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Measurement of Soft X-Ray Image by Using CCD Camera for Long Pulse Discharge

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Abstract

The measurement of soft x-ray image using CCD camera was installed to a tangential port in LHD. The large number of pixels (1024 × 512) of CCD gives a good spatial resolution of 1.8 mm. The tangential soft x-ray image is measured during long pulse discharge on LHD with a time resolution of 0.5 s. The shift of x-ray emission profile is found for plasmas with different magnetic axes.

Keywords:

soft x-ray CCD camera, soft x-ray image, magnetic axis

1. Introduction

The x-ray CCD camera with photon counting capability has been widely applied to measure x-ray image and energy spectra in space physics and laser fusion field [1,2]. Because the readout time of CCD is about few hundred milliseconds and the time resolution was considered to be too poor, this type of CCD has never been applied to the experiment in magnetically confined plasma. In recent years, the long pulse discharge above a minute with a temperature of >1 keV was achieved in Large Helical Device (LHD). Then the x-ray CCD camera becomes more useful diagnostics, even the time resolution is poor.

The soft x-ray CCD camera system has been applied to measure magnetic axis and two-dimensional x-ray energy spectra on compact helical system (CHS) with image mode and photon counting mode, respectively [3,4]. By using this soft x-ray CCD camera, the Shafranov shift of plasma magnetic axis was measured in CHS. The Shafranov shift is larger than that estimated from diamagnetic loop, which is due to the beam pressure driven by tangentially injected neutral beam.

In the end of 1999, the soft x-ray CCD camera was installed on LHD and soft x-ray image data was measured during long pulse discharge with time resolution about 0.5 s. The LHD is a superconducting helical device (l/m = 2/10) with a major radius of 3.9 m and a minor radius of 0.65 m. One of the mission for LHD project is to achieve high-β plasma with $\langle\beta\rangle > 5\%$ and the measurement of Shafranov shift of magnetic axis becomes very important. In this paper, the soft x-ray CCD camera system on LHD and the preliminary results of soft x-ray image measured with CCD camera during long pulse discharge are described.

2. Experimental Set-up

The soft x-ray CCD camera system was installed on a tangential port in LHD. The distance between the port axis and LHD middle plane is 0.21 m.

The top view and the schematic of soft x-ray CCD camera optic assembly are shown in Fig. 1. The soft x-ray CCD camera optic assembly consists of pinhole,

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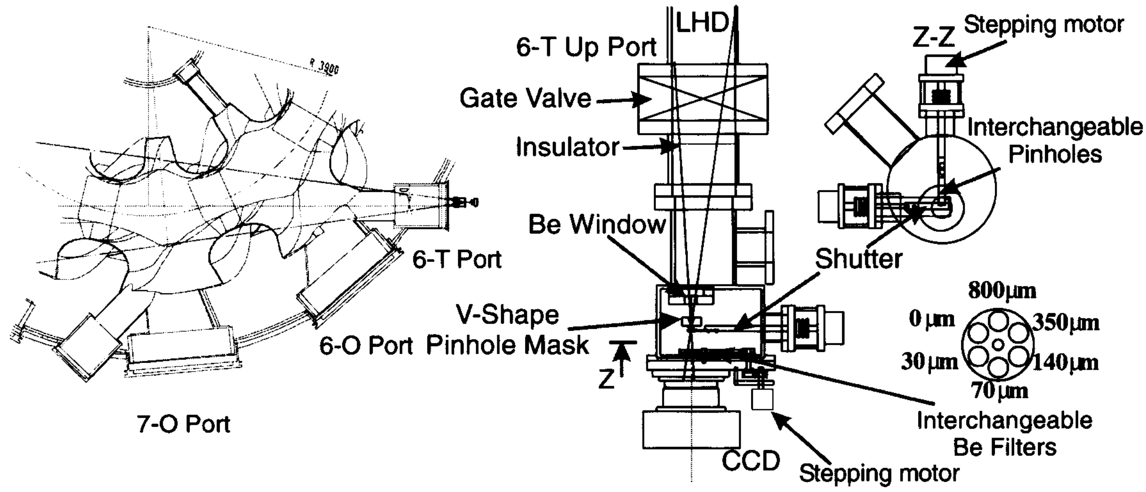

Fig. 1 Top view and scheme of soft x-ray CCD camera optic assembly installed on LHD.

absorption Be foil, shutter, and soft x-ray CCD camera.

The soft x-ray CCD camera is made by Princeton Instruments (model number SX-TE/CCD-1024S) with TEK 1024 × 1024D frame transfer back illumination CCD detector (the imaging is 512 × 1024 pixels). The detector is cooled down to –40°C using multistage Peltier devices to reduce the dark current of CCD. The readout time of CCD is about 5 s with 100 kHz A/D rate and 0.5 s with 1 MHz A/D rate.

Four sets of pinhole with different diameter of 0.4 mm, 0.2 mm, 0.1 mm, 0.05 mm, are installed to adjust the flux of soft x-ray. The stainless-steel strip is fixed on the pinhole selector. The size of pinhole can be changed by using a stepping motor. The distance from pinhole to CCD surface is 87 mm. The CCD camera views the plasma at a tangency radius of 3.65 m with the viewing angle of ±8.0° (horizontal directions) and ±4.0° (vertical direction). The observation region at horizontally elongated cross section of LHD plasma is from R = 2.710 m to 4.590 m horizontally and from Z = –0.780 m to +0.160 m vertically. Since the thickness of pinhole plate is only 1mm, it is too thin to stop the hard x-ray (>30 keV). Therefore a 12-mm-thick tantalum mask (V-shape hole) with pinhole diameter of 0.5 mm had been installed in front of the pinhole plate.

A 50-μm-thick Be window is arranged between LHD plasma and CCD to prevent visible light from plasma. The Be window isolates the CCD chamber from LHD chamber. Between the pinhole and the CCD surface, a Be filter disk is arranged. The filter disk has five Be filters with different thickness of 30 μm, 70 μm, 140 μm, 350 μm, 800 μm, respectively, and it is

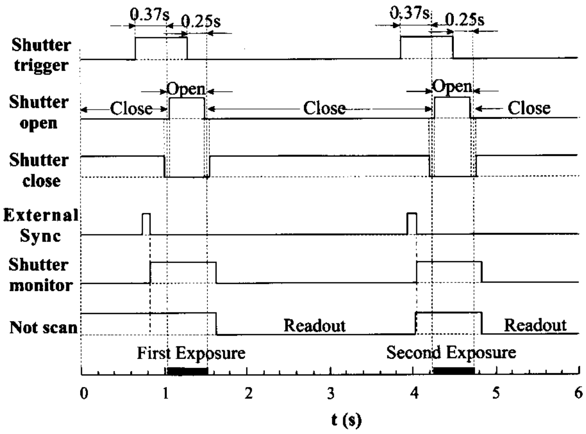

Fig. 2 Timing chart of CCD camera with A/D rate 100 kHz and 752 × 320 pixels transferred.

controlled by a stepping motor. The x-ray flux is adjusted to the level enough for the imaging mode or photon counting mode by choosing various combinations of pinhole and absorption foils. The low-energy cut-off of soft x-ray measured depends on the thickness of Be filter. The cut-off energy is about 1 keV for 50 μm Be filter. The upper limit of x-ray energy is 10 keV, which is determined by the quantum efficiency of CCD.

Because of strong magnetic field near the LHD device during experiments, a shutter controlled by magnet does not work. An air-controlled shutter is installed between pinhole and CCD to prevent x-ray photons coming to CCD surface during the readout of image data. The minimum pulse width of shutter trigger is about 0.3 s.

Another important thing for CCD camera system is the timing setting of external sync pulse and shutter trigger. Figure 2 shows an example of the CCD camera timing option with A/D rate of 100 kHz and 752 × 320 pixels transferred. The CCD camera reads out one frame for every external sync pulse received. The exposure time setting and the readout time indicated by shutter monitor output and not scan output is 0.8 s and 2.385 s, respectively. By reason of the slow speed of air-controller, the shutter requires 0.335 s to start open action and another 0.037 s to open completely after every shutter trigger received. To avoid the image smearing which is due to continuous exposure during readout, the timing of shutter open should be inside of exposure time setting and the second exposure time setting should start after the first frame readout completed. This can be done by adjusting the delay time and pulse width of external sync pulse and shutter trigger. In the case shown in Fig. 2, the start trigger is received before discharge 12 s with pulse width of 2 s. The external sync pulse and the shutter trigger are delayed 0.742 s and 0.665 s with pulse width 0.1 s and 0.623 s, respectively. The time region for the first x-ray image frame is from 1.037 s to 1.527 s, and the repetition time is 3.2 s.

3. Experimental Results

A) Tangential soft x-ray images during long pulse discharge

The tangential soft x-ray image during long pulse discharge on LHD is measured in the last two weeks of LHD 1999 experimental campaign. The time evolution of various signals relevant to the present experiment is shown in Fig. 3(a) for a long pulse LHD plasma heated by ICRF with vacuum magnetic axis of 3.6 m and magnetic field of 2.750 T. The line-averaged electron density is measured using microwave interferometer at R = 3.69 m, and the stored energy is measured using diamagnetic loop.

Figures 3(b) and (c) show four contour plots and horizontal profiles of soft x-ray emission measured by using soft x-ray CCD camera with a 50-μm-thick Be filter and a 0.2-mm-diameter pinhole in different time region which have been indicated in Fig. 3(a). The x-ray image accumulated from 1.04 s to 1.53 s shows the weak x-ray intensity and flat x-ray emission profile which are due to the low electron temperature and electron density in the beginning of discharge. Other three x-ray contour plots accumulated from 23.44 s to 23.93 s, from 33.04 s to 33.53 s and from 61.84 s to 62.33 s, respectively, show that the x-ray emission profile is peaked, flat, then peaked again while both plasma electron density and stored energy are increasing, decreasing and increasing again, as seen in Fig. 3(a). It is seen that not only the x-ray intensity but also the shape of x-ray profile varies as discharge time in this experiment.

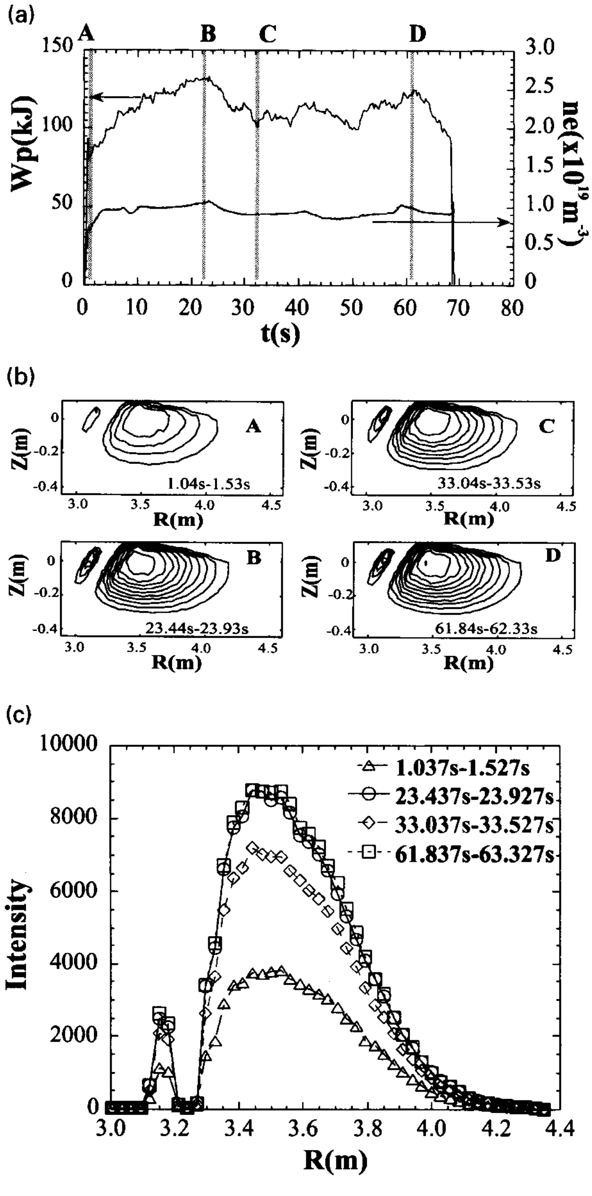

Fig. 3 (a) The time evolution of plasma electron density and stored energy for a long pulse LHD plasma. (b) Contour plots of soft x-ray image measured by soft x-ray CCD camera in four different time regions. (c) Horizontal profiles of soft x-ray emission.

B) Soft x-ray image with different magnetic axes

The soft x-ray image is also measured from LHD plasmas with different magnetic axes. In these experiments, target plasmas are produced by ECH during 0.15–0.75 s. The plasma, with vacuum magnetic axis of 3.6 m and magnetic field of 2.893 T, is heated by ICRF from 0.3 s to 10.5 s. Another plasma, with magnetic axis of 3.75 m and magnetic field of 1.5 T, is heated by NBI from 0.3 s to 9.22 s. Line-averaged electron densities are $0.5 \times 10^{19}\ m^{-3}$ and $3.5 \times 10^{19}\ m^{-3}$, respectively.

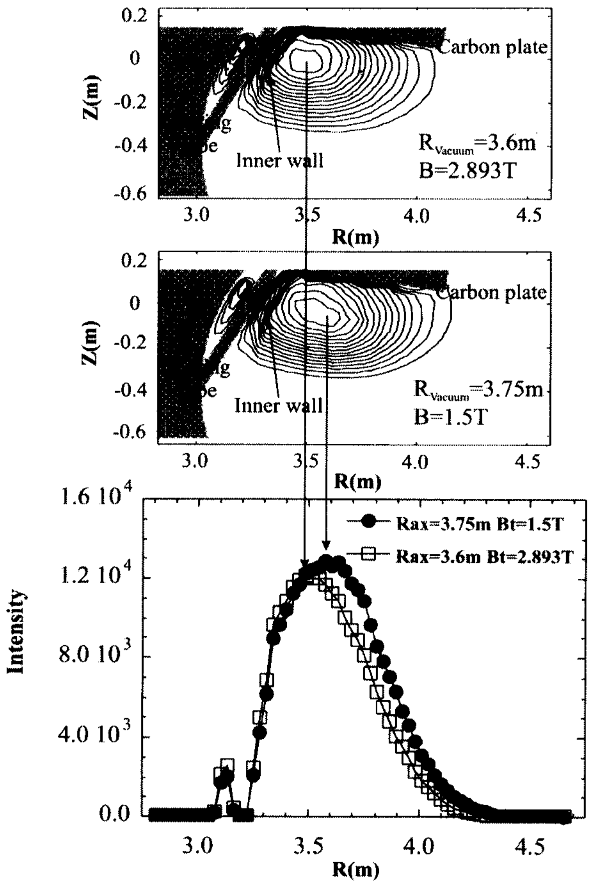

Fig. 4 Contour plots and horizontal profiles of soft x-ray emission measured by soft x-ray CCD camera for different magnetic axis LHD plasmas.

Figure 4 shows the contour plots and horizontal profiles of soft x-ray emission measured with soft x-ray CCD camera from LHD plasmas with different magnetic axes. The soft x-ray image data are integrated from 6.0 s to 6.75 s with 50-μm-thick Be filter and 0.2-mm-diameter pinhole. Although the number of pixel is 1024 × 512, the x-ray image measured is divided to 64 × 32 spatial channels (averaged by 16 × 16 pixels) to reduce noise. The two of steep gradient of x-ray intensity in the contour plot indicate the shadow of carbon plate and cooling pipe, which are installed at #6-T port. The third steep gradient of x-ray intensity at about R = 3.3 m indicates the shadow of inner wall, which gives the excellent reference for the position. The shift of x-ray intensity center, which is due to different magnetic axis for these two discharges, is measured about 11.0 cm in major radius.

4. Summary

The soft x-ray CCD camera system has been developed for long pulse discharge experiments on LHD. The soft x-ray image with time resolution of 0.5 s has been measured during long pulse ICRF and NBI heating experiments. The shift of x-ray intensity center for LHD plasmas with different magnetic axes is measured by using soft x-ray CCD camera.

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