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Design and fabrication of the prototype system for development of the ITER vacuum ultraviolet spectrometers

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Introduction: The ITER vacuum ultraviolet (VUV) survey spectrometer for measuring impurities through equatorial port has been designed as a 5-channel spectral system, which is based on the design concept of the high-efficiency XUV overview spectrometer (HEXOS) system. [1] Wavelength ranges and grating specifications of each channel are optimized to meet ITER requirements of measurement. In this article, a prototype system, which was designed and fabricated for development of the ITER VUV survey spectrometer with a calibration source of hollow cathode lamp [2], is described. The prototype spectrometer employs two-channel system, i.e., No. 3 and No. 4 among five channels of the ITER VUV system. (Table 1) Two gratings are placed at different positions in a single vacuum chamber. The overall ray tracing from the light source to the detectors was calculated and analyzed using the ray tracing software developed by the FZJ and the ZEMAX.

Five-channel spectral system for ITER vacuum ultraviolet survey spectrometer: The VUV survey spectrometer for monitoring core plasma through equatorial port is designed to use a 5-channel spectral system. As shown in Table 1, the wavelength range 2.3 nm - 160 nm are divided into five channels, so that each channel includes important impurity lines with relatively high resolutions. Some overlaps of wavelength ranges are made for cross calibrations between spectrometers.

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
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 (degree)	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

Table 1. *The optimized optical distances and angles for each five channel.*

Design process: In the design process, a toroidal holographic diffraction grating is used as the only optical and dispersive component. As a detector, an open MCP (multi channel plate) with about 40.96 mm diameter is considered.[3] In the first step of the system design, distances between optical components, i.e., slit, grating, and detector, were optimized to minimize the interference between channels. In the following step, radius of curvature of grating, entrance slit size, and solid angle were calculated to give the minimum line width at a predefined etendue (0.2-1 x 10^{-4} mm^2sr) [4], using a special software developed by the FZJ. Then, the groove density and shape of each grating were optimized to give a high efficiency of the first order and a low efficiency of the second order using the software PCGRATE from International Intellectual Group, Inc. As results of the design process, the optical distances and angles are obtained, as shown in Table 1. The overall spectral resolutions ($\lambda/\Delta\ \lambda$) are ranged from about 232 (Ch. 1) to 465 (Ch. 4).

The prototype system with two channel spectrometer: The prototype system with a calibration source of hollow cathode lamp was designed and fabricated. As shown in Fig. 1(a), the pumping system is installed at bottom and the prototype system can be moved totally. The prototype spectrometer is designed with two channels of No. 3 (14.4 nm – 31.8 nm) and No. 4 (29.0 nm – 60.0 nm). Two gratings are placed at different positions in a single vacuum chamber as shown in Fig. 1(b). The distances and angles of the system are given by the values of No. 3 and No. 4 channels in Table 1. For installation of the toroidal mirror with 70 deg. angle of incidence, the toroidal mirror chamber is used. The distances from the source to the toroidal mirror and between the toroidal mirror and the slit are 700 mm and 575 mm, respectively. The slit size is 90 μm width, 4 mm height.

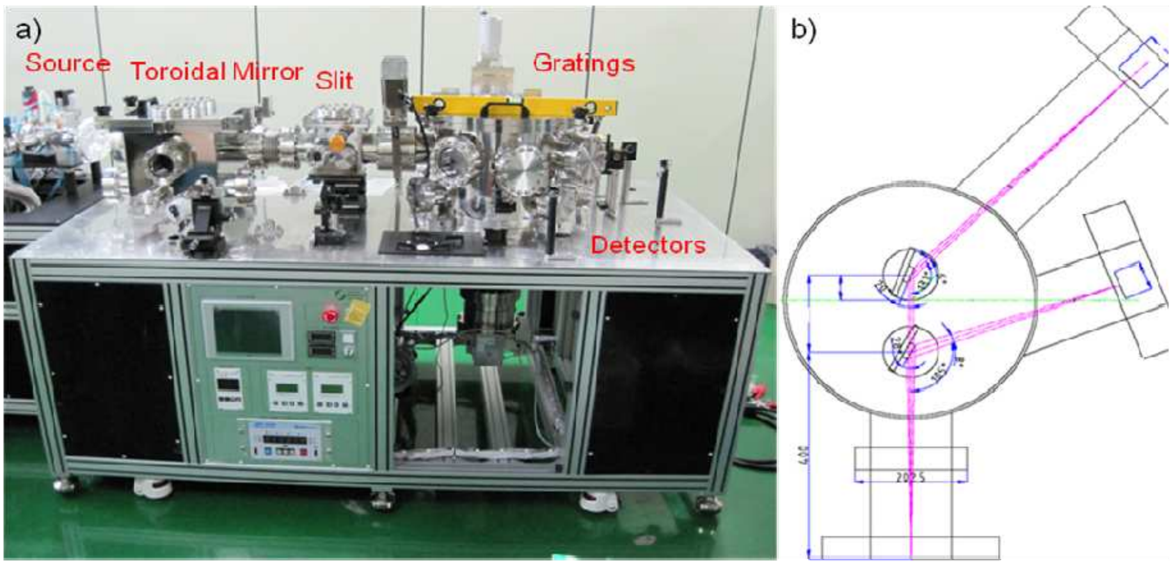

Figure 1. *a) The VUV spectrometer prototype system. b) The top view of the grating chamber.*

Components of the prototype system: Holographic diffraction gratings with toroidal shape are used to implement higher spectral resolution and to collimate the light. Two gratings are positioned with the height difference of 20 mm, which is the minimum value to prevent the interference between gratings. The dimension of each grating is about 25 mm (height) x 25 mm (width) with effective height of 12 mm, therefore about 20 mm displacement between two gratings is required. A single common slit is used for both channels, and each grating height is positioned at 10 mm high or low from the slit center, as shown in Fig. 2. Because of these grating displacements from the optical axis, the orientations of the spectral lines on the detector are slightly inclined, but the orientations of spectral lines could be corrected to the normal spectral lines by some slight rotation of grating in ZEMAX modeling. Therefore, the 5-axis stage on detector and the 6-axis stage on grating are implemented, for accurate alignments. In addition, the baffles are installed on each port and vacuum chamber to block the stray light. As a detector, MCP of 40 mm diameter with CsI coating and L/D ratio = 60:1 is used and accompanied with a phosphor screen, a fiber optic taper, and a CCD (26 μm pixel).

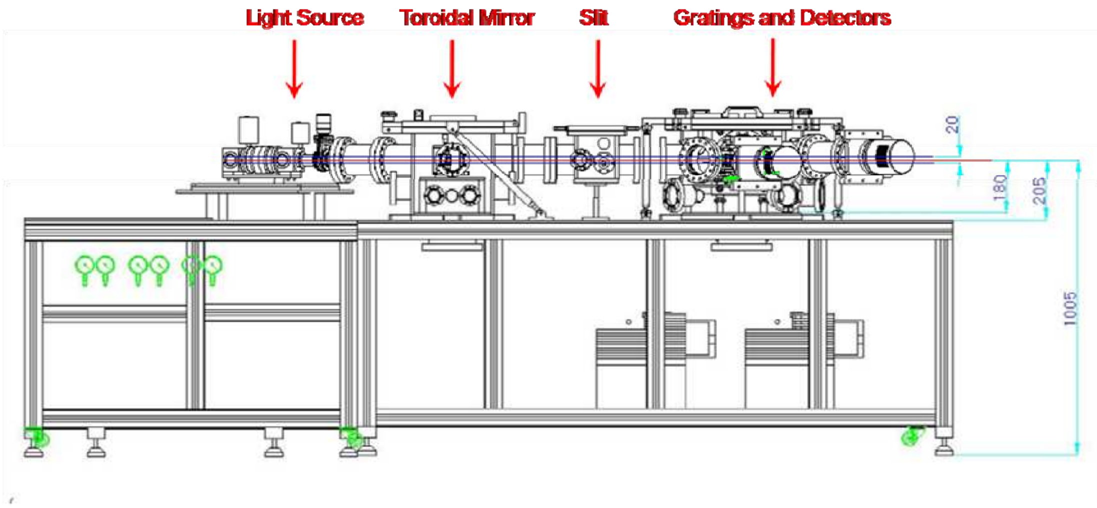

Figure 2. *The front view. Height difference between gratings is 2 cm from center to center.*

Toroidal mirror design: The overall ray tracing from the hollow cathode lamp to the detector including the toroidal mirror, the slit, and the grating was calculated using the ZEMAX program, as shown in Fig. 3(a). The toroidal mirror is used to focus the source light to the slit. The radius of curvature of the toroidal mirror in the meridional plane (horizontal plane) is given by the equation,

$$\frac{1}{r_i}+\frac{1}{r_r}=\frac{2}{R_m \cos\alpha}, \tag{1}$$

where r_i is the distance between light source and the toroidal mirror, and r_r is the distance between the toroidal mirror and the slit. [5] α is the incident angle on the toridal mirror, and R_m is the radius of curvature of the toroidal mirror in the meridional plane. From Eq. (1), R_m was calculated for r_i = 700 mm, r_r = 575 mm, and α =70 deg. In the sagittal plane, the radius of curvature R_s and the size (height) of toroidal mirror was optimized to make a focused image on the slit with 4 mm height (slit width = 90 μm), and to make rays after slit illuminate two gratings coincidentally. From optimization processes using Eq. (1) and the ZEMAX, R_m =1843 mm, R_s = 200 mm radius of curvature, and 50 mm (width) x 50 mm (height) size of the toroidal mirror are obtained.

Calculation of the grating efficiency and the reflectivity of a toroidal mirror: With the help of the software PCGrate, the grating efficiency for the first order diffracted light is calculated for Ch. 3. The toroidal mirror reflectivity is also calculated for the Au coating Mirror (with surface roughness 0.5 nm) for the incidence angle 70 deg. The mirror reflectivity for this wavelength range is about 0.3-0.4 and the grating efficiency is about 0.1. By multiplying the two factors, the efficiency of the total system is calculated as shown in Fig. 3 (b).

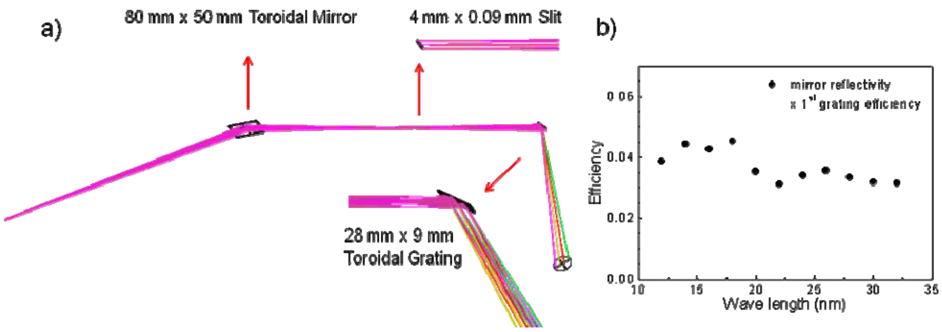

Figure 3. *a) Ray tracing by ZEMAX program. b) Calculated efficiency.*

Summary and future work: In this work, the prototype spectrometer was designed and fabricated with two channels of No. 3 (14.4 nm – 31.8 nm) and No. 4 (29.0 nm – 60.0 nm) among 5 channels of ITER VUV system and two gratings are placed at different positions in a single vacuum chamber. As a backup study of the VUV detector, a back-illuminated CCD is under consideration. It is noted that while the quantum efficiency of MCP is higher than the BI CCD, the spatial resolution of BI CCD (~20 μm) is better than MCP (~80 μm). By using the prototype spectrometer system, a comparison study on the two different VUV detectors (MCP and BI CCD) will be conducted for development of the effective ITER system.

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