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** See annex of F. Romanelli et al, "Overview of JET Results",*
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**ABSTRACT.**

The ITER-oriented JET research program brings new requirements for the low-Z impurity monitoring, in particular for Be - the future main wall component of ITER. Monitoring based on Bragg spectroscopy requires an absolute sensitivity calibration which is challenging for large tokamaks. This paper describes the calibration method used for the BeIV channel (75.9Å) of the Bragg rotor spectrometer deployed on JET. The calibration technique presented here relies on multi-order reflectivity calculations and measurements of continuum radiation emitted from helium plasmas. These offer excellent conditions for the absolute photon flux calibration due to their low level of impurities.


## 1. INTRODUCTION

Spectroscopic monitoring of the Be and other low-Z impurities will be essential for the ITER-like wall research program on JET (Joint European Torus) as well as for future experiments on ITER where Be will be the main wall component. The value of a spectroscopic diagnostic depends greatly on there being an absolute sensitivity calibration. In general two methods can be used. The first one, called the component-by-component method, must take into account the multilayer/crystal reflectivities, window transmissions and geometrical factors. The second one is based on continuum radiation measurements and theoretical calculations of free-free and free-bound radiation emitted by a plasma. However, since the radiation can originate not only in the first order of diffraction but also come from higher orders, the continuum calibration method must be consistent with the component-by-component method including calibration functions for the higher diffracted orders.

In the case of the calibration method based on the continuum measurements, the main difficulties come not only from uncertainties due to the higher diffracted orders of the multilayers or crystals but also from the uncertainty of the impurity composition in the plasma, and the extremely high absorption in the detector window. These contributed to the extremely high (up to factor of 100) uncertainty of the absolute sensitivities that were found in previous calibration attempts [1]. In order to minimize the uncertainty of the impurity composition of the plasma, the calibration measurements were performed throughout the 2009 Helium Experiment Campaign on JET. The 'Ohmic' He plasmas ($f_{He}$~70-90%) offer uniquely favorable conditions for an absolute calibration. Firstly, the relatively low He plasma temperature causes less physical sputtering, while very low levels of deuterium decrease the chemical sputtering. As a consequence the level of impurities is significantly suppressed and the freebound and bound-bound radiation is much less intense (Fig.1).

Other important consequences are related to the stable $Z_{eff}$ ~2 during the whole discharge except for the limiter phase and the stable intensity of free-free continuum radiation. Helium plasmas also offer a low level of n and É¡ background radiation, highly undesired in calibration measurements. Fig.1 shows the temporal characteristics of the main plasma parameters during the Ohmically heated JET Pulse No: 79039.

## 2. CALIBRATION

### *A. CALIBRATION MEASUREMENTS*

The Bragg rotor spectrometer deployed on JET was described in detail in previous works [2,3]. Therefore, we only present here some features specifically important for the instrument's sensitivity calibration. The instrument is situated outside the JET torus hall, at a distance of 22m from the plasma - its radial line of sight, in the geometric mid plane lies around 0.3m below magnetic axis.

During the 2009 Helium Experiment Campaign the spectrometer used three low-energy channels to monitor the Ly$\alpha$ of Be, C and O, while the forth channel observed radiation in a higher energy range from 2.5Å up to 5.8Å. Only the Be channel is considered in this work; the others will be the subject of a separate paper. Typical survey spectra from JET (raw signals) are presented in Figure 2.

### *B. COMPONENT-BY-COMPONENT CALIBRATION METHOD*

In order to obtain the calibration functions one has to take into account the transmission of the structural elements $\eta_S$ (collimators and the window support frames), integrated crystal (or multilayer) reflectivity and the overall detector efficiency $\eta$, which is a function of wavelength (Bragg angle). All these factors must be calculated for all orders of reflection that contribute significantly to the total radiation registered by the detector. Therefore, the calibration function (counts ph$^{-1}$ rad m$^2$) can be written as:

$$C(n, \theta) = R_c\,(n, \theta)\,\frac{\psi_x\psi_y h_x h_y}{4_\pi}\,\eta_s\eta(n, \theta) \tag{1}$$

where $R_c$ is integrated reflectivity dependent on the order of reflection ($n$) and Bragg angle ($\theta$), $\psi_x$ and $\psi_y$ are the collimator acceptance angles parallel and perpendicular to the plane of dispersion and $h_x$ and $h_y$ are the projected height and width, respectively.

Calibration functions for the V-C multilayer obtained for the first three orders of diffraction are shown in Fig.3. Rc values were calculated by means of X-ray Oriented Programs (XOP) [4]. In order to cross-check the consistency of the Rc values, some of them were re-calculated by the codes provided by Henke et al. [5]. In the case of the V-C multilayer with parameters $\Gamma = 0.3$ (ratio of bottom layer thickness to period) and $N = 150$ (number of periods), the reflectivities obtained by means of the XOP were found to be in a good agreement with values obtained by the Henke code (differences up to 25%).

Once the calibration factors are known, it is possible to determine the absolute sensitivity of the instrument:

$$S_\lambda = \frac{4_\pi}{h\nu}\,C(n, \theta) \tag{2}$$

### *C. CONTINUA CALIBRATION METHOD*

In the 'continua' calibration method, the free-free and freebound continuum emission has to be calculated along the diagnostic line of sight and compared with signals registered by the detector. The calculated calibration factors can be employed in order to assess the potential contribution of the radiation originating from higher orders of diffraction to the measured signal.

The free-free continuum emission for a given charge Z on the ion in units of $Wm^{-3}sr^{-1}s^{-1}$ can be written as:

$$\varepsilon_{\lambda}^{ff} = 5.1 \times 10^{-54}\, n_e\, n_z T_e^{-1/2}\, Z^2\, G_{\lambda, Te}^{ff} \tag{3}$$

where $n_e$ and $n_z$ are the electron and ion densities, Te the electron temperature and $G^{ff}$ is free-free Gaunt factor. The free-bound emission ($Wm^{-3}sr^{-1}s^{-1}$) was assumed to be a result of the recombination to all n shells of fully stripped ions:

$$\begin{aligned} \varepsilon_{\lambda}^{fb} &= 1.4 \times 10^{-52}\, \frac{n_e\, n_z Z^4}{T_e^{-3/2}}\, exp\,(-h\nu / T_e) \\ &\times \sum \frac{G_{\lambda, Te}^{fb}}{n^3}\; exp\left(\frac{13.6Z^2}{T_e n^2}\right) \end{aligned} \tag{4}$$

where $G^{fb}$ is free-bound Gaunt factor. All Gaunt factors were calculated be means of the 'continuo' numerical code [6] based on the pure LS-couple approximation [7].

Figure 4 shows the total (free-free and free-bound) continuum intensities calculated for JET Pulse No: 79039 (15s<t<17s) as a function of the wavelength and Bragg angle of the V-C multilayer. The calculations based on measured $n_e$ and $T_e$ profiles were performed for the selected time period. The same calculations were performed for Pulse No's: 79039 to 79072. They assumed that the bulk plasma consists of only the He and H ions. Any contributions from higher Z elements were neglected in the present analysis. We believe that this assumption is justified in that the $Z_{eff}$ values do not exceed 2 (see Fig.1). The criterion of $Z_{eff} \leq 2$ was fulfilled throughout the whole JET Helium Campaign for all 'Ohmic' plasmas except during the limiter phase. In Fig.4 one can clearly see, that the intensity of the radiation reflected in the second and third orders is much higher than that originating from the first order for the whole range of Bragg angles.

## 3. RESULTS AND DISCUSSION

The product of the continuum intensities and calibration factors (see Fig.5) brings information about components of the measured signal originating from different orders of diffraction. For the main part of the spectrum ($\theta < 52^o$) the radiation diffracted by the V-C multilayer is by far most significant component of the signal. At a wavelength of 75.9Å (Be IV, $\theta = 43.6^o$) the higher order component contributes only 16%. This value defines our systematic error related to higher order reflection. An additional check was made for the 33.7Å, CVI line that should appear as second order component of the spectra at Bragg angle $\theta \sim 38^o$. No evidence of this line was found in any of the analyzed spectra. Therefore, in the further analysis based on the continua measurements we neglected higher order components of the spectra. These can be additionally suppressed by a low discriminator level setting.

The absolute sensitivities determined from the comparison of continua calculations with experimental measurements for the BeIV channel of the Bragg rotor spectrometer are shown as a function of Bragg angel in Fig. 6 (scattered points). These values were obtained assuming that all counts in the detector are due to the first order of diffraction. Therefore, in our view they represent an upper limit of the absolute sensitivity. The sensitivities for the first three spectral orders of the V-C multilayer obtained by the component-by-component method are also shown in Fig.6 (solid, dashed and dotted lines). The absolute sensitivities obtained by both methods for the Bragg angle of $43.6^{o}$ corresponding to the 75.9Å, Be IV line are presented in Table 1.

The 'component-by component' method gives results which are significantly higher than those obtained by means of the 'continua' method. The differences are especially high for the low values of the Bragg angle (high energy spectral range). At a Bragg angle ∏=43.6o corresponding to the 75.9 AÅã (Be IV) the absolute sensitivities differ by a factor of ~4. The disagreement is thought due to the lower than expected efficiency of the detector and some geometrical factors affecting the x-ray optics in the detector chamber which were not fully included in the present analysis.

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**REFERENCES**

[1]. K.Lawson et al., UKAEA, Government Division Report, TAN 96/19 (1996).
[2]. R. Barnsley, K.D. Evans, N.J. Peacock, and N. C. Hawkes, Rev. Sci. Instrum. **57**, 2159 (1986).
[3]. R. Barnsley, Ph.D. thesis, University of Leicester, (1993).
[4]. M. Sanchez del Rio and R. J. Dejus, SPIE proceedings **3448**, 340 (1998).
[5]. B. L. Henke, E. M. Gullikson, and J. C. Davies, At. Data Nucl. Data Tables **54**, 181 (1993).
[6]. ADAS, www.adas.ac.uk
[7]. A. Burgess and H. P. Summers Mon. Not. R. astr. Soc. **225**, 257 (1987).

| order | $S_{\lambda}^{comp}$ | $S_{\lambda}^{continua}$ |
|---|---|---|
| 1st | 3410 | 849Å–338 |
| 2nd | 56 | – |
| 3rd | 174 | – |

*Table 1: Sensitivities (counts rad $s^{-1}$/ $Wm^{-2}$ sr) for the $43.6^{o}$ Bragg angle*

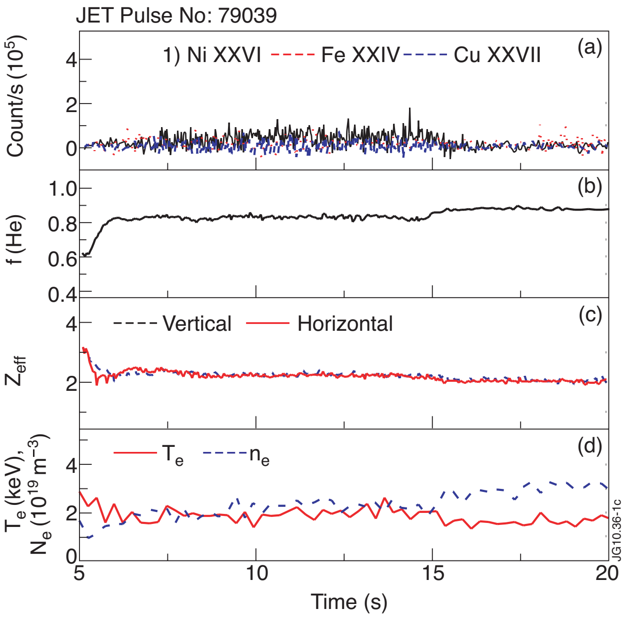


*Figure 1: (Color online). Time evolutions of the main plasma parameters: (a) Ni XXVI, Fe XXIV and Cu XXVII line intensities (VUV diagnostic survey), (b) fraction of He ions in plasma, (c) $Z_{eff}$ (visible spectroscopy) and (d) $T_e$ and $N_e$ (Thomson scattering).*

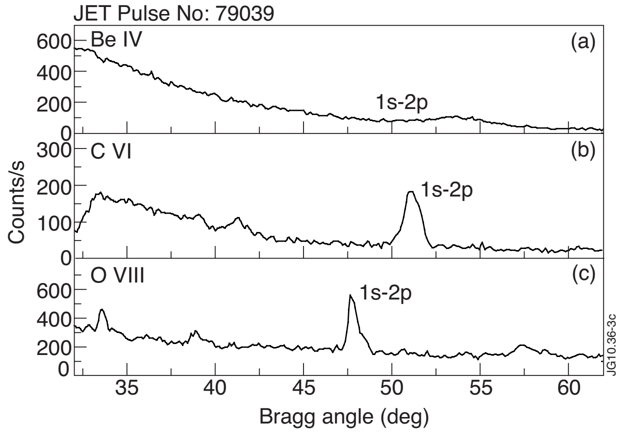


*Figure 2: Typical survey spectra (15s<t<17s) from JET (raw signals), using (a) the V-C and (b) W-Si multilayers and (c) TlAP crystal.*

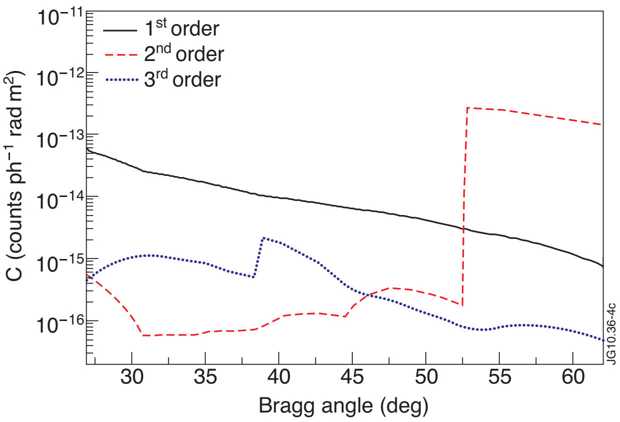


*Figure 3:(Color online). Calibration functions for the V-C multilayer obtained for the first three orders of diffraction.*

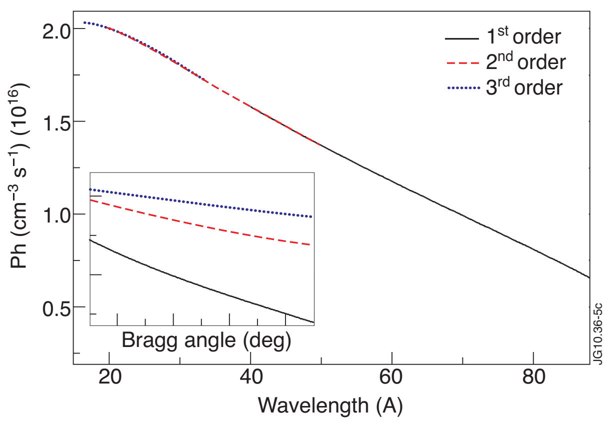


*Figure 4: (Color online). Total (free-free and free-bound) continuum intensities calculated against wavelength and Bragg angle (inside the main figure) of the V-C multilayer.*

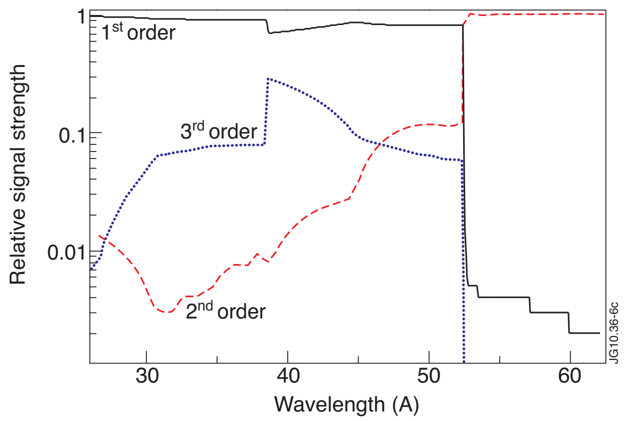


*Figure 5: (Color online). Simulation of relative signal strengths originating from different order of reflections as a function of Bragg angle, evaluated for V-C multilayer channel.*

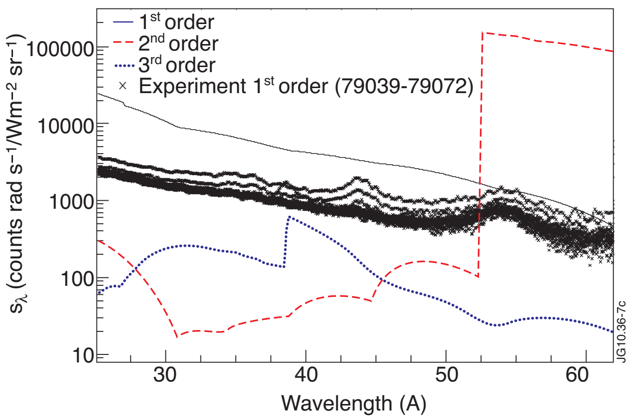


*Figure 6: (Color online). The comparison of the sensitivities obtained from the 'continua' method for the first order and from the' 'component-by component' for the first three orders of the VC multilayer.*