The study of experimental apparatus for vacuum ultraviolet spectroscopy with high spectral resolution

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The performance of a conventional normal incidence (15°) vacuum ultraviolet monochromator was studied with the main emphasis on the spectral resolution available. It was shown that high diffraction orders may be obtained efficiently for the wavelengths as low as 500 Å. Main mechanisms responsible for the observed broadening of the spectral lines emitted by VUV capillary source have been discussed. The possibility to have spectral resolution up to 0.2 Å in VUV region, which is required for fine high-temperature plasma spectroscopy investigations, by use of high diffraction orders (up to 5th), has been demonstrated. Some ways for further enhancement of spectral resolution are proposed.

A performance de um monocromador convencional de ultravioleta no vácuo com incidência normal (15°) foi estudada com ênfase especial na sua resolução espectral. Mostrou-se que ordens de difração mais altas podem ser obtidas eficientemente para comprimentos de onda abaixo de 500 Å. Os principais mecanismos responsáveis pelo alargamento observado em linhas espectrais emitidas por uma fonte capilar de VUV são discutidos. Demonstrou-se a possibilidade de obtenção, por meio de ordens de difração altas (até a 5 a), de uma resolução espectral de até 0.2 A na região VUV. Resoluções espectrais desta ordem são requeridas para investigações por espectroscopia fina em plasmas de alta temperatura. Os meios para um subsequente aprimoramento na resolução espectral são sugeridos.

I. Introduction

Vacuum ultraviolet (VUV) spectroscopy is an important tool for studying of the present thermonuclear plasmas[1,2]. The most intensive lines of the majority of plasma atoms and ions belong to VUV or to X-ray spectral ranges. Many important plasma properties as ion temperature, plasma rotation or turbulence may be evaluated by means of the measurements of the line widths and shifts in VUV region. However, relatively high spectral resolution is required for these purposes. Resolving power of the spectral device should exceed 10^4, which is hardly attained with conventional apparatus.

In Table 1 some impurity lines, often used in plasma studies, are presented. Doppler widths $\Delta\lambda_D$ for these lines, corresponding to the ion temperature (T_i) range expected for medium size plasma devices (tokamak, theta-pinch), are also shown.

From the data presented in the Table 1, it follows that for measurements of ion temperatures in the range of interest, the spectral resolution of the monochromator should be at least 0.2 Å, i.e. resolving power $\lambda/\Delta\lambda$ - better than 10^4.

This work presents the results of the study of spectral resolution available with conventional normal inci-

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dence VUV monochromator. It has been shown, that resolution may be substantially improved by use of the highest orders of diffraction, which can be obtained with relatively high efficiency.

Table 1. Doppler width (in Å) for some lines, often used in plasma studies.

Line	T_i = 100 eV	T_i = 500 eV
O III 835 Å	0.16	0.36
O VI 1032 Å	0.19	0.45
O VII 1623 Å	0.31	0.70
C IV 1548 Å	0.34	0.77
C V 2271 Å	0.51	1.13

II. Experimental techniques

For VUV spectroscopy we use a McPherson 225 Model vacuum monochromator (the same model was used in [3]), which uses normal incidence (15°), Rowland geometry, with one meter curvature concave grating (Al, overcoated with MgF_2). The grating has 600 grooves/mm, and it is blazed at 2000 Å. The reciprocal linear dispersion of the monochromator with this grating is 16.6 Å/mm.

An EMI 9635B photomultiplier with bialkali photocathode was used as a detector of VUV radiation. Sodium salicylate scintillator placed behind the exit slit was used to reemit VUV radiation to visible region. Sodium salicylate is known to have almost constant efficiency about 100% in UV and VUV spectral range with maximum emissivity at 4000- 4500 Å [4], which fits well to the bialkali photocathode spectral sensitivity.

A windowless capillary discharge was used as a VUV light source for wavelength calibrations and evaluating of the monochromator parameters. The source was operated with hydrogen or helium filling gases at pressures up to 10 Torr, with the discharge current of 100 mA. The differential pumping of the entrance slit volume was used to decrease the gas pressure in this volume and in the main monochromator chamber as well, in order to reduce possible line self absorption. To distinguish emission of different diffraction orders, filters with different cut-off lower wavelength limits (lithium fluoride-1040 Å, quarts-1750 Å, glass-3000 Å) were used. Spectral profiles of the line emission of hydrogen atoms, helium atoms and ions as well as oxygen impurity atoms in different orders of diffraction (up to 5th order) in a wide spectral region (500-6100-Å) were recorded.

III. Results of experiments and discussion

The lower wavelength limit available with this monochromator is at least 500 Å. The efficiency of the grating falls down rapidly for wavelengths shorter, than hydrogen Lyman a (1215 Å), however much slower than was observed in [3], likely due to the better quality of the grating employed. The reflectivity of the grating drops about one order of magnitude as the wavelength changes from 1200Å to 1000 Å. With further reduction of the wavelength the reflectivity changes only slightly. This is consistent with the results of [5], where the same behavior of the MgF_2 overcoated grating reflectivity was observed, with the fast drop of efficiency in the wavelength region shorter than 1200 Å being followed by slow oscillations at the level less than 10% for wavelengths as low as 700-500 Å.

The results of the line profile measurements in different orders of diffraction M are presented in Table 2, where measured spectral widths (FWHM - full width at half maximum) and relative intensities for some observed lines are listed. Line widths as referred to the first diffraction order are also shown (in parenthesis).

As it can be seen from the Table 2, the relatively high reflection efficiency for up to 4th diffraction order may be obtained, depending on the resulting wavelength ($\lambda * M$).

Grating efficiency falls down rapidly, when $\lambda * M$ goes apart from the blazing angle, corresponding to the wavelength of 2000 Å.

3. For the first diffraction order the minimum recorded values of the line width were about 0.35 Å and 0.55 Å for the slits of 10 and 25 microns, respec-

tively (see Fig.1). The excess of these values over those defined by the width of the slits (0.17 and 0.42 Å, respectively) for hydrogen and especially for helium resonance lines partly m..y be explained by the line broadening caused by self absorption of line emission [4] . The self absorption may occur inside the VUV source itself, in the entrance slit volume and in the monochromator main chamber. This effect was quite evident for helium lines, resulting in a well-defined dip observed in the center of the line spectral profiles. Self absorption of helium lines was only partly eliminated by use of differential pumping. This means, that even in this case the pressure of helium in the main chamber remained high enough for substantial line absorption in the 2 m length way inside the main chamber with helium pressure of about 10^{-4} Torr. Note, that when emission originates from the species existing only in the source volume, but not in the main chamber (for instance, H I, O I and He II), self absorption in the main chamber should be negligible. Indeed, the obtained line widths were at a minimum for these emitting species. However, even for these cases the observed first order line widths were no less than 0.35 Å. Thus it was defined mainly by the instrumental bandwidth. Regarding the longer wavelengths, some increasing of observed line widths was evident (see for example, data for 2nd, 3rd and 5th orders of hydrogen Lyman a line in Table 2). In part this may be a result of astigmatism, which is intrinsic for monochromators with concave gratings. However, the effect of astigmatism (and possible line curvature as well) on the line width was in fact minimized in our measurements, since the light source had a rather small output aperture (about 4 mm) placed just in front of the entrance slit. So, only the central part of the slit was illuminated by the light. Hence, the observed increase of the line widths with wavelength was more likely due to some defocusing of the monochromator as the wavelength scanning from WV to visible region in this geometry may be accompanied by the increasing deviation of the slits from their optimum positions on the Rowland circle. This assumption is confirmed by the fact that the equal widths were observed for the lines of different orders, but obtained for the same position of the grating (i.e., the same value of the resulting wavelength $\lambda * M$) It is clear from the data, shown in the Fig.2, which presents the dependence of observed widths on $\lambda * M$ number for some H I and O I lines. For different diffraction orders of hydrogen Lyman α the line widths (as referred to the first order) are also shown by dashed curve.

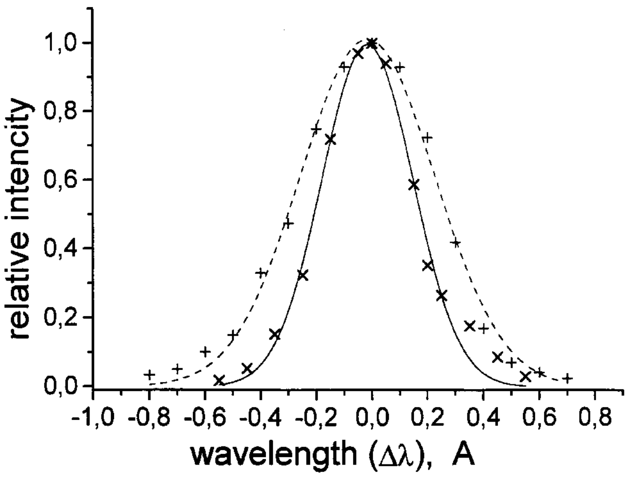

Figure 1. Hydrogen Lyman a line spectral proffles, observed with different slit widths d: 10 microns (solid) and 25 microns (dashed). The center of line corresponds to $\Delta\lambda = 0$.

Thus, in these experiments it has been shown that the possibility to obtain high diffraction orders with high efficiency for the wavelengths down to 500 Å exists. The effective spectral resolution obtained (taking into account the diffraction order) is as low as 0.2Å for concave grating with 600 grooves per mm. By use of classically ruled gratings with the higher number of grooves per mm the further improvement of the resolution may be obtained. For example, it may exceed 0.1 Å for 1200 gr./mm and 0.05Å (corresponding resolving power of about $5 * 10^4$) for 2400 gr./mm. In order to increase the efficiency of the grating for the wavelength region shorter than 1200 Å, the use of other overcoatings (W, Re, Os) instead of MgF_2 is preferable [6]. For instance, W overcoating may increase the signals obtained in 500-700 Åregion by a factor of 3 (see [5,6]).

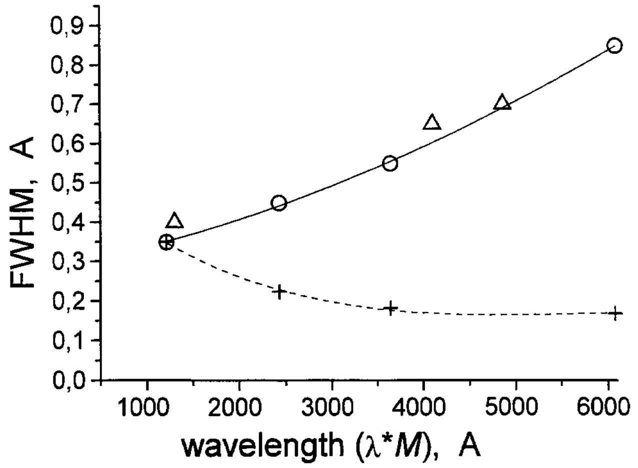

Figure 2. Dependence of observed line widths on $\lambda * M$ number: circles - Lyman α line 1, 2, 3 and 5th orders (solid), triangles- H β (4861 Å), H δ (4101 Å) and OI (1302 Å), crosses - Lyman α line width referred to the first order (dashed).

IV. Conclusion

The performance of conventional normal incidence VUV monochromator was studied with the main emphasis on the spectral resolution available. The main mechanisms, responsible for the observed line broadening, have been discussed. The possibility to have spectral resolution up to 0.2 Å in VUV region for fine spectroscopy studies with this monochromator by use of high diffraction orders (up to 5th) has been demonstrated.

In further experiments we are going to use the W-overcoated grating with 1200 gr./mm, in order to attain spectral resolution better than 0.1 Å for wavelength as low as 300 Å. The development of multichannel detection of VUV spectral line profiles by the use of an OMA (optical multichannel analyzer) techniques is in progress, as well as the search for the efficient VUV-visible light converters. These tools will be used for the investigations of high temperature pulse plasmas (theta-pinch, tokamak) with fine spectral resolution.

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Table 2. Line widths and relative intensities for some lines observed in different diffraction orders, with slit widths *d* (for both entrance and exit slits) of 10 or 25 microns.

Filling gas	Line	Diffraction order, M	$\lambda * M$, Å	FWHM, Å d=10 μm	FWHM, Å d=25 μm	Relative intensity	Note
Hydrogen	Lα	1	1215.67	0.35	0.55	1.0	
		2	2431.34	0.45	0.60	0.75	a)
				(0.22)	(0.30)		b)
		3	3647.01	0.55	0.60	0.07	a)
				(0.18)	(0.20)		b)
		4	4862.68	-	-	-	c)
		5	6078.35	0.85	0.85	0.004	a)
				(0.17)	(0.17)		b)
	Hβ	1	4861.33	0.70	0.70	0.45	a)
Helium	He II Lα	1	1215.17	0.35	-	1.0	
		2	2430.34	0.40	-	0.7	d)
	He I, 584Å	2	1168.66	0.60	0.60	1.0	
		3	1752.99	0.80	1.0	1.2	e)
		4	2337.32	1.0	1.2	0.9	e)
	O I, 1302Å	1	1302.17	0.4	-	-	

a) Relatively to La first order line intensity. b) As referred to the first order. c) Not resolved on the strong Hβ wing background. d) Relatively to the first order line intensity. e) Relatively to the second order line intensity.