Development of two-channel prototype ITER vacuum ultraviolet spectrometer with back-illuminated charge-coupled device and microchannel plate detectors

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Development of two-channel prototype ITER vacuum ultraviolet spectrometer with back-illuminated charge-coupled device and microchannel plate detectors[a)]

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A vacuum ultraviolet (VUV) spectrometer of a five-channel spectral system is designed for ITER main plasma impurity measurement. To develop and verify the system design, a two-channel prototype system is fabricated with No. 3 (14.4–31.8 nm) and No. 4 (29.0–60.0 nm) among the five channels. The optical system consists of a collimating mirror to collect the light from source to slit, two holographic diffraction gratings with toroidal geometry, and two different electronic detectors. For the test of the prototype system, a hollow cathode lamp is used as a light source. To find the appropriate detector for ITER VUV system, two kinds of detectors of the back-illuminated charge-coupled device and the microchannel plate electron multiplier are tested, and their performance has been investigated. [doi:10.1063/1.3478550]

I. INTRODUCTION

Monitoring of the impurity contents and transports is important for the plasma performance and the lifetime issue of the plasma facing components in ITER.[1,2] The strongest spectral lines of most impurity ions in typical magnetic fusion experiments are within the vacuum ultraviolet (VUV) wavelength range.[3] To clearly identify all relevant impurity species in ITER plasma, the spectroscopy of a high resolution ($\lambda/\Delta\lambda$) is demanded. For this reason, the ITER VUV spectrometer through the equatorial port has been designed as a five-channel spectral system as shown in Table I, so that the high spectral resolution of several hundred could be achieved in the wide range of wavelength of 2.4–160 nm. Wavelength coverage and grating of each channel are optimized to include the suitable spectral lines in the overlap region between the adjacent channels for the relative intensity calibration. In this work, to verify the optimal design of ITER VUV spectrometer system, a two-channel prototype VUV spectrometer has been developed and chosen among the five channels and spectral lines of each channel were measured with the hollow cathode light source. Then, the overall system performance has been investigated.

The selection of an appropriate detector for ITER VUV spectroscopy is one of the interesting design issues. The promising candidate electronic detectors are the microchannel plate (MCP) electron multiplier with camera and the back-illuminated charge-coupled device (CCD). So far, the MCP detectors have been widely used for VUV spectroscopy.[4] However, the back-illuminated CCD detectors recently emerged as alternatives.[5] Each detector of MCP and back-illuminated CCD has pros and cons, respectively. The MCP detector has a high quantum efficiency of about 10%–60% for the VUV light,[6] but the spectral resolution is rather poor with about 80 μm,[7] and the required vacuum is high (10^{-7} Torr) for a safe operation. On the other hand, it is noted that the back-illuminated CCD has a good point where it does not need high vacuum facility while having a similar quantum efficiency of 41%–45% at VUV wavelength of 10–100 nm. However, the utilization of the back-illuminated CCD might give a concern such as the visible stray light noise. In this paper, by using the fabricated prototype system, two electronic detector candidates are investigated in their performance and usefulness to give technical criteria for decision of the ITER VUV detection.

II. EXPERIMENTAL SETUP

The ITER prototype VUV spectrometer employs two channels, No. 3 (14.4–31.8 nm) and No. 4 (29.0–60.0 nm), among the designed five channels in Table I. The developed prototype system is illustrated in Fig. 1. The pumping system is positioned at the bottom of the chamber so the entire system can be moved simultaneously. The base pressure of the vacuum chamber is high 10^{-8} Torr and the pressure of the grating chamber during the operation is as low as 10^{-7} Torr due to MCP detection. The mirror chamber is located between the light source and the slit with a 70° angle of incidence for installation of a convex mirror and differential pumping. The distances from the source to the collimating mirror and from the collimating mirror to the slit are 700 and 575 mm, respectively. A single slit with width of 90 μm and height of 20 mm is used for both channels and two gratings for each channel are placed inside a single vacuum chamber at different places with the height difference of 20 mm, which is the minimum value to prevent the interference between two gratings.

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TABLE I. Designed optical distances and angles for each five channels.

	Spectral channel				
	1	2	3	4	5
Wavelength range (nm)	2.4–7.8	7.0–16.2	14.4–31.8	29–60	55–159
Mean line width (nm)	0.022	0.039	0.061	0.096	0.285
Spectral resolution ($\lambda/\Delta\lambda$)	~232	~296	~382	~465	~377
Incidence angle (deg)	86.5	83	70	62	45
Distance: slit to grating (mm)	650	500	543.5	400	300
Distance: grating to det. (mm)	~650	~500	~543.5	~400	~300
Groove density (lines/mm)	1547.5	2177.8	1865.2	1929.0	1004.6

Each holographic diffraction grating (Jobin Yvon Co.) has the toroidal shape to implement higher spectral resolution and also to collimate the light into the linear image plane. The radii of curvature of each toroidal grating are optimized from the ray-tracing calculation to give the high spectral resolution as well as the high spectral etendue of about 10^{-5}–10^{-4} etendue/mm^2 sr.[4] The Au coating for Ch. 3 and the Pt coating for Ch. 4 are selected for a high reflection of gratings. By the suitable design of the grating groove density and groove profile, the second order grating efficiency is made to be less than about 10% of the first order grating efficiency. The dimension of each grating is about 25×32 mm^2 (height$\times$width) with an effective area of 12×28 mm^2, so about 20 mm height difference between two gratings is required. Because of these grating displacements from the optical axis, the orientations of the spectral image lines on the detector may be slightly inclined if two gratings are parallel aligned. Hence, the normal image lines are adjusted by a slight rotation of grating based on the ZEMAX modeling.[8] Therefore, the five-axis stage on detector and the six-axis stage on grating are implemented for an accurate alignment. In addition, the baffles are installed on each port of vacuum chambers to block the stray light.

The hollow cathode lamp is adopted as a VUV light source, and for these experiments the discharges are operated in the condition of current of 2 A and dc voltage of 400 V.

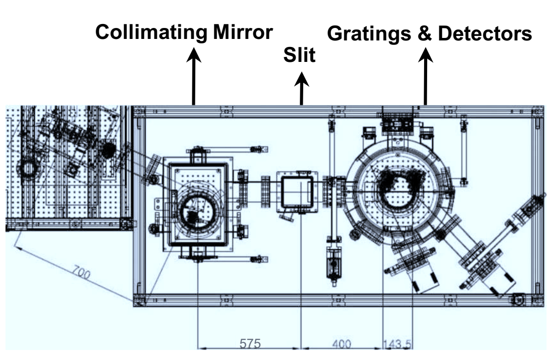

FIG. 1. The VUV spectrometer prototype system. Two gratings with height difference of 20 mm, one slit, and two different detectors were installed. The convex mirror was used to collimate light to the slit.

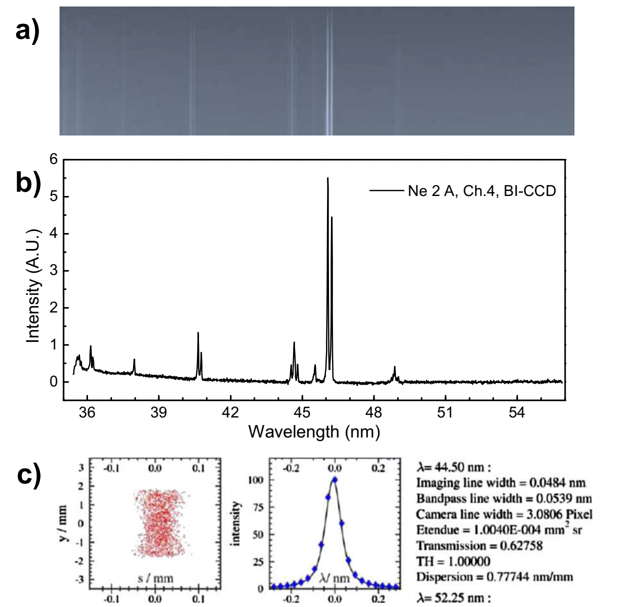

FIG. 2. (Color online) (a) Back-illuminated CCD image at Ch. 4 in Ne 2 A discharge, (b) spectrum with vertical binning of Back-illuminated CCD image, and (c) ray-tracing calculation result for the 44.50 nm line.

The Ne or He inert gas is used, because intensive emission lines of Ne and He exist in the wavelength range of 20–60 nm.[9] The power output of He II 30.4 nm line from the hollow cathode lamp at the above discharge condition is reported to be approximately 5.9×10^{12} photons/s cm^2 sr, which is comparable to the emission output of 2.8×10^{13} photons/s cm^2 sr by the typical impurity C VI line of 2.85 nm from TEXTOR plasmas.[2]

For a study of the ITER VUV detector, two kinds of detectors of the MCP electron multiplier with camera (McPherson Co.)[10] and the back-illuminated charge-coupled device (PIXIS-XO, Princeton Instruments Co.) are installed at the image planes with manipulation stages at the port of each channel. The MCP has 40 mm diameter with CsI coating, 10 μm pore size, 12 μm pitch length, and L/D ratio =60:1. It is accompanied with a phosphor screen, a fiber optic taper, and a visible CCD camera, so that the effective resolution of the MCP detector would be about 80 μm. The MCP is operated with the bias voltage of 800 V and the phosphor screen voltage of 4950 V. On the other hand, the back-illuminated CCD has the imaging area of 27.6×6.9 mm^2 with pixel size of ~13.5 μm and is thermoelectrically cooled to −50 °C in the experiment. So, the back-illuminated CCD with ~13.5 μm pixel size would be compared with the MCP detector with ~80 μm resolution.

III. RESULT AND DISCUSSIONS

In experiments, the spectral image obtained from Ch. 4 in the Ne discharge of $I_{hc}=2$ A with the back-illuminated CCD detector is shown in Fig. 2. The measured full width at half maximum (FWHM) of the Ne II spectral line of $\lambda=46.07$ nm is 0.045 nm in Fig. 2(a) of the image and Fig. 2(b) of the vertical binning. The measured FWHM is in a good agreement with the calculated FWHM of 0.048 nm for $\lambda=44.50$ nm, which is the calculated spectral resolution by ray-tracing code,[1] as shown in Fig. 2(c). This result implies

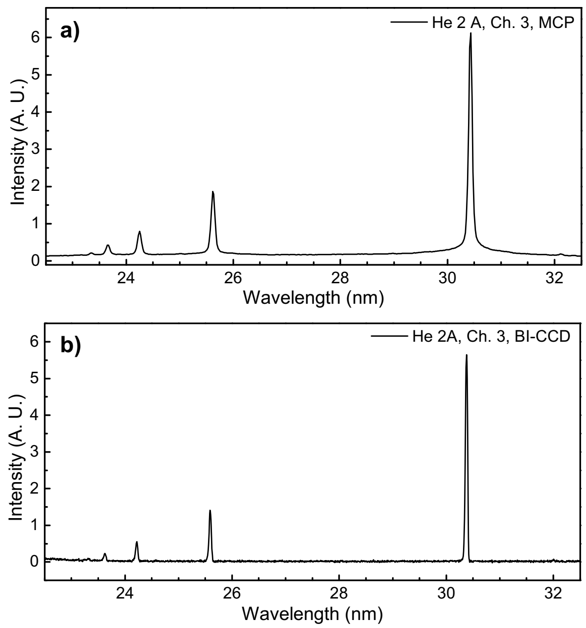

FIG. 3. (a) MCP spectrum at Ch. 3 in He 2 A discharge and (b) back-illuminated CCD spectrum at Ch. 3 in He 2 A discharge.

that the experimental setup, i.e., optical distances and components, is appropriately implemented in accordance with the designed optical parameters. In addition, the coincidence between the calculated imaging line width and the measured line width shows that the back-illuminated CCD detector has a good performance for VUV detection, and there is little broadening of the line width due to the back-illuminated CCD detection, because the pixel size of 13.5 μm corresponds to ~0.006 nm width, which is negligible to the calculated imaging line width of 0.048 nm. High background signal near wavelength 36–39 nm in Fig. 2(b) is due to the visible light noise, but it would be reduced if suitable baffles are fitted to block the stay light.

For further understanding of VUV detectors, i.e., MCP and back-illuminated CCD, experiments with these different detectors have been performed at Ch. 3 in the same condition of He discharge at $I_{hc}=2$ A. Figure 3 shows the measured spectra with different detectors, (a) MCP and (b) back-illuminated CCD. The $\lambda=30.4$ nm of He II line is chosen for the comparison, and in this case, the calculated imaging line width from the ray-tracing program is about 0.038 nm for $\lambda=31.80$ nm. As shown in Fig. 3, the measured FWHM of 30.4 nm He II line is (a) 0.080 nm for the MCP detector and (b) 0.046 nm for the back-illuminated CCD detector. In other words, the spectral resolution of the back-illuminated CCD is superior to the MCP detector in this experiment setup. This difference of spectral resolution is caused by the fact that the back-illuminated CCD shows negligible effect on instrumental line width, while the MCP detection system, composed of microchannel plate, fiber optic taper, and visible CCD camera, has a relatively poorer detector resolution. The effective spatial resolution ~80 μm of the MCP detection system corresponds to ~0.034 nm line width in wavelength, so that the measured 0.080 nm width of the MCP detection is a considerable value, in case of taking into account a convolution between two line widths of ~0.034 and 0.038 nm. However, it should be noted that the detector size of the back-illuminated CCD of 27.6 mm is smaller than the MCP diameter of 40 mm, so the equivalent resolution of the back-illuminated CCD would be reduced approximately to 70% (=27.6/40.0) of the current overall resolution. In addition, the back-illuminated CCD spectrum is obtained from vertical binning of about 4 mm height of the image, while the MCP spectrum is obtained from full vertical binning of the image. The error by this difference of binning is estimated to be less than about 20%. Consequently, it is deduced that the back-illuminated CCD shows better or at least comparable spectral resolution compared to the MCP detector, so the back-illuminated CCD could be a good candidate of the ITER VUV spectrometer detector, because the back-illuminated CCD does not need the local high vacuum condition and partial pumping during ITER operation.

IV. CONCLUSION

In this article, the experimental results of the design and performance of the two-channel ITER prototype VUV spectrometer are described. From the spectral measurements of He and Ne discharge emissions, the overall system performance has been verified according to the optical design of ITER VUV system. It is noted that the measured spectral resolution is in a good agreement with the calculated spectral resolution and the design parameters. The detector comparison study demonstrates that the back-illuminated CCD has a higher spectral resolution than the MCP and similar sensitivity in the VUV wavelength ranges, so that the back-illuminated CCD could be a good candidate for ITER VUV detector with no high vacuum condition required during operation. In addition, in the experiment, it is shown that the visible light noise concern of the back-illuminated CCD may not be a significant issue in case of the utilization of baffles inside the vacuum chamber.

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