passive diagnostic methods, which measure the electromagnetic radiation emitted from the plasma itself, are desirable especially when the disturbance of the plasma state should be minimized or avoided.

The type of radiation emitted from plasma ranges from the infrared to high-energy x-ray, but soft x-ray with energy from hundreds of eV to several keV gives an useful information about the temperature, density and the ion species in the plasma.

We have developed a soft x-ray spectroscopic imager for experimental studies of the temporal behavior of plasma in the Hanbit device in Korea Basic Science Institute. Though similar imagers have been studied by others [2, 3], the developed imager not only can detect the dynamic behavior of plasma but also can measure a spectroscopic information about the x-ray photons with certain energy bands.

This paper describes the basic features of the developed imager and a calibration method and the results to obtain the conversion coefficients of the pixel brightness value into the x-ray photon flux density within the selected energy bands and a correction method of the image non-uniformity due to the bias angle of MCP channels and the pin-hole geometry.

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II. Soft x-ray Spectroscopic Imager

The developed imager consists of a pin-hole collimator, a changeable aluminum filter array, a micro-channel plate (MCP) of 28 mm diameter, a CCD camera and a personal computer as shown in the **Fig. 1**. The brightness of each pixel in CCD image is related to the photon fluence of x-ray from bulky plasma, passing through the pinhole and arriving onto the pixel-equivalent area of the MCP front surface.

The space between the pin-hole collimator and the MCP is kept to vacuum with pressure below a few times of 10^{-7} torr by a turbo molecular pump so that the MCP is secured from the influence of the relatively high pressure in the plasma chamber.

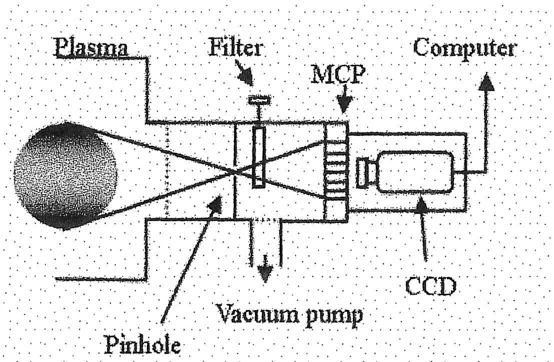
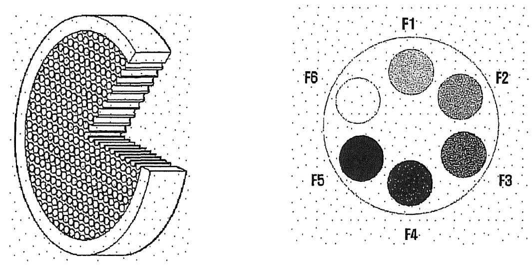


Fig. 1 The apparatus of soft x-ray imager

The MCP is a thin planar detector of UV and x-ray with energy up to a few hundreds of keV. It consists of a bundle of individual capillary glass tubes as shown in the **Fig. 2 (a)**. The hole of the tube is called as a channel through which the incident photons are converted into many electrons through multiple steps of the secondary electron emission process before they finally arrive at the rear surface of the

MCP. The multiplication gain is set often as high as a million. The angles of all holes are slightly tilted from the normal direction of the MCP front surface in order to increase the detection efficiency of the incident radiation. The MCP used in this study has a phosphor layer attached at the back, from which 2-D image is captured by a CCD camera and the exposure time is set in the computer.



(a) **(b)**

Fig. 2 (a) Microstructure of the MCP (b) the changeable filter array; F1~F6 are the main aluminum filters of different thicknesses, and F5 and F6 are the shielded and the open holes.

The filter array is a circular disk with 6 holes, as shown in the **Fig. 2 (b)**. Among them, four holes (F1 ~ F4) are covered by thin aluminum sheets with different thicknesses, 9.26, 18.52, 37.05, and 74.1 μm in sequence. These values are determined with Monte Carlo simulations in order to produce three subtracted transmission rates with peak values at energies separated with the equal intervals as shown in the **Fig. 3**, when two of them are used as a pair.

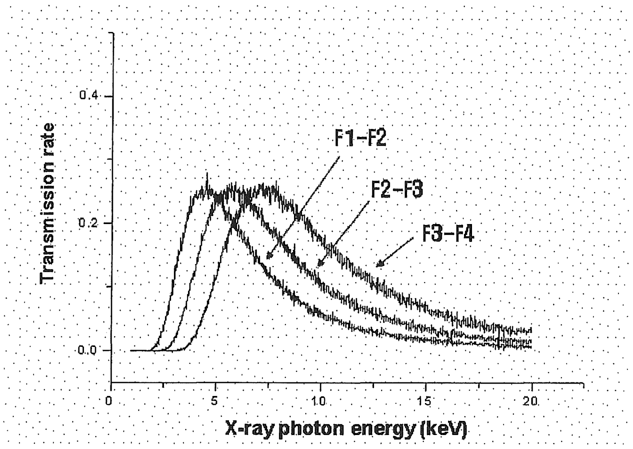


Fig. 3 Transmission rates of x-ray photons with a constant spectrum after filtration and subtraction. Three curves are obtained by using three pairs of filters, F1-F2, F2-F3 and F3-F4, and they have a peak at 4.38, 5.61 and 7.18 keV.

The fifth hole (F5) is covered by a thick Al plate to completely shield x-ray with energy up to 20 keV and the last hole (F6) is open to sense all radiation from the plasma including UV photons.

The imager is developed to capture the dynamic x-ray image but it can also generate spectroscopic x-ray images, which is useful in studying the temperature distribution and the local densities of ion species in plasma. The spectroscopic image of x-ray with a certain energy band will be generated by subtracting each pixel value of a stationary image data from those of another one after obtaining them using two filters in sequence for the same plasma, or for plasma pulses generated under the same condition, precisely speaking.

III. Calibration of Pixel Response and Correction of Image Distortion

Before installing the imager in the Hanbit device, we need to estimate the energy response coefficients for each set of filters in order to correlate the subtracted pixel brightness to the intensity of x-ray photon produced in the plasma having energy within specific energy bands. We also need to correct the image distortion due to the bias angle of MCP channels and the pin-hole geometry.

1. Conversion of pixel brightness to the absolute photon flux density

If we assume the perfectness of the pin-hole collimation and the dominance of the photo-electric effect in soft x-ray energy range, we can neglect the scattered x-ray, so the subtracted pixel brightness value, $D_S(x,y)$, can be expressed as simply as follows

$$\begin{aligned} D_S(x,y) &\equiv D_{Fi}(x,y) - D_{Fj}(x,y) \\ &= \int_0^{E_{\max}} \phi(E)\cdot\left(T_{Fi}(E) - T_{Fj}(E)\right)\cdot R(E)\cdot \tau_{\exp}\cdot A_{\Delta x\Delta y}\cdot dE \\ &\approx \psi(E_S)\cdot R(E_S)\cdot T_{Fi-Fj}(E_S)\cdot \tau_{\exp}\cdot A_{\Delta x\Delta y}\cdot \Delta E_S \end{aligned} \tag{1}$$

where $\phi(E)$ is the incoming x-ray spectral flux density and $T_{Fi}(E)$ and $T_{Fj}(E)$ are the transmission rates of x-ray through the filter Fi and Fj respectively. $R(E)$ is the conversion coefficient of a single photon with energy E into the digital value of a pixel brightness, τ_{exp} is the exposure time of the CCD for a single image capture = 33 mec, $A_{\Delta x\Delta y}$ is an MCP area equivalent to a CCD pixel at (x,y) = 0.028×0.028 cm^2, and ΔE_S is the effective energy bandwidth of the transmission curves. As shown in the equation, the integral is approximated as a product of several energy-band parameters for the filter pair of Fi and Fj; the x-ray photon flux density, $\psi(E_S)$, the conversion coefficient, $R(E_S)$, and the subtracted transmission rate, $T_{Fi-Fj}(E_S)$.

The conversion coefficient is physically related to the interaction efficiency of a single x-ray photon with energy E with the MCP, the electron multiplication gain of the MCP, the scintillation gain of the phosphor layer, the optical efficiency of the CCD camera and finally the electronic amplification gain and conversion factor to yield a numeric value of the pixel brightness in the data processing electronics.

In this study, we propose to use a conventional x-ray generator instead of real plasma for the calibration of pixel values for each energy band, so we define a center pixel conversion coefficient, $R_{(0,0)}(E_S)$, as a representative value by using the following equation.

$$R_{(0,0)}(E_S)=\frac{D_S(0,0)}{\psi(E_S)\cdot T_{Fi\text{-}Fj}(E_S)\cdot \tau_{\exp}\cdot A_{\Delta x\Delta y}\cdot \Delta E_S}$$
$$\approx\frac{D_S(0,0)}{\psi_0\cdot\int_0^{E_{\max}}\phi_N(E)\cdot\left(T_{Fi}(E)-T_{Fj}(E)\right)\cdot \tau_{\exp}\cdot A_{\Delta x\Delta y}\,dE} \qquad (2)$$

where $D_S(0,0)$ is the center pixel data measured by the imager and $\phi_N(E)$ is the normalized x-ray spectrum measured by a silicon pin-diode with a 2048-ch multi-channel analyzer (MCA). ψ_0 is the total x-ray photon flux density from the x-ray generator at the given distance and it is calculated by the following equation,

$$\psi_0=\frac{\dot{X}}{C\cdot\int_0^{E_{\max}}\phi_N(E)\cdot E\cdot\frac{\mu_{abs\text{-}air}(E)}{\rho_{air}}\cdot dE} \qquad (3)$$

where the numerator is the exposure rate measured by an ion-chamber dosimeter (RAD-CHECK REMOTE, Model 06-528), C is the theoretical dose conversion coefficient = $6.58\text{x}10^{-11}$ (R/hr)/(eV/g-air×sec), and the mass absorption coefficients of the air were obtained from the database in the National Institute of Standards and Technology (NIST). [4]

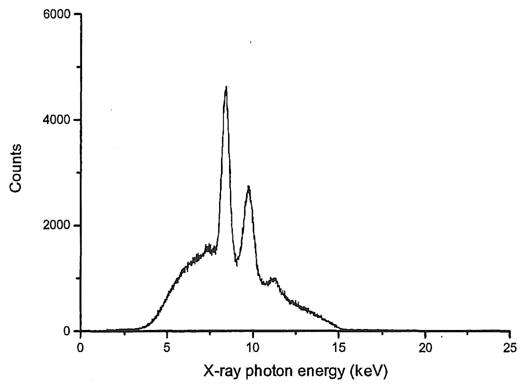


Fig. 4 The x-ray spectrum of the x-ray generator (15 kV, 0.3 mA) measured by a Si pin-diode with a 2048-ch MCA. See the three L-edges of the tungsten, which are L_α = 8.37 keV, L_β = 9.82 keV, and L_γ = 11.29 keV in sequence.

Table 1 Parameters of the developed imager for calibration of the central pixel brightness with three pairs of filters

Pair of filters	F1-F2	F2-F3	F3-F4
Subtracted peak transmission rate, $T_{Fi\text{-}Fj}(E_S)$	0.25	0.25	0.25
Peak energy, Es [keV]	4.38	5.61	7.18
Effective energy bandwidth, ΔE_S [keV]	5.66	6.97	8.54
Center pixel brightness value, $D_S(0,0)$	3.76	1.75	0.93
Conversion coefficient, $R_{(0,0)}(E_S)$ ($\times10^{-5}$)	5.85	1.81	0.756

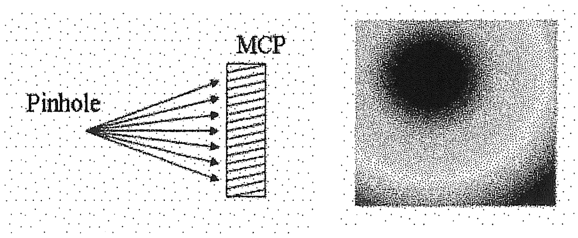
Figure 4 shows the measured spectrum of the x-ray generator when the tube voltage is 15 kV and the tube current is 0.3 mA. The measured exposure rate was 127 R/hr and the photon flux density, ψ_0, calculated by the above equation was 1.69×10^9 photons/cm^{2}sec. For three energy bands, the calculated conversion coefficients, $R_{(0,0)}(E_S)$, were given in **Table 1** together with other parameters related to each pair of filters. Using these values and the last part of the equation (1) we can calculate the photon flux density from the pixel brightness values.

2. Correction of image distortion due to MCP bias-angle

Since an MCP consists of a bundle of parallel micro-capillary tubes, some radiation incident onto the MCP with the direction in parallel to the tube axis, may transit the tube without creating secondary electrons, so in order to increase the radiation interaction efficiency and electron multiplication gain of the MCP, all these tubes are arranged with a fixed bias angle against to the normal direction of the MCP surface.

Especially the developed imager uses a pin-hole geometry, the radiation passing through the pin hole with the same angle as the bias angle do not produce the same brightness as the other pixels as shown in the **Fig. 5**. In order to correct this non-uniformity, we made a simple calculation about the interaction efficiencies of every pixel as a function of its position relative to the center pixel considering the bias angle, 8° and the distance between the pin hole and the MCP front surface.

Figure 5 (a) shows the schematic geometry of the x-ray beam and the slanted MCP channels, and (b) shows the calculated image of pixel brightness from an isotropic point source located at the pin hole position. This image data will be used as a look-up table (LUT) to correct the non-uniformity of the real x-ray image obtained through the pin hole.

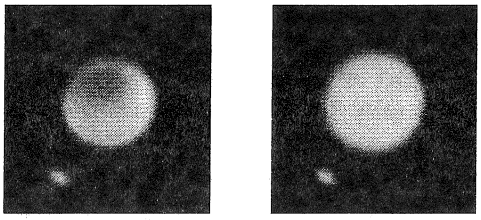


(a) **(b)**

Fig. 5 **(a)** the schematic geometry of the x-ray beam and the MCP channels with a bias angle, **(b)** the calculated results of pixel brightness due to an isotropic point source located at the pin hole position of the imager

Figure 6 (a) is the measured 2-d image obtained from the x-ray generator located at the same position of the pin hole. Note that there is a dark area of which center coincides with the position of x-ray with a direction angle same to the bias angle of the MCP channels. **Figure 6 (b)** is the corrected image using the calculated LUT.

The suggested simple correction is applicable only for a small bias angle. If the angle is larger than 20 degree, other factors like the viewing cross section of channels become more important factors for the higher accuracy of the image correction. [2]



(a) (b)

Fig. 6 **(a)** the measured and **(b)** LUT-corrected image of an x-ray generator located at the same position as the pin hole

IV. Summary and Conclusions

A soft x-ray spectroscopic imager was developed based on a pin-hole collimator, a filter array, an MCP and a CCD camera. This device has the x-ray energy selectivity among three bands set by 4 aluminum filters. The absolute calibration of the x-ray photon flux density can be done by using the center pixel brightness values. Also the image distortion due to the bias angle of MCP channels can be corrected by using a simple look-up-table. The developed soft x-ray imager will be used as a passive diagnostic tool for the characterization of Hanbit device.

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