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Extension of the energy-resolved soft X-ray imaging system using two CCD cameras in LHD

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An existing imaging system using a soft X-ray CCD (Charge Coupled Device) camera and beryllium (Be) filters installed to a tangential viewport of the Large Helical Device (LHD) has been utilized not only for the measurement of the flux surface shape, but also for the energy resolved imaging in long pulse discharges. In order to obtain simultaneously soft X-ray energy spectra necessary for the analyses of the imaging results, we have extended the present diagnostic system by adding another soft X-ray CCD camera mainly used for the photon counting mode. This new camera has been installed in a vertical viewport and equipped with two mounting disks rotating independently. This setup enables us to choose any combination of Be filter thickness and slit width according to the amount of photon flux, and it can be combined with the kinetic mode operation if temporal resolution is the first priority. The details and capability of the simultaneous measurements of the soft X-ray images and energy spectra are described.

Keywords: soft X-ray, CCD camera, imaging, photon counting, energy spectrum, LHD

1. Introduction

Soft X-ray imaging technique using a CCD (Charge Coupled Device) camera sensitive directly to soft X-ray photons has ever been applied to the diagnostics of magnetically confined high temperature plasmas [1, 2, 3, 4]. In the Large Helical Device (LHD) experiment, an imaging system using the soft X-ray CCD camera and beryllium (Be) filters has already been installed to a tangential viewport. This existing system is mainly utilized for the measurement of flux surface shape, especially the derivation of the magnetic axis shift (Shafranov shift) from the fitting of the pre-calculated equilibria to the measured soft X-ray profile assuming that the emissivity profile could be expressed by Fourier-Bessel expansion [3].

On the other hand, information on a soft X-ray energy spectrum is often necessary for further analyses of recent experimental results of the soft X-ray imaging. In the analysis of the energy resolved soft X-ray imaging demonstrated recently [5], for example, the evaluation of the contribution of K_α spectral lines from impurity ions to the measured signal intensity is important especially in higher energy range. Another example is hollow soft X-ray emissivity profiles often observed in high ion temperature discharges together with the formation of carbon impurity hole. Since this phenomenon is considered to be closely related to impurity transport, it is important to determine which impurity line or continuum radiation dominantly contributes to the observed hollow soft X-ray profile. Therefore it would be helpful for further discussions on the results of the imaging if soft X-ray energy spectra are measured simultaneously.

CCD cameras can also be utilized for the measurements of soft X-ray energy spectra by operating them in photon counting mode [1, 2]. Furthermore, spatial and energy resolutions of this method are expected to be better than those of conventional X-ray pulse height analyzer (PHA). Therefore we are planning to extend the existing system by adding another soft X-ray CCD camera mainly used for the photon counting mode. The arrangements of the sights of the two cameras are illustrated in Fig. 1, where a top view of horizontal cross section at the equatorial plane and a vertical cross section are drawn. The existing and new cameras have been installed in tangential and vertical viewports, respectively. The details and capability of the measurements of the soft X-ray images and energy spectra by the two cameras are described in this article.

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2. Recent imaging results

As mentioned in the previous section, two examples which indicate the importance of soft X-ray energy spectra are found in the recent imaging results obtained by the existing camera. These results are reviewed in this section. Since the details of the existing system have already been published elsewhere [5], only a brief explanation is given here. The system consists of a soft X-ray CCD camera (Andor Technology, DO435-BV) together with a pinhole, a pneumatic mechanical shutter, and a remotely rotatable filter disk which mounts eight Be filters. The quantum efficiency curve of the CCD chip ranges roughly from 1 to 10 keV. In order to adjust cutoff energy of photons, filter thickness is selectable from 50–1650 μm. The camera is equipped with a back illuminated CCD chip of frame transfer type of which image area is 13.3×13.3 mm^2 composed of 1024×1024 pixels. The output of the CCD camera is

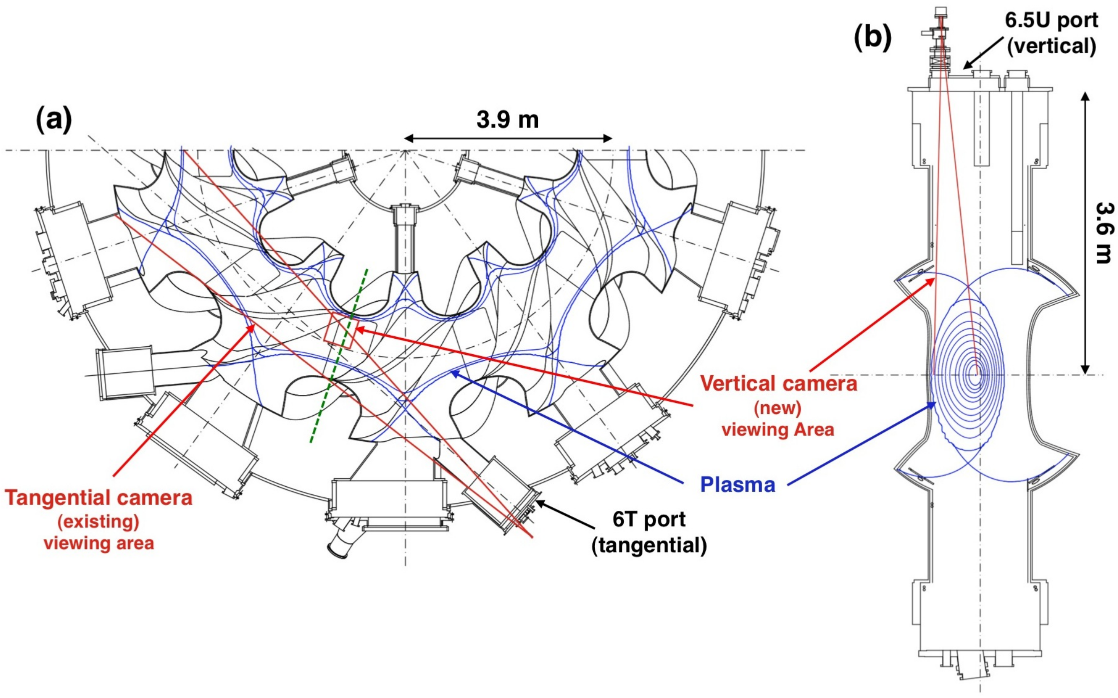

Fig. 1 Arrangement of the viewing areas of the existing and new soft X-ray CCD cameras. (a) Top view of horizontal cross section at the equatorial plane and (b) vertical cross section at the green broken line in (a) are drawn. The existing and new cameras have been installed in the tangential (6T) and the vertical (6.5L) viewports, respectively.

read out by a 1 MHz analog-to-digital (A/D) converter with a resolution of 16 bit. The total readout time is about 0.6 s for 2×2 pixel binning. The diameter of the pinhole can also be chosen out of 0.05, 0.1, 0.2 and 0.4 mm.

The differential images of specific photon energy range obtained in the energy resolved soft X-ray imaging have also been reported in ref. [5]. The measurement has been carried out by changing the Be filter thickness during a long pulse discharge sustained for several minutes [6] whose electron density and temperature are of the order of 10^{19} m^{-3} and 1 keV, respectively. Eight two-dimensional images with different cutoff energies are measured by rotating a filter disk. Assuming continuum radiation and spatially uniform effective charge, it can possibly be applied to the measurements of line-averaged effective electron temperature and change in soft X-ray profile due to locally distorted electron energy distribution. However, if the measured soft X-ray emissivity contains not only the continuum but also K_α spectral lines from impurity ions, they would affect the signal intensity especially in higher energy range. Therefore the simultaneous measurement of the soft X-ray energy spectra would be helpful for further discussions.

Another example of the recent results is given in Fig. 2 which shows tangential soft X-ray images in a high ion temperature discharge accompanied by the formation of carbon impurity hole. The soft X-ray emissivity profile suddenly changes from peaked one to hollow one when the formation of carbon impurity hole (around 2.25 s) is observed in charge exchange spectroscopy [7]. Since the filter thickness is 450 μm corresponding to a cutoff energy of about 4 keV, K_α lines from titanium (4.8 keV), chromium (5.7 keV) and iron (6.6 keV) would possibly contribute to the measured intensity together with the continuum radiation due to bremsstrahlung. Since this phenomenon is considered to be closely related to impurity transport, it is important to determine which impurity line or continuum radiation dominantly contributes to the observed hollow soft X-ray profile.

3. Energy calibration

As described previously, CCD cameras can also be utilized for the measurements of soft X-ray energy spectra by counting pulse heights in the photon counting mode. We have prepared another soft X-ray CCD camera (Andor Technology, DO432-FI) for this purpose. The camera is equipped with a front illuminated CCD chip of which image area is 28.1×25.9 mm^2 composed of 1250×1152 pixels. Before the installation of this camera, energy sensitivity and resolution were evaluated by the calibration using standard X-ray sources. Radiations from the X-ray sources of Fe^{55}, Am^{241}, and Cd^{109} were measured repeatedly by this camera in the photon counting mode with an appropriate integration time. The results of this procedure are summarized in Fig. 3.

Figure 3 (a) shows the histogram of the CCD signal counts generated by individual incoming photons, which

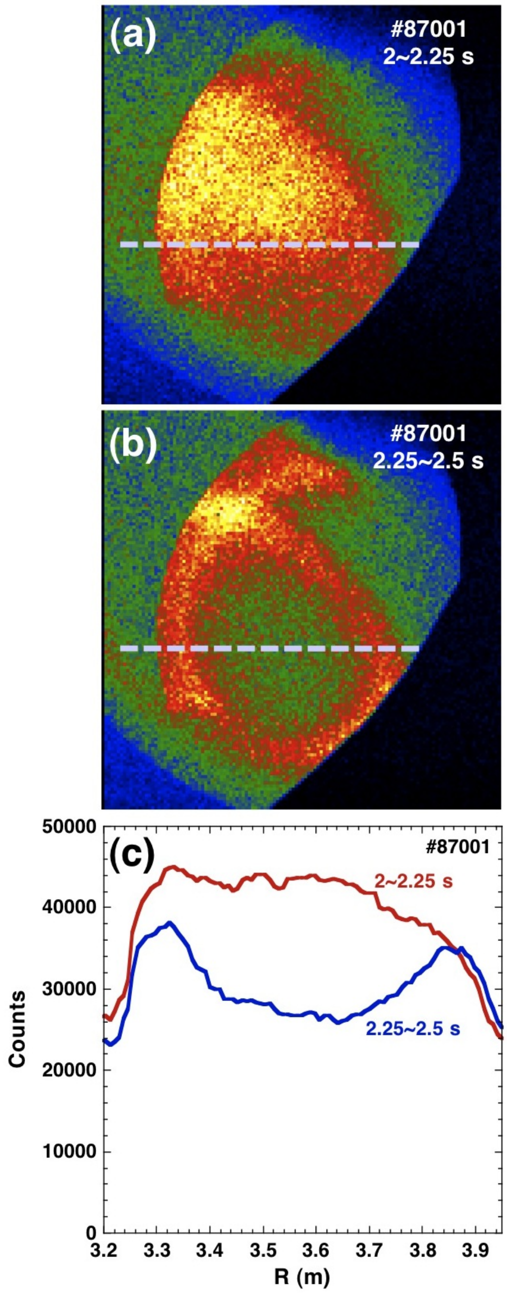

Fig. 2 An example of soft X-ray emissivity profile in a high ion temperature discharge with the formation of carbon impurity hole. The profile suddenly changes from (a) peaked one to (b) hollow one around 2.25 s when the formation of carbon impurity hole is observed in the charge exchange spectroscopy measurement. The change in the horizontal profile along the broken lines indicated in (a) and (b) is drawn in (c). The thickness of the Be filter is 450 μm.

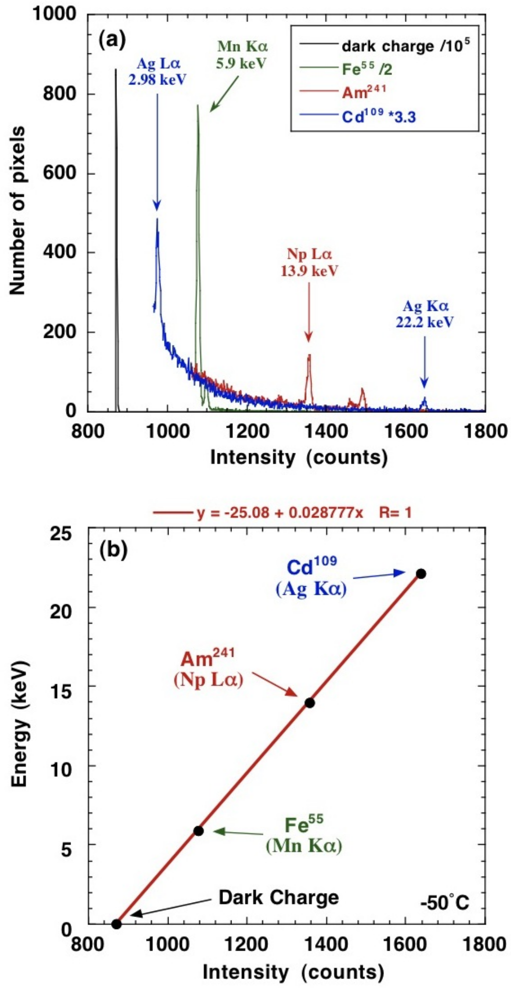

Fig. 3 Calibration of energy sensitivity and resolution of the new soft X-ray CCD camera. (a) Energy spectra obtained by several standard X-ray sources. (b) Plot of photon energy versus CCD count to obtain energy sensitivity from the slope.

corresponds to the energy spectra since the generated charges are proportional to the incoming X-ray photon energy in the photon counting mode. Several sharp peaks of K_α and L_α lines corresponding to the characteristic X-rays of known energies are clearly observed. The highest peak around 870 counts (indicated by a black line) is not from the X-ray, but is due to the dark charge of the CCD chip. As a result, a relation between the X-ray energy and the signal intensity (in counts) is derived as shown in Fig. 3 (b).

The energy resolution is evaluated to be 230 eV at the photon energy of 5.9 keV from the width of the spectral line. This value is better than that of conventional X-ray PHA. The sensitivity evaluated from the linear slope of Fig. 3 (b) is 29 eV/count. These results indicate that the energy resolution and sensitivity of this camera is good enough as an alternative way to measure the soft X-ray energy spectra.

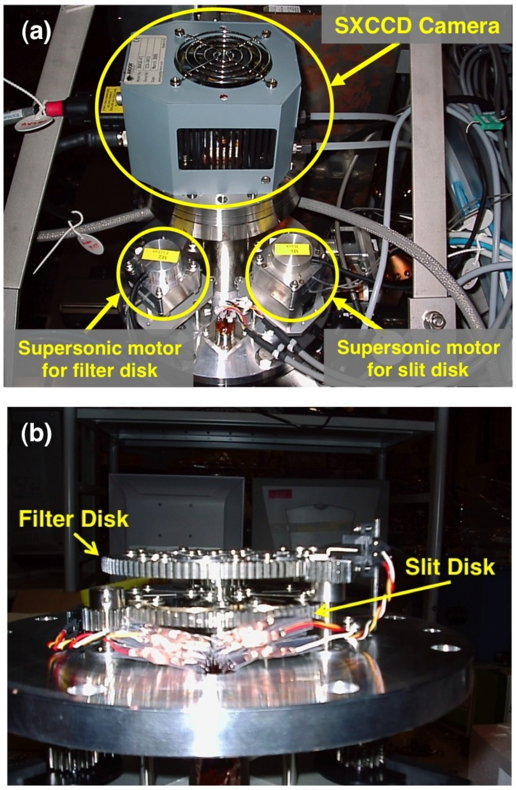

Fig. 4 Photographs of the installation of the new soft X-ray CCD camera system. (a) Installed CCD camera and two supersonic motors. (b) Filter and slit disks installed in front of the camera.

4. Installation of new CCD camera

Though the setup of the newly added system is basically similar to the existing one, it has been installed in the upper viewport as shown in Fig. 1. A photograph of the installed CCD camera and supersonic motors for the mounting disks are shown in Fig. 4 (a). The specification of the A/D converter and pinhole are the same as those of the existing CCD camera. A unique feature of this system is that two mounting disks which rotate independently are equipped in front of the camera as shown in Fig. 4 (b). Be filters are mounted on the first disk to control the cutoff energy, while several slits with various widths are attached to the second disk so as to limit the photon illumination to the top rows of the CCD chip. The slits are used in the kinetic mode operation of the CCD if temporal resolution is the first priority. Namely, images are exposed only on a part of rows at the top of the CCD array and other rows are masked for temporary storage by using a slit. Time resolution (minimum frame rate) in this mode is determined by the vertical shift speed of charges, which is much faster than that in the normal acquisition mode. The fast kinetics mode combined with the photon counting mode can be applied to the one-dimensional electron temperature measurement.

5. Summary and prospects

The importance of information on soft X-ray energy spectra has been revealed in the analyses of the recent imaging results of the diagnostic system using a soft X-ray CCD camera and Be filters in LHD. In order to obtain soft X-ray energy spectra, we have extended the existing diagnostic system by adding another soft X-ray CCD camera mainly used for the photon counting mode, and installed it in a vertical port of LHD. The high sensitivity and energy resolution of the new camera is expected according to the calibration using X-ray sources. Two independently rotating disks for Be filters and slits allow us flexible control of photon flux on the CCD chip. They can be combined with the kinetic mode operation if temporal resolution is the first priority.

In the near future, algorithms for the photon counting mode from the CCD readout will be prepared. After the complete installation of the new camera, the effect of line emissions from impurities will be studied during the next experiment. Finally, this extended diagnostic system will be applied in the future to the trial of the detection of difference in two-dimensional soft X-ray image by energy range caused by local generation of non-Maxwellian electrons in a stable long pulse discharge by electron cyclotron resonance heating (ECRH).

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