The Role of Higher Diffraction Order to Determine Ion Temperature in Vacuum Ultraviolet Region Using Multichannel Detector

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Vacuum ultraviolet region, 50nm to 320nm, of tokamak plasma light emission from NOVA-UNICAMP and TCABR has been analyzed using one-meter focal length VUV spectrometer and open MCP/CCD detector. About 86 spectral emissions are detected, where 35 lines are from first diffraction order and others are from second, third and fourth diffraction order. The first order spectral lines are mainly emitted below 150 nm, and the region from 100 nm to 320 nm is useful to observe higher diffraction order lines. Impurity species such as OII, OIII, OIV, OV, OVII, CII, CIII, CIV, are very common lines also present in the larger tokamak plasma. The use of higher diffraction order emissions and the control of pixel distribution over Gaussian profile show to be very important in order to obtain correct ion temperature, due to the narrow Doppler broadening in the VUV region and large instrumental broadening. We conclude that the effect of Gaussian width difference is caused by the wavelength interval covered by each pixel on the Gaussian fit.

vacuum ultraviolet spectrometry, MCP/CCD multi-channel detector, tokamak plasma diagnostic, ion temperature measurements, higher order diffraction.

1. Introduction

The line emissions from impurity particles in tokamak plasmas are routinely used in many analyses as radiation power loss, transport/rotation phenomena, and ion temperature measurements in different regions of the plasma [1-3]. In addition, many impurity emissions met in divertor or edge regions of large tokamaks [4, 5] can be comparable to the plasma produced by smaller tokamaks such as TCABR [6].

The traditional forms to support these studies are the measurements in the VUV region of ion line Doppler broadening and/or shifting [7, 8], and effective charge calculations using calibrated absolute intensity measurements. However in VUV region, the Doppler broadening is smaller than in the visible region due to its wavelength, the absolute calibration is much more arduous, and measurable spectral range are smaller compared to the visible region [9].

Moreover, several first diffraction order spectral lines are emitted below 150 nm, so the interval from 100 nm to 320 nm is a useful region to observe higher diffraction order lines. Impurity species as OII, OIII, OIV, OV, OVII, CII, CIII, CIV, are very common lines also present in the larger tokamak plasmas [10-13].

In previous works, we presented over 100 spectral lines from 50 nm to 320 nm, obtained from TCABR tokamak (R=0.615 m, a=0.18 m, I_p=100 kA, B_T=1.0 T) [14], and an initial study of higher diffraction order lines was started [15].

In this work we show that the very small NOVA-UNICAMP (R=0.30 m, a=0.06 m, I_p=10 kA, B_T=0.8 T) tokamak [16] also presents a similar spectra. Also, detail studies about influences of pixel distribution over Gaussian profile, in order to determine ion temperature using higher diffraction order lines is discussed.

2. Higher Diffraction Order of the Spectral Lines

The VUV spectrometer is a 225 McPherson, which has one-meter focal length and 82.5° incidence. It is provided with a 1200 groves/mm concave grating with Al and MgF_2 coating. The spectrometer has the reciprocal linear dispersion of 0.83 nm /mm and can cover 50nm to 350 nm.

The multi-channel detector, consisting of an open 40 mm diameter MCP plate (BrightView XUV2010 G, XSI

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instruments) is coupled to a CCD device (Marconi CCD30-11, Andor Technology) with 1024x256 pixels, and each pixel has 26 micrometers. The MCP plate is coated with CsI and each channel have 10 micrometers diameter. A reducing coherent glass fiber array was used to couple the MCP to the CCD, more details is in the ref. [8].

The spectrometer is pumped below $1x10^{-6}$ Torr by a 250 L/s turbomolecular pump and is connected to the tokamak chamber by a 3.6 cm diameter, 4.80 meter long stainless steel tube with differential pumping, and is aligned to observe the equatorial plane of the tokamak.

Taking a certain ion temperature (T_i constant), one can see from Eq. 1 that the Doppler broadening, $\Delta\lambda_{D1/2,}$ due to ion temperature, will be lower for larger ion mass number A_i for a fixed wavelength $\lambda_{0.}$ On the other hand, for a fixed $A_{i,}$ $\Delta\lambda_{D1/2}$ will be small for lower wavelength as in the VUV region.

$$\Delta\lambda_{D1/2} = 7.69 \quad x \quad 10^{-5}\,\lambda_0\left(\frac{T_i}{A_i}\right)^{1/2} \qquad (1)$$

where, T_i is the ion temperature in eV.

The measured line emission FWHM $\Delta\lambda_{meas}$ will be directly affected by the instrumental broadening $\Delta\lambda_{ins}$ according to Eq. 2.

$$(\Delta\lambda_{meas})^2 = (\Delta\lambda_{D1/2})^2 + (\Delta\lambda_{inst})^2 \qquad (2)$$

One way to overcome these difficulties is to work using second, third and fourth diffraction orders of a λ_0 line. At higher diffraction order, the measured line broadening, $\Delta\lambda^N$meas , increases with diffraction order number, Eq. 3, but the instrumental broadening measured in the CCD pixel domain is almost the same, leading to more accurate values of $\Delta\lambda_{D1/2}$.

$$(\Delta\lambda^N_{meas})^2 = (N\Delta\lambda_{D1/2})^2 + (\Delta\lambda_{inst})^2 \qquad (3)$$

where N is the diffraction order number and N = 1,2,3,4...

Also using two distinct measurements of different diffraction order, N and M, we can eliminate $\Delta\lambda_{inst.}$

$$(\Delta\lambda^N_{meas})^2 - (\Delta\lambda^M_{meas})^2 = (N^2 - M^2)(\Delta\lambda_{D1/2})^2 \qquad (4)$$

where N > M.

The main drawback of using higher order emissions is the lower intensity of these spectral lines, comparing with first order emissions. Also, the higher diffraction order of some emissions can overlap with other spectral lines, avoiding its use for diagnostics.

3. Experiments

Majority of the first diffraction order spectral lines are obtained below 100 nm as can be seen on Fig. 1 for TCABR tokamak and Fig. 2 for NOVA-UNICAMP. Most of these lines are also obtained in the major tokamaks as in the references [10-13].

The emissions from our two tokamaks are about the same, although the plasma current and temperature are about 10 times different. We can observe that leak problem at TCABR is not present as much as in the NOVA-UNICAMP by looking at nitrogen line emission NIV at 765 nm. In addition, the fluorine lines (FVII at 883 and 890 nm) [10] seen at TCABR due to Teflon material used at microwave interferometer window are not observed in the NOVA-UNICAMP machine.

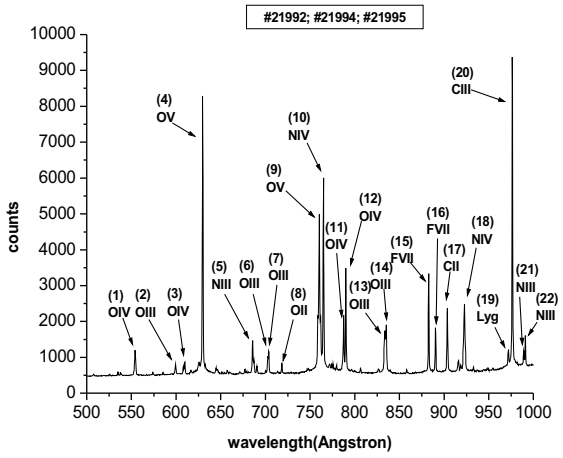

Figure 1: Spectral lines from 50 nm to 100 nm obtained in TCABR tokamak.

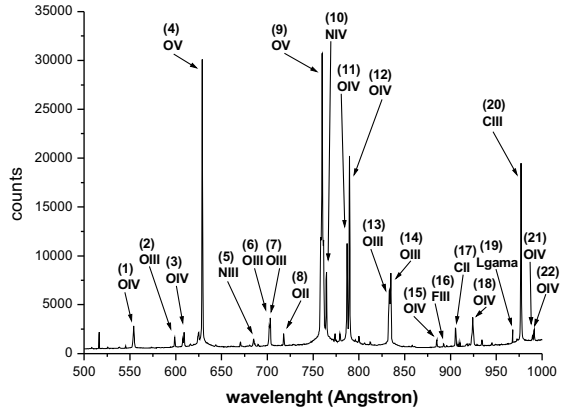

Figure 2: Spectral lines from 50 nm to 100 nm obtained in NOVA-UNICAMP tokamak.

Almost 100 emissions from 50 nm to 320 nm measured in the NOVA-UNIAMP and TCABR tokamaks are listed in Table 1. In this table, N is the spectral appearance order starting from lower wavelengths, Spectra represents the ion species with their ionization degree, Higher order are the respective diffraction order lines observed in the interval, and λ_{meas} is the observed wavelength in the NOVA-UNICAMP and TCABR tokamaks respectively. λ_{NIST} is the reference wavelength obtained from reference [17]. There are 35 first, 28 second, 18 third and 5 fourth diffraction order lines. Ion species observed in different stages of ionization are OII, OIII, OIV, OV, OVII; CII, CIII, CIV; NIII, NIV, NV and FVII, besides excited hydrogen lines, such as Lyman gamma, beta and alpha.

To determine ion temperature of different species, one could measure any first diffraction order line and use Eq. 1 and Eq. 2 to determine ion temperature. As an example, using the first order emission of OV line, Fig. 3a, at 62.973

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nm and instrumental broadening of 0.0868 nm, we obtain T_i of about (90±46)x10 eV, which is of course too high for our machine. However, if one takes the fourth order emission at 251.896 nm, Fig. 3c, the result will be T_i of about (110±27) eV, which is more reasonable for our tokamak.

This is the consequence of very narrow FWHM obtained at first diffraction order line, 0.0940 nm, against 0.1005 nm from fourth diffraction order. Since the instrumental broadening is (0.0868±0.0035) nm, measurement error involved in the first diffraction order line is much larger, resulting in wrong ion temperature determination. This behavior is very common for most of the spectral lines measured.

TABLE 1: List of spectral lines from NOVA-UNICAMP and TCABR tokamaks.

N	*Spectra*	*Observed Higher Order*	λ_{meas}^{NOVA}	λ_{meas}^{TCABR}	λ_{NIST}
1	OIV	2nd,3rd,4th	554.00	554.07	554.07
2	OIII	2nd,3rd	599.00	599.40	599.60
3	OIV	2nd,3rd	608.98	609.75	609.83
4	OV	2nd,3rd,4th	629.00	629.73	629.73
5	NIII	2nd	685.93	685.76	685.82
6	OIII		703.09	702.53	702.33
7	OIII	2nd	704.45	703.61	703.85
8	OII	2nd	717.77	718.24	718.50
9	OV	2nd,3rd,4th	760.00	760.35	760.45
10	NIV	2nd,3rd,4th	764.65	764.99	765.15
11	OIV	2nd,3rd,4th	787.20	787.47	787.71
12	OIV	2nd,3rd	790.07	789.97	790.11
13	OIII	2nd,3rd	833.37	833.51	833.74
14	OIII	2nd,3rd	834.81	835.29	835.29
15	FVII	2nd,3rd	883.13[a]	882.74	883.10
16	FVII	2nd,3rd	891.00[b]	890.23	890.76
17	CII	2nd,3rd	904.60	903.79	903.62
18	NIV	2nd,3rd	924.33[c]	922.70	922.52
19	$L\gamma$	2nd	972.79	971.96	972.54
20	CIII	2nd,3rd	977.00	976.24	977.03
21	NIII		989.67[d]	989.09	989.79
22	NIII		991.43[e]	990.87	991.51
23	$L\beta$	2nd,3rd	1024.89	1025.46	1025.72
24	OVI	2nd,3rd	1031.59	1031.66	1031.91
25	OVI	2nd,3rd	1036.88	1037.28	1037.61
26	CIII	2nd	1174.97	1175.49	1175.26
27	$L\alpha$	2nd	1215.00	1215.68	1215.67
28	NV	2nd	1238.45	1238.65	1238.82
29	NV	2nd	1242.41	1242.59	1242.80
30	CIV	2nd	1548.00	1548.19	1548.19
31	CIV	2nd	1550.49	1550.70	1550.77
32	OVII		1623.00	1624.05	1623.64
33	OVII		1637.71	1638.74	1638.27
34	OVII		1639.15	1640.18	1639.88
35	OIII		1670.00	1669.21	1669,31

883.13[a] is OIV(882.04), 891.00[b] is FeIII(890.76), 924.33[c] is OIV(923.37), 989.67[d] is OIV, and 991.43[e] is OIV in the NOVA-UNICAMP tokamak

Another very important issue is the care that must be taken about CCD pixel distribution on the spectral profiles during the measurements. Considering the first (Fig. 3a), third (Fig. 3b) and fourth (Fig. 3c) diffraction order lines from the same OV emission, the obtained FWHM from them are (0.0940±0.0011) nm, (0.1032±0.0023) nm, and (0.1005±0.0022) nm with ion temperature T_i of $(9,0±4,6)x10^2$ eV, (235±58) eV, and (110±27) eV respectively.

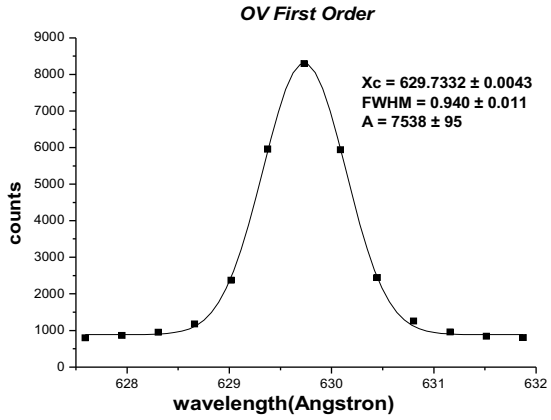

Figure 3a: First order emission of OV at 62.973 nm.

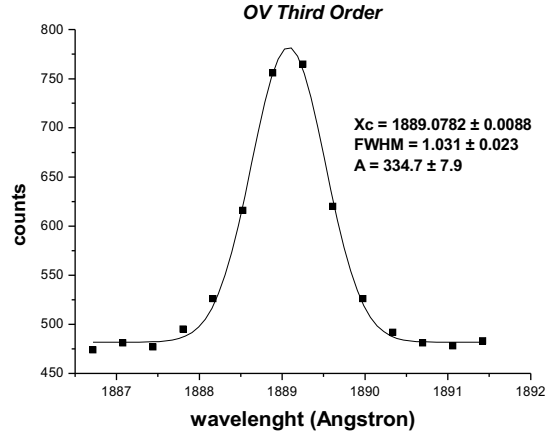

Figure 3b: Third order emission of OV at 188.907 nm.

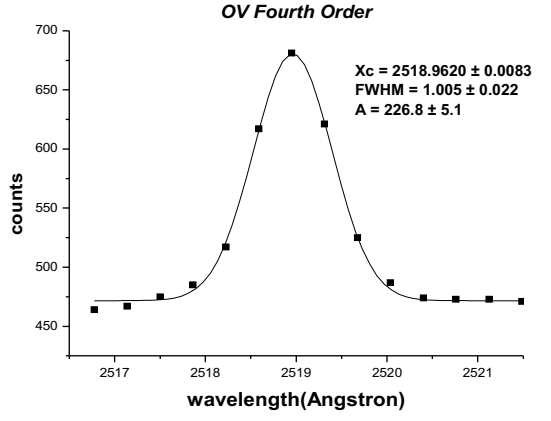

Figure 3c: Fourth order emission of OV at 251.896 nm.

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However, the FWHM of the spectral lines must increase with diffraction order number according to Eq. 3, therefore, the third diffraction order line FWHM at Fig. 3b is not a correct measurement. This is the consequence of the differences in pixel distribution on the Gaussian spectral profile.

In principle, if the area covered by pixels in the Gaussian profile fit is the same for any form of distribution, the FWHM should be the same.

However, the following Gaussian fit test was realized. Initially, an experimental spectral line, CIII (97.64 nm), in the discharge cleaning, has been chosen with one pixel point at the top of Gaussian profile as can be seen in Fig. 4a. Then, the spectrometer wavelength was modified by changing gradually the grating position, until a new profile distribution was obtained, such as in Fig. 4b. Pixel distributions in Fig. 3c and Fig. 3b are about the same as in Fig. 4a and Fig. 4b. The FWHM difference between Fig. 4a and 4b is 0.00133, which can produce the ion temperature difference between Fig. 3b and 3c.

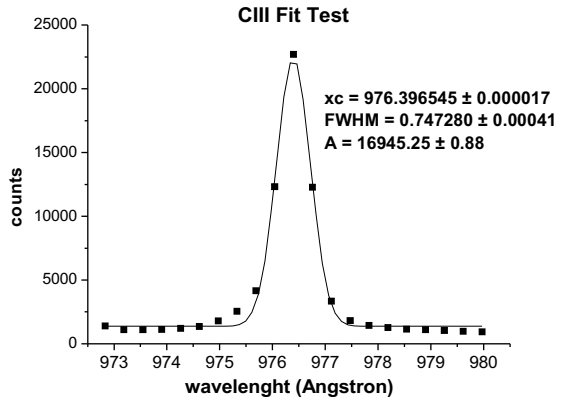

Figure 4a: Initial line spectra with one pixel at the top of the Gaussian profile fit.

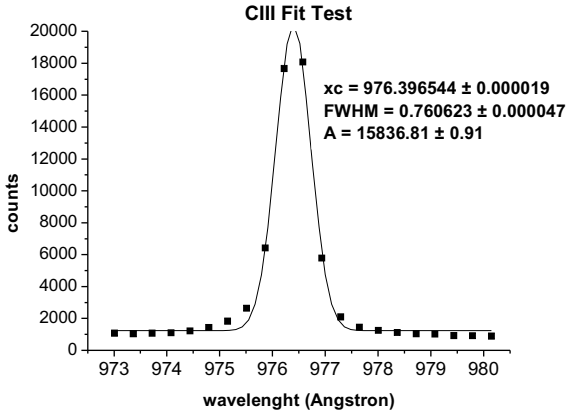

Figure 4b: Spectrometer wavelength change in order to move pixel points on the Gaussian profile.

As can be seen, the FWHM has changed much more than statistical error and this difference is enough to cause temperature change on the calculations. The effect of FWHM difference is caused by the wavelength interval covered by each pixel on the Gaussian fit. The wavelength interval covered by a pixel that is positioned on the rise or fall of the Gaussian profile is larger than one at the top giving bigger FWHM. Therefore, in order to obtain coherent temperature measurement using higher diffraction order lines, the same pixel distribution on the Gaussian profile need to be taken.

4. Conclusion.

Spectral emission lines from main impurity species in tokamak plasmas are very abundant in the vacuum ultraviolet region of spectra regardless of tokamak size.

Most of impurity emissions have wavelengths below 100 nm and direct ion temperature measurement using first diffraction order line can give large measurement errors due to strong instrumental broadening influence. The use of higher diffraction order lines can minimize this error giving possibility to cross check the obtained results.

In order to use different higher diffraction order lines from the same spectral emission, care must be taken in order to obtain and use all the spectral lines with the same pixel distribution over the Gaussian fit profile.

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