Investigation of a Novel X-Ray Tube for the Calibration of the X-Ray Crystal Spectrometer in the KSTAR Machine

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A novel x-ray tube with a line filament has been developed for the *in-situ* calibration of the x-ray crystal spectrometer (XCS) in the KSTAR machine. The characteristics of the x-ray tube are investigated from the x-ray images obtained by using a pinhole and a CCD detector. It is found that the image has the width of about 0.1 mm, which is much improved as compared with the previous experimental results. In addition, there is a uniform region around the center of the image within its full length of 13.5 mm. This work may lead to the development of a novel x-ray tube with a line focus, which is required for the calibration of the XCS. Experimental results from the investigation of the x-ray tube are presented and the technical issues in a design of the *in-situ* calibration system using the x-ray tube for the KSTAR XCS are discussed.

Keywords: the novel x-ray tube, line filament, x-ray image, the x-ray crystal spectrometer, the KSTAR machine

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1. Introduction

Considerable progress on the research and development of the x-ray crystal spectrometer (XCS) for the KSTAR was done [1–3]. A large area two-dimensional position-sensitive detector (10 cm by 30 cm 2D detector) and a spherically bent crystal are used in the KSTAR XCS in order to provide simultaneous x-ray spectra from a number of lines of sight through the plasma. Thus, plasma rotation velocity and the radial profiles of electron and ion temperature can be obtained from the x-ray image by the KSTAR XCS [1]. A novel x-ray tube, which consists of an anode and a line filament as a cathode, was developed for the performance test of the fabricated 2D detector. The x-ray image from the x-ray tube was measured by using a pinhole and a CCD detector. It was found that the image was a slightly curved line perpendicular to the direction of the filament, and the orientation and the width of the image were changed with the polarity of the filament current and the different anode geometry, respectively [4]. For the application of the x-ray tube to the calibration of the 2D detector for the KSTAR XCS, the experimental investigation on the characteristics of the x-ray image from the x-ray tube using several shaped anodes was carried out. In the experiment, the comparison between the image characteristics such as the line width and the uniformity for different anodes was done to choose the optimal shape of the anode for the application.

In this paper, x-ray tube was described in Sec. 2, the characteristics of the x-ray image from the x-ray tube were presented in Sec. 3, and technical issues on a design for the calibration of the XCS were written in Sec. 4. Finally, the summary was given in Sec. 5.

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2. X-Ray Tube

The x-ray tube consists of a copper anode and a line filament made of a thorium-coated tungsten wire as a cathode, and the anode and the filament are mounted in a vacuum cross tube. Components of the x-ray tube and the assembled x-ray tube are shown in Fig. 1. The diameter and the length of the filament were 0.5 mm and 25 mm, respectively. Anodes of the planned and focusing types were used in the x-ray tube. The tilting angle of the anode surface in the planned anode was selected as 20°, 25° and 30° (see the drawing in Fig. 1). The diameter of the anode was 40 mm.

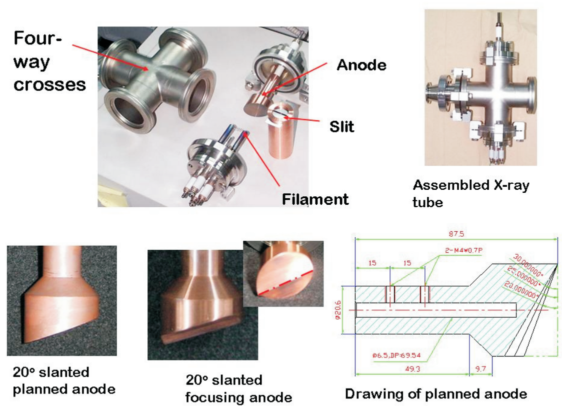

Fig. 1 Photographs of the x-ray tube and two anodes, and drawing of the planned anode. The focusing anode has a sharp knife edge and the planned anode has a flat surface.

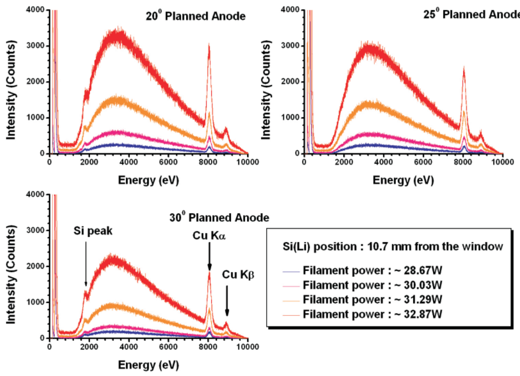

Fig. 2 Energy spectrum from the x-ray tube for three different anodes.

The filament current was varied from 14 to 19 A, and the bias voltage on the anode was varied from zero to +10 kV in the experiment of the x-ray tube. The vacuum pressure inside the x-ray tube was less than 5.0×10^{-5} Torr during the experiment.

The energy spectrum from the x-ray tube was measured with an energy resolving Si(Li) detector, which was calibrated with the Mn Kα and Mn Kβ lines at 5.899 and 6.490 keV from a ^{55}Fe source. In the spectrum, characteristic x-rays were superimposed upon the bremsstrahlung continuum that extended from zero up to the anode bias voltage of 10 kV. The characteristic peaks were Cu Kα and Cu Kβ lines from the copper anode at 8.047 and 8.905 keV, and an additional peak was a Si line that induced by x-rays from the x-ray tube within the Si(Li) detector. At low energies, the intensity was reduced due to the attenuation by materials between the detector and the x-ray tube. There were materials such as a polyester vacuum window for emitting x-ray from the x-ray tube and an air gap, and a beryllium vacuum window in front of the Si (LI) detector. Figure 2 shows the energy spectrum obtained for three anodes with different surface angles in the x-ray tube. The surface angles in the measurement were 20°, 25° and 30°, respectively. The highest intensity of the x-ray is obtained for the 20° planned anode. The intensity becomes strong as the filament current increases. In the previous experiment [4], it was found that the axis of electron trace image on the anode was perpendicular to the direction of the filament after measurement of energy spectrum from the x-ray tube, and the slight curvature in the image might be caused by the magnetic field due to the filament current. In addition, from the observation of thin copper foil covered with the anode during experiment, it could be estimated that the appearance of the line on the anode was due to the energetic electron beam from the filament and x-rays were emitted from the line. Figure 3 shows a typical image on the anode which is similar with the image in the previous experiment.

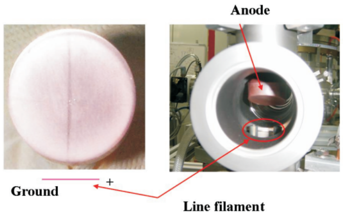

Fig. 3 Image on the anode in the x-ray tube after experiments.

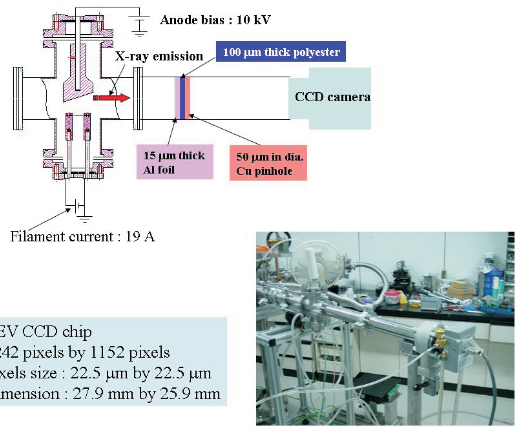

Fig. 4 Experimental set-up for the investigation of the image of x-ray from the x-ray tube.

3. Image Characteristics from the X-Ray Tube

From the observation of the image on the anode, it was required to investigate the image of x-ray from the x-ray tube. Figure 4 shows experimental set-up of the x-ray pinhole camera for the investigation of the image. In the experiments, the 20° planned anode was installed in the x-ray tube. A copper plate with a 50 μm diameter pinhole was installed half way between the x-ray source and an x-ray sensitive CCD camera. The CCD camera consists of 1152×1242 pixels with a pixel size of $22.5\,\mu\text{m} \times 22.5\,\mu\text{m}$. In front of the pinhole, there were a 15 μm thick Al foil to block the visible light from the hot filament and a 100 μm thick polyester film to block the infrared radiation from the Al foil heated due to the filament during the measurement.

An image from the x-ray tube is obtained from the pinhole camera as shown in Fig. 5(a). The maximum width of the image is about 1.2 mm near the center of the image, which is equal to the FWHM obtained from the Gaussian fit for the intensity distribution along the x-axis obtained by binning the pixels along y-axis as shown in Fig. 5(b). The width was close to a half of the FWHM of the calculated thermionic emission current distribution given in Ref. 4. From the intensity distribution along the y-axis obtained by binning the pixels in the x-direction as shown in Fig. 5(c), the total width of the distribution is about 600 pixels or 13.5 mm, which is the length of the image in the y-direction. The length L of the image can be expected

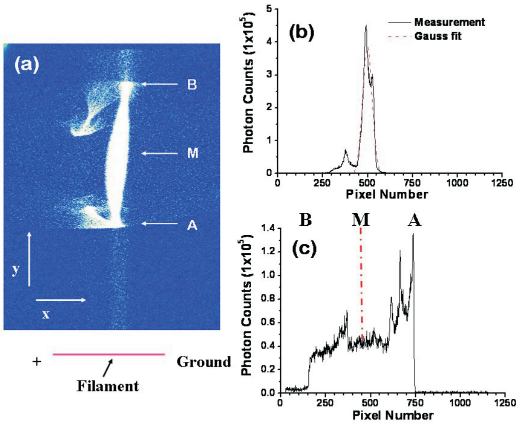

Fig. 5 (a) X-ray image from the CCD pinhole camera in the case of 20° planned anode. (b) Intensity distribution along the x-axis. (c) Intensity distribution along the y-axis. Here 1 pixel is equal to 22.5 µm.

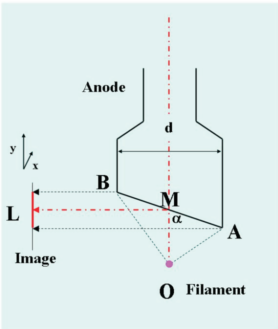

Fig. 6 Geometry of anode and filament in the x-ray tube.

as 14.6 mm from the relation as $L = d \cdot \tan(\alpha)$, where $d = 40$ mm is the diameter of the anode and $\alpha = 20°$ is the tilting angle of the anode surface (see Fig. 6). The intensity distribution along the y-axis is asymmetric, and has a uniform region which locates around the center of the anode surface ('M' in Figs 5(a), 5(c) and 6). The width of the uniform intensity is about 200 pixels or 4.5 mm.

Figure 7(a) shows the image of the x-ray obtained when the polarity of the filament current is reversed and the other experimental conditions are kept the same. The image looks like a mirror image of the image as shown in Fig. 5(a). It means that the orientation of the image changes with the polarity of the magnetic field produced by filament current. Figures 7(b) and 7(c) show the intensity distribution along the x-axis and the y-axis, respectively. The distribution along y-axis is similar with Fig. 5(c) as it is expected. From two distributions, it is found that the maximum width of the image is about 0.96 mm near the center of the image, and the width of the uniform image is about 4.5 mm in the length of 13.5 mm.

Figure 8(a) shows the anode image when the 20° focusing anode is used and the polarity of the filament current is reversed. From two distributions as shown in Figs.

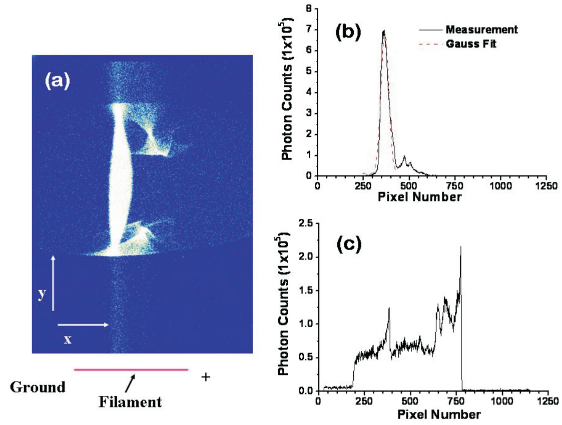

Fig. 7 (a) X-ray image from the CCD pinhole camera in the case of 20° planned anode. (b) Intensity distribution along the x-axis. (c) Intensity distribution along the y-axis.

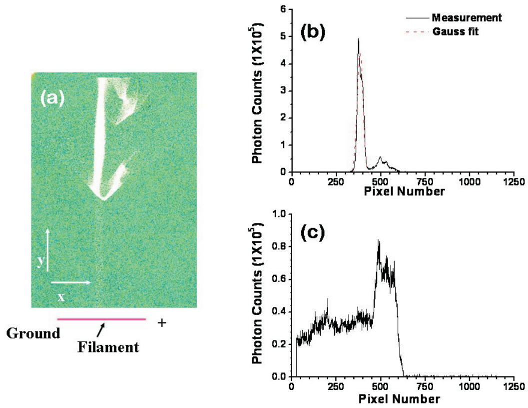

Fig. 8 (a) X-ray image from the CCD pinhole camera in the case of 20° focusing anode. (b) Intensity distribution along the x-axis. (c) Intensity distribution along the y-axis.

8(b) and 8(c), it is found that the maximum width of the image is about 0.73 mm near the center of the image, and the width of the uniform image is about 4.5 mm in the length of 13.5 mm. The uniform region is similar to image by using the planned anode, but the width of the image was improved as compared with that from by using the planned anode.

In this work, there were two major improvements in the x-ray image as compared with the previous experimental results. One was the reduction of the width of the image up to about 1.0 mm, which was a half of the previous value. The other was the appearance of a uniform intensity around the center in the intensity distribution along the y-axis. There had been no uniform region in the distribution obtained from the previous measurement [4]. The length of the uniform region was about 4.5 mm, which corresponded to 33% of the full length of the image.

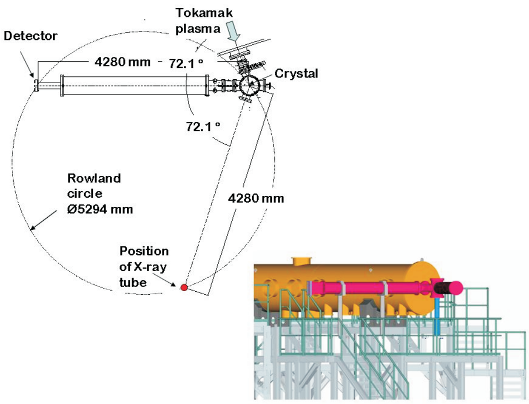

Fig. 9 Experimental arrangement of the XCS at a horizontal port of the KSTAR machine including the position of the x-ray tube for the calibration of the XCS.

4. Technical Issues in the Design for the Calibration of the KSTAR XCS

The x-ray crystal spectrometer (XCS) was proposed to measure the x-ray lines from helium like argon Ar XVII in the KSTAR tokamak plasma [2]. Figure 9 shows a horizontal XCS, providing ion and electron temperature profiles, which will be installed at the horizontal midplane of the KSTAR machine. Detailed specifications of the KSTAR XCS were described in Ref. 2. In the image measurement by using the KSTAR XCS, the uniformity and the spatial resolution of the large area 2D detector are important factors. The x-ray tube with line focusing will be installed in a branch port in the KSTAR machine for the *in-situ* calibration of the XCS as shown in Fig. 9. Some technical issues in the application of the x-ray tube to the calibration are following : It is required that the 2D detector, the crystal and the x-ray source should be positioned on the Rowland circle in order to expose the best focused x-rays on the detector. To get the line focused x-ray source, a slit with a gap of about 50 μm is positioned in front of the x-ray tube, which experienced in the position calibration using a ^{55}Fe source in a laboratory [2]. It is essential to investigate the spatial resolution in the detector required for the image measurement. The additional optic system for scanning x-rays is needed for the exposure of the line focused x-rays on the full area of the detector, which is required for both of the position calibration and the examination of the uniformity in the detector.

5. Summary

The x-ray image from the x-ray tube had a uniform region near the center region and the width of the image was reduced up to about 1.0 mm, which was much improved as compared with the previous experimental results. From experimental results, it was found that the width and the length of the image depended upon the thermionic emission current distribution along the filament and the diameter of the anode, respectively. The further study on the geometry between the filament and anode in the x-ray tube will be carried out to explain the improvements in the image characteristics of the x-ray tube, which is essential to get a further improved line focused x-rays for the calibration of the KSTAR XCS.

Acknowledgments

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