



# Absolute sensitivity calibration of an extreme ultraviolet spectrometer for tokamak measurements

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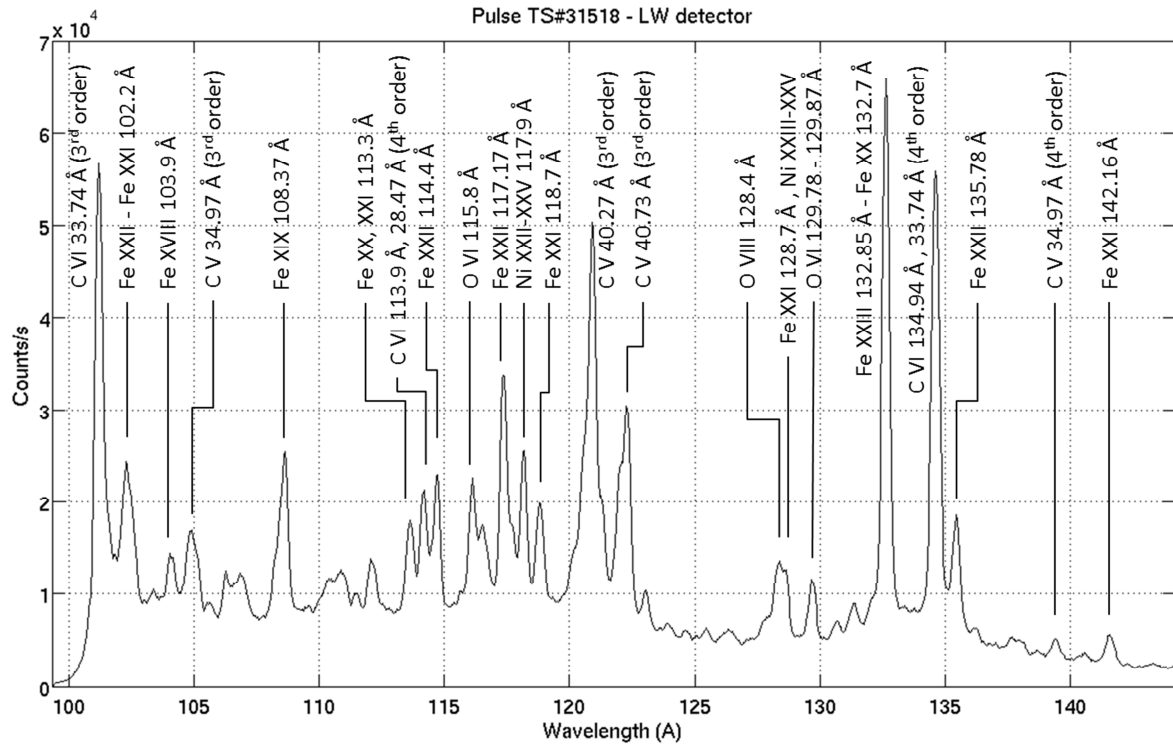
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32 A commonly used method is the so-called line intensity branching ratio method [1, 2].  
33 It consists of selecting spectral line pairs emitted by the same ion from one given upper level  
34 to two different lower levels and comparing their measured intensity ratio with the theoretical  
35 one. For this purpose, usually the spectrometer to be calibrated includes a visible line of sight  
36 as close as possible to the EUV line of sight and connected to a visible spectrometer (for  
37 which an absolute calibration is relatively easy). One line of the pair is chosen in the visible  
38 range, and thus the sensitivity of the EUV spectrometer at the second line wavelength can be  
39 deduced. This method has been used already many years ago on the TA 2000 torus [3, 4] and  
40 is still in use nowadays, for example at JET for the SPRED VUV spectrometer in the range  
41 130-360 Å [5]. Another way of calibrating an EUV spectrometer in absolute intensity units is  
42 to compare the spectrometer signals with those of an already absolutely calibrated instrument,  
43 as was done in [6] in the soft-X ray range.

44 In the present work, the Tore Supra tokamak is equipped with a high resolution, duo-  
45 multichannel grazing incidence spectrometer [7] of the Schwob-Fraenkel type. Two  
46 interferometrically aligned, ruled, concave gratings are mounted permanently on the  
47 spectrometer. For most of the applications and in particular for the present measurements, a  
48 600 g/mm grating blazed at  $1.5^\circ$  is used. It covers the 10-340 Å wavelength range. The  
49 spectrometer is supported by a mobile structure which allows to spatially scan the lower half  
50 of the plasma at a frequency 0.5 Hz.

51 Detection on this spectrometer is performed by means of two double microchannel  
52 plate (MCP) detector assemblies in chevron configuration mounted on two carriages moved  
53 independently along the materialised Rowland circle. The range of one detector is limited on  
54 one end by the shortest wavelength mechanically accessible and on the other end by the  
55 second detector assembly. It is thus called the 'short wavelength' (or SW) detector.  
56 Conversely, the other assembly is limited by the SW detector and the longest wavelength  
57 mechanically accessible, hence its name: 'long wavelength' (or LW) detector. The electrons  
58 produced in the microchannels by impact of the incident EUV photons are converted into  
59 visible photons by phosphor screens behind the MCPs and recorded by PDA (photodiode  
60 array) cameras (one for either MCP assembly). An example of a spectrum recorded on the  
61 LW detector is shown in Fig. 1.

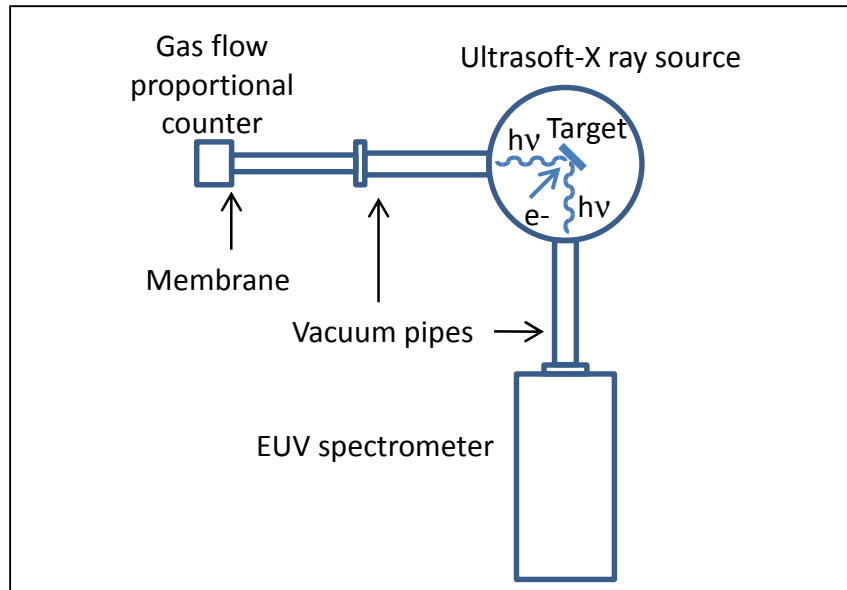


**Figure 1:** Spectrum recorded by the long wavelength detector with identification of the most prominent lines.

This spectrometer is not built with a visible line of sight so we could not use the branching ratio method exactly as presented in [1]. For the short wavelength part of the accessible domain we have used a combination of methods which are reported in this article. Section 2 describes the use of an ultrasoft-X ray source for absolute calibration in the 10-113 Å range. Section 3 describes the method used for calibration in the longer wavelength range, which combines the branching ratio method with a comparison of line intensity ratio measurements with collisional-radiative calculations, a method already used in [8]. Section 4 contains the results with a discussion on the uncertainties and a study of the spatial variation of the detector sensitivity. Section 5 presents a summary and conclusions.

## **2. Sensitivity calibration in the short wavelength range**

### **2.1 Experimental setup and method**



82  
83  
84

**Figure 2:** Absolute calibration setup with the ultrasoft-X ray Manson source

Target element	Wavelength (Å)
Mg	9.9
O	23.7
N	31.6
C	44.4
B	67.0
Be	113.0

85  
86  
87  
88

**Table 1:** List of emitting elements in the various targets and wavelengths of the corresponding spectral lines.

89 In the short wavelength range, an absolute calibration was performed in the  
90 spectroscopy laboratory with the help of a Manson Model 5 multi-anode ultrasoft-X ray  
91 source [9]. The set-up is sketched on Fig. 2. The source emits photons at a given wavelength  
92 (the so-called  $K\alpha$  line) by electron beam impact on targets (playing the role of anodes for the  
93 electrons) of various materials. A carousel of six targets allows to produce as many spectral  
94 lines between 9.9 and 113 Å (see Table 1).

95 A gas flow proportional counter (GPC) is placed at  $45^\circ$  from the electron beam axis (a  
96 setup very similar to the one used in [10]) to monitor the photon emission which can be as  
97 high as  $10^{12}$  photons/(s.sr). The GPC is set up so that it has a 100% efficiency. In order to  
98 preserve its operating pressure, which is different from that in the source volume, a membrane

99 is placed in front of the counter as a separation from the source volume. The membrane  
 100 transmission factor  $T_{GPC}$  depends on the wavelength, as shown in **Table 2**.

101

Wavelength (Å)	9.9	23.7	31.6	44.4	67.0	113.0
$T_{GPC}$ (%)	55	42	32	19	50	37

102

103 **Table 2:** transmission factor of the membrane in front of the gas flow proportional counter

104

105 In addition, we have used a grid filter (transmission  $T_F = 0.108$ ) to attenuate the GPC  
 106 signal. The photon rate (in  $s^{-1}$ ) measured by the GPC is thus given by:

$$107 \quad N_{GPC}^m(\lambda) = T_{GPC}(\lambda) \times T_F \times N_{GPC}^i(\lambda) \quad (1)$$

108

109 where  $N_{GPC}^i(\lambda)$  and  $N_{GPC}^m(\lambda)$  are the incident and measured photon rates respectively.

110 The spectrometer beam line is placed in a position symmetric to the GPC with respect  
 111 to the electron beam to take advantage of the photon emission symmetry around the electron  
 112 beam axis. The ratio of the photon rate incident on the spectrometer  $N_{sp}^i(\lambda)$  to the photon rate  
 113  $N_{GPC}^i(\lambda)$  incident on the GPC using a given target is equal to the solid angle ratio of the two  
 114 detectors:

$$115 \quad \frac{N_{sp}^i(\lambda)}{N_{GPC}^i(\lambda)} = \frac{\Omega_{sp}}{\Omega_{GPC}} \quad (2)$$

116

117 Note here that  $N_{sp}^i(\lambda)$  represents the total number of photons within the whole spectral line  
 118 width excluding the background in the same spectral interval.

119 The spectrometer sensitivity at wavelength  $\lambda$  is defined as the ratio of the measured count rate  
 120 to the incident photon rate:

$$121 \quad \eta(\lambda) = \frac{N_{sp}^m(\lambda)}{N_{sp}^i(\lambda)} \quad (3)$$

122 where  $N_{sp}^m(\lambda)$  is the count rate measured by the spectrometer readout and acquisition system  
 123 (expressed in counts/s in our setup). Due to the 100% efficiency of the gas counter and using  
 124 **Eqs. 1** and **2**, one has:

$$125 \quad N_{sp}^i(\lambda) = \frac{\Omega_{sp}}{\Omega_{GPC}} N_{GPC}^i(\lambda) = \frac{\Omega_{sp}}{\Omega_{GPC}} \frac{N_{GPC}^m(\lambda)}{T_{GPC}(\lambda) T_F}$$

126 and thus:

127 
$$\eta(\lambda) = \frac{N_{sp}^m(\lambda)}{N_{GPC}^m(\lambda)/(T_{CP}(\lambda)T_F)} \frac{\Omega_{GPC}}{\Omega_{sp}} \quad (4)$$

128

129 The spectrometer sensitivity can thus be deduced from the geometric parameters of the setup,  
130 which are known, and the measurements of the detectors.

131

132 The tokamak plasma observed with the spectrometer is an extended light source. The  
133 measurement performed by the spectrometer is thus the radiance (also commonly called  
134 brightness) defined as:

135 
$$B = (4\pi)^{-1} \times \int \varepsilon(l) dl \quad [\text{photons} / (\text{cm}^2 \text{ sr s})] \quad (5)$$

136

137 where  $\varepsilon$  (in  $\text{cm}^{-3}\text{s}^{-1}$ ), called emissivity, is the photon rate emitted by plasma unit volume in a  
138 given spectral line and  $l$  is the abscissa along the line of sight. The integral is performed over  
139 the whole line of sight path within the plasma. The quantity we aim at determining is the  
140 brightness calibration coefficient  $K(\lambda)$  defined by:

141

142 
$$B(\lambda) = K(\lambda) \times N_{sp}^m(\lambda) \quad (6)$$

143

144 over the whole wavelength range of the spectrometer. This quantity is crucial for plasma  
145 applications since it is needed to relate the measured quantity  $N_{sp}^m(\lambda)$  with the density of the  
146 emitting ions. It can be obtained in the following manner. When a spectral line emitted in the  
147 plasma is observed, the incident photon rate is by definition of  $\eta(\lambda)$ :

148 
$$N_{sp}^i(\lambda) = \frac{N_{sp}^m(\lambda)}{\eta(\lambda)} \quad (7)$$

149

150 The spectral line brightness is thus given by:

151

152 
$$B(\lambda) = \frac{N_{sp}^i(\lambda)}{(S\Omega)_{sp}} = \frac{N_{sp}^m(\lambda)}{\eta(\lambda) \times (S\Omega)_{sp}} \quad (8)$$

153

154 where  $(S\Omega)_{sp}$  is the spectrometer geometric etendue (here  $S$  is the entrance slit area). The  
155 brightness calibration coefficient is thus given by:

156

$$K(\lambda) = \frac{1}{\eta(\lambda) \times (S\Omega)_{sp}} \quad (9)$$

157

158 and is expressed in [photons/(s cm<sup>2</sup> sr)]/(counts/s).

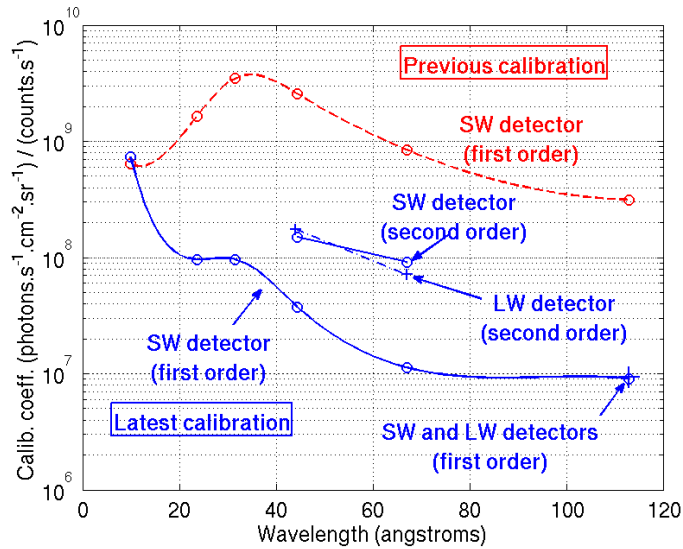
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160

161 **2.2 Results and comparison with a previous calibration**

162

163 The method exposed in the previous section has been applied to both the 'shorter wavelength'  
 164 (SW) and 'longer wavelength' (LW) detectors. The brightness calibration coefficient has been  
 165 determined for the six wavelengths available with the calibration source. It is shown in **Fig. 3**.  
 166 As the LW detector cannot be positioned to observe wavelengths shorter than 77 Å, only the  
 167 coefficient at 113 Å could be obtained by this method. Interestingly, it has almost the same  
 168 value as for the SW detector at the same wavelength. This observation results from the fact  
 169 that the two detectors are practically identical. It also denotes the accuracy of the  
 170 interferometric alignment of the spectrometer [7] and of the mechanical positioning of the  
 171 detectors along the Rowland circle to better than 25 µm. In the following we will thus not  
 172 distinguish between the two detectors on the calibration curves.



173

174 **Figure 3:** Absolute brightness calibration coefficient as a function of wavelength. SW  
 175 detector: (red ○ and dashed line) previous calibration in the first order and (blue ○ and  
 176 solid line) latest calibration in the first and second orders. LW detector: (blue + and dashed-  
 177 dotted line) latest calibration in the first two orders.

178



179           It can be seen from the slope of the calibration curve that on the short wavelength side  
180 the spectrometer sensitivity (proportional to  $1/K$ ) decreases with decreasing wavelength,  
181 which illustrates the difficulty to measure spectral line intensities below  $10 \text{ \AA}$  with this  
182  $600\text{g/mm}$  gold coated ruled grating. The comparison of the latest calibration curve with the  
183 previous one shows that the various improvements to the spectrometer (use of two  
184 microchannel plates in chevron configuration for each detector assembly, installation of a new  
185 grating, better performance PDA camera) have enhanced the spectrometer sensitivity by about  
186 a factor 30 over the whole calibrated wavelength range except below about  $20 \text{ \AA}$ . The latter  
187 feature is most likely due to the characteristics of the previous  $600 \text{ l/mm}$  holographic grating  
188 which was platinum coated, while the new grating is a ruled one and gold coated with a  
189 steeply decreasing efficiency toward the very short wavelengths below  $15 \text{ \AA}$ .

190

191           As this new grating is not designed to suppress the higher diffraction orders, the  
192 ultrasoft X- ray source lines at  $44.4 \text{ \AA}$  and  $67 \text{ \AA}$  have also been observed in the second order  
193 and have been used for the calibration, as shown in **Fig. 3**. They show that the spectrometer  
194 sensitivity in the second order is poorer than in the first order, but only by a factor of 5 to 8.  
195 We have actually observed intense spectral lines emitted by the tokamak plasma in as high an  
196 order as the 7<sup>th</sup> or the 8<sup>th</sup>. Notice that the second order calibration is almost the same for the  
197 SW and the LW detectors, another indication that the two detectors are practically identical.

198

199

### 200 **3. Sensitivity calibration in the long wavelength range**

201

#### 202 **3.1 Use of the branching ratio method**

203

204           The mechanical design of the spectrometer presently equipped with two detector  
205 carriages sets a lower limit of about  $77 \text{ \AA}$  to the spectral range accessible to the LW detector  
206 (this limit is actually reached when the SW detector carriage is itself positioned at the shortest  
207 possible wavelength position). The only line emitted by the ultrasoft X-ray calibration source  
208 above this limit, and thus the only available one for the LW detector calibration in the first  
209 order, is at  $113 \text{ \AA}$ . Therefore, another method has to be used in order to calibrate the  
210 spectrometer up to its maximum wavelength, which reaches  $340 \text{ \AA}$  with the routinely used  
211  $600 \text{ g/mm}$  grating.

212 The first additional method we use here is the so-called branching ratio method [1, 2],  
 213 which we will now describe briefly. The emissivity ratio of two spectral lines of a given ion  
 214 emitted by transitions from the same upper level to two different lower levels depends only on  
 215 atomic constants and not on the plasma conditions. In tokamak plasmas the emission is  
 216 completely dominated by spontaneous decay (rather than collisional de-excitation) so that the  
 217 ratio can be written as:

218

$$219 \quad \frac{\varepsilon_{ij}}{\varepsilon_{ik}} = \frac{n_i A_{ij}}{n_i A_{ik}} = \frac{A_{ij}}{A_{ik}} \quad (10)$$

220

221 where  $n_i$  is the population density of the upper level  $i$  and  $A_{ij}$  and  $A_{ik}$  are the Einstein  
 222 coefficients for spontaneous decay from levels  $i$  to levels  $j$  and  $k$  respectively. This relation  
 223 holds as long as neither spectral line is self-absorbed by the plasma, i.e. when the plasma  
 224 optical thickness can be neglected, which is the case here since the impurity ion density is  
 225 always far below the main plasma ion density of about  $5 \times 10^{19} \text{ m}^{-3}$ . The effect of radiation  
 226 trapping on the line brightness has been calculated using a mean transmission factor approach  
 227 [2, 11] and the predictions were confirmed by measurements on the TA2000 torus [4]. It was  
 228 found that for an optical thickness of the plasma below 0.1, the self-absorption is less than  
 229 3.5%. It is thus negligible in the present experimental conditions.

230 Using Eq. (5) it is easy to show that the same relation can be used for the brightness  
 231 ratio  $B_{ij}/B_{ik}$  measured by a spectrometer along a line of sight through the plasma. The relation  
 232 between the measured signal ratio and the brightness ratio can be deduced from Eqs. 6 and  
 233 10:

234

$$235 \quad \frac{K(\lambda_{ij})N_{ij}^m}{K(\lambda_{ik})N_{ik}^m} = \frac{B_{ij}}{B_{ik}} = \frac{A_{ij}}{A_{ik}} \quad (11)$$

236

237 This leads to the relation:

$$238 \quad \frac{K(\lambda_{ij})}{K(\lambda_{ik})} = \frac{N_{ik}^m}{N_{ij}^m} \frac{A_{ij}}{A_{ik}} \quad (12)$$

239

240 This relation shows that the ratio of calibration coefficients at two different  
 241 wavelengths can be deduced from line intensity measurements, which can be performed using

242 the tokamak plasma itself as a calibration source, and from Einstein coefficients, which are  
 243 well known atomic constants in our case. This relation can thus be used for *relative*  
 244 calibration for the two wavelengths  $\lambda_{ij}$  and  $\lambda_{ik}$ . This is particularly useful to determine the  
 245 absolute calibration factor at either wavelength when it is already known at the other. As  
 246 already said, the latter application is often used for VUV spectrometers using a visible  
 247 spectrometer having the same line of sight [3,4,5].

248 As we did not have such a setup, we took advantage of the absolute calibration over  
 249 the SW range described in the previous paragraph to calibrate the longer wavelength range by  
 250 using spectral line pairs with one line below 113 Å (measured in absolute units with the SW  
 251 detector) and the other at a wavelength to be calibrated above this value (measured with the  
 252 LW detector). This procedure relies on the assumption that the two detectors have the same  
 253 sensitivity at any given wavelength, an assumption supported by their identical design and by  
 254 the identical absolute calibration coefficient found at 113 Å in Section 2.

255 In our case, the plasma emits few pairs of lines obeying the constraints imposed by the  
 256 branching ratio method and the spectrometer wavelength coverage (two lines emitted from the  
 257 same initial level of the same ion with a sufficient intensity, the wavelength of one between  
 258 10 and 113 Å, the other between 113 and 340 Å). Only two suitable pairs were found, emitted  
 259 by Carbon, the dominant impurity in Tore Supra plasmas. They are shown in **Table 3**. The  
 260 calibration coefficients at 28.5 Å and 27.0 Å are calculated by a linear interpolation between  
 261 the two closest calibration points obtained in Section 2, namely 23.7 Å and 31.6 Å.

262

LW spectral line			SW spectral line			Theoretical intensity ratio $A_{ij}/A_{ik}$
Transition	$\lambda$ (Å)	$A_{ij}$ ( $s^{-1}$ )	Transition	$\lambda$ (Å)	$A_{ik}$ ( $s^{-1}$ )	
n=3 $\rightarrow$ n=2 (C VI)	182.2	$5.72 \times 10^{10}$	n=3 $\rightarrow$ n=1 (C VI Ly $\beta$ )	28.5	$7.23 \times 10^{10}$	0.79
n=4 $\rightarrow$ n=2 (C VI)	134.9	$1.09 \times 10^{10}$	n=4 $\rightarrow$ n=1 (C VI Ly $\gamma$ )	27.0	$1.66 \times 10^{10}$	0.66

263

264 **Table 3:** Pairs of spectral lines and theoretical intensity ratios which have been used for  
 265 relative calibration of the spectrometer above 113 Å.

266

267 This method provides invaluable information in that it allows to link the absolute  
 268 calibration in the shorter wavelength range with the relative calibration in the longer

269 wavelength range. Nevertheless it is clearly not sufficient to calibrate the whole longer  
 270 wavelength range of the spectrometer coverage. A complementary method is presented below.

271

### 272 3.2 Collisional-radiative modelling of line intensity ratios

273

274 The results of the branching ratio method exposed in the previous paragraph do not  
 275 depend on the experimental conditions such as the plasma parameters and their time evolution  
 276 or the spectrometer line of sight geometry. However, as it has just been shown, there are in  
 277 general very few pairs of spectral lines which can be used in a given experimental situation.  
 278 Relaxing the constraint of an identical upper level for the spectral line pairs used for the  
 279 calibration, we find many groups of lines emitted by a given ion in the plasma within the  
 280 relevant wavelength range. The drawback is that the relative intensities of the lines within a  
 281 group depend not only on atomic physics but also on the plasma parameters. They can be  
 282 calculated in the frame of a collisional-radiative model (CRM).

283 This calibration method, less accurate than the branching ratio method, has been  
 284 applied on the SPRED VUV spectrometer at JET for the 360-980 Å range using spectral lines  
 285 from mostly low ionisation stages [5]. In the present work, we aimed at calibrating a shorter  
 286 wavelength range (130-340 Å) than at JET. We also wanted to avoid using spectral lines  
 287 emitted near the plasma edge, where the plasma parameters are not so well known (in  
 288 particular the electron temperature). For both these reasons we did not select very low  
 289 ionisation stages, as can be seen on **Table 4**.

290

<b>Emitter</b>	<b>Wavelength (Å)</b>	<b>Transition</b>
<b>C IV</b>	222.8	$1s^2 2s^2 S - 1s^2 5p^2 P^o$
	244.9	$1s^2 2s^2 S - 1s^2 4p^2 P^o$
	259.5	$1s^2 2p^2 P^o - 1s^2 5d^2 D$
	262.6	$1s^2 2p^2 P^o - 1s^2 5s^2 S$
	289.2	$1s^2 2p^2 P^o - 1s^2 4d^2 D$
	296.9	$1s^2 2p^2 P^o - 1s^2 4s^2 S$
	312.4	$1s^2 2s^2 S - 1s^2 3p^2 P^o$
<b>C VI</b>	<b>27.0</b>	<b>1 – 4 (Ly γ)</b>
	<b>28.5</b>	<b>1 – 3 (Ly β)</b>

	<b>134.9 + 135.0</b>	<b>2 – 4 (Balmer <math>\beta</math>)</b>
	<b>182.1 + 182.2</b>	<b>2 – 3 (Balmer <math>\alpha</math>)</b>
O V	151.5	2s2p $^3P^o$ - 2s4d $^3D$
	192.8 + 192.9	2s2p $^3P^o$ - 2s3d $^3D$
O VI	129.8 + 129.9	1s <sup>2</sup> 2p $^2P^o$ - 1s <sup>2</sup> 4d $^2D$
	150.1	1s <sup>2</sup> 2s $^2S$ - 1s <sup>2</sup> 3p $^2P^o$
	172.9 + 173.1	1s <sup>2</sup> 2p $^2P^o$ - 1s <sup>2</sup> 3d $^2D$
	183.9 + 184.1	1s <sup>2</sup> 2p $^2P^o$ - 1s <sup>2</sup> 3s $^2S$
Fe XXIV	192.0	1s <sup>2</sup> 2s $^2S$ - 1s <sup>2</sup> 2p $^2P^o_{3/2}$
	255.1	1s <sup>2</sup> 2s $^2S$ - 1s <sup>2</sup> 2p $^2P^o_{1/2}$

291

292 **Table 4:** *Spectral lines used in the branching ratio method for absolute calibration transfer*  
 293 *(in bold) and in the CRM line ratio method for relative calibration.*

294

295 In the collisional-radiative modelling, instead of expressing the line emissivity as a  
 296 function of the population density of the initial level of the transition (as in **Eq. 10**), we use  
 297 the total density  $n_z$  of the emitting ion. The emissivity of a given line between levels  $i$  and  $j$   
 298 can be written as:

299

$$300 \quad \varepsilon_{ij} = n_e n_z PEC_{ij}(n_e, T_e), \quad (13)$$

301

302 where  $n_e$  and  $T_e$  are the electron density and temperature respectively. The  $PEC_{ij}$  quantity,  
 303 called photon emission coefficient, is calculated with a collisional-radiative model (CRM). It  
 304 depends in a complex way on the collisional and radiative atomic processes in the plasma,  
 305 namely transitions between excited levels of the emitting ions, recombination onto and  
 306 ionisation from excited levels. The PEC dependence on  $n_e$  is generally weak and will be  
 307 neglected here. In the present case the PEC values were obtained from the ADAS data and  
 308 model **[12]**.

309 From **Eq. 13** it can be deduced that the emissivity ratio of two lines  $ij$  and  $kl$  emitted  
 310 by the same ion is equal to the PEC ratio. For the brightness, which is the quantity actually  
 311 measured by the spectrometer, the situation is slightly more complex:

$$312 \quad \frac{B_{ij}}{B_{kl}} = \frac{\int n_e n_z PEC_{ij}(T_e) dl}{\int n_e n_z PEC_{kl}(T_e) dl} \quad (14)$$

314 where the integration is done along the line of sight. The exact calculation requires that we  
 315 know the spatial distribution of all quantities in the integrals, in particular the emitting ion  
 316 density profile along the line of sight. The most accurate way to obtain this is from a  
 317 dedicated transport study [13], a sophisticated and somewhat lengthy procedure. Instead, we  
 318 make here the rougher assumption that the PECs do not depend on  $T_e$ . This is verified in our  
 319 case because the emitting layer of the selected ions in this study is very narrow. As an  
 320 additional precaution, we have rejected lines with PECs depending strongly on the  
 321 temperature in the  $T_e$  range where the emitting ion is abundant (e.g. C V 40.3 Å,  $1s^2 \ ^1S_0 -$   
 322  $1s2p \ ^1P_1^o$ ). As a consequence, denoting  $T_e^{em}$  the electron temperature of the emitting layer, the  
 323 measured brightness ratio will thus be approximately equal to the PEC ratio:

$$324 \quad \frac{B_{ij}}{B_{kl}} = \frac{PEC_{ij}(T_e^{em})}{PEC_{kl}(T_e^{em})} \quad (15)$$

325  
 326 An accurate determination of  $T_e^{em}$  would require either a full transport study, as  
 327 already mentioned, or enough lines of sight to determine experimentally the position of the  
 328 emission layer. The weak  $T_e$  dependence requested from the PECs retained in this study  
 329 allowed to estimate  $T_e^{em}$  without loss of accuracy from the position of the emitting layers as  
 330 calculated by a local ionisation balance calculation.

331 Denoting again  $N_{ij}^m$  the measured signal and  $K(\lambda_{ij})$  the corresponding calibration  
 332 coefficient, one gets by definition of the calibration coefficient (**Eq. 6**):

$$333 \quad \frac{B_{ij}}{B_{kl}} = \frac{K(\lambda_{ij}) N_{ij}^m}{K(\lambda_{kl}) N_{kl}^m} \quad (16)$$

337

338 Provided the calibration coefficient is known at one wavelength, say  $\lambda_{ij}$ , the coefficient at the  
 339 other wavelength  $\lambda_{kl}$  can be obtained by using **Eq. 15**:

340

$$341 \quad K(\lambda_{kl}) = K(\lambda_{ij}) \frac{N_{ij}^m}{N_{kl}^m} \frac{PEC_{kl}}{PEC_{ij}} \quad (17)$$

342

343 Comparing the calculated and measured C VI line brightness ratios, we have  
 344 calculated the absolute calibration coefficients at 134.9 Å and 182.2 Å. Note that at 134.9 Å  
 345 the Balmer  $\beta$  line is blended with the fourth order of the C VI Ly  $\alpha$  line at 33.7 Å. In order to  
 346 subtract the latter contribution it was necessary to estimate the grating efficiency in the fourth  
 347 order. This was done by measuring the intensity of the well resolved C V 34.97 Å line in the  
 348 first and fourth orders in identical pulses designed for the calibration described here (see next  
 349 Section). This allowed us to deduce that the grating efficiency in the fourth order with respect  
 350 to that in the first order is about 10% at this wavelength. The contribution of the fourth order  
 351 C VI Ly  $\alpha$  line to the measured 134.9 Å intensity was then calculated using the measured first  
 352 order C VI Ly  $\alpha$  line intensity and the fourth order efficiency. It was then subtracted from the  
 353 measured intensity at 134.9 Å before the calibration coefficients were calculated.

354 Then we interpolate the calibration coefficient of the 150.1 Å line of the O VI group  
 355 between the values at 134.9 Å and 182.2 Å. From there, we use **Eq. 17** with the O VI line  
 356 group to obtain the calibration coefficients at 129.9 Å, 173 Å and 184 Å. Then with the same  
 357 hypothesis we obtain the 151.5 Å (O V group) calibration coefficient, and this allows us to  
 358 obtain the calibration coefficient at the second wavelength of the O V group, 192.9 Å. With  
 359 the same reasoning, we obtain the calibration coefficients at 192.0 Å and 255.1 Å (Fe XXIV  
 360 group) and at the six wavelengths of the C IV group. It has been checked that the final result  
 361 (the curve which will be fitted to the data points) remains within the error bars if the order in  
 362 which the line groups are added is changed.

363

## 364 **4. Results and uncertainties**

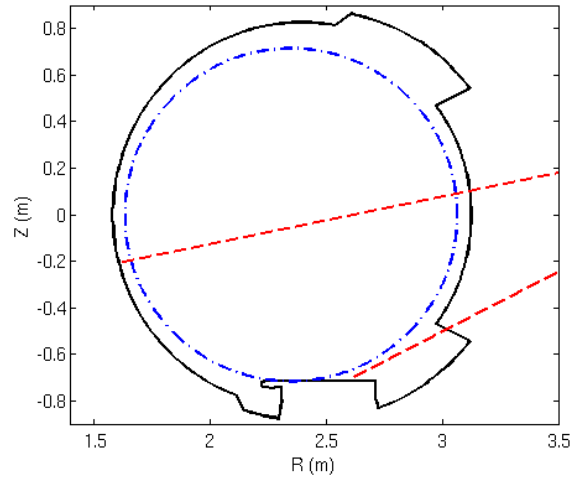
365

### 366 **4.1. Results**

367

368 A series of identical, ohmic pulses have been performed to record the useful spectral  
 369 line brightnesses (Tore Supra pulses TS#31512 to TS#31519). The plasmas are found to be

370 very stationary and reproducible so there was no need to perform a multi-pulse statistical  
371 study of the line ratios. The spectrometer was used in its spatial scanning mode, which means  
372 that the whole spectrometer was rotated around a horizontal axis located in front of the  
373 apparatus. In this mode of operation, the lower half of the plasma (see **Fig. 4**) could be  
374 scanned at a period of 0.5 Hz.



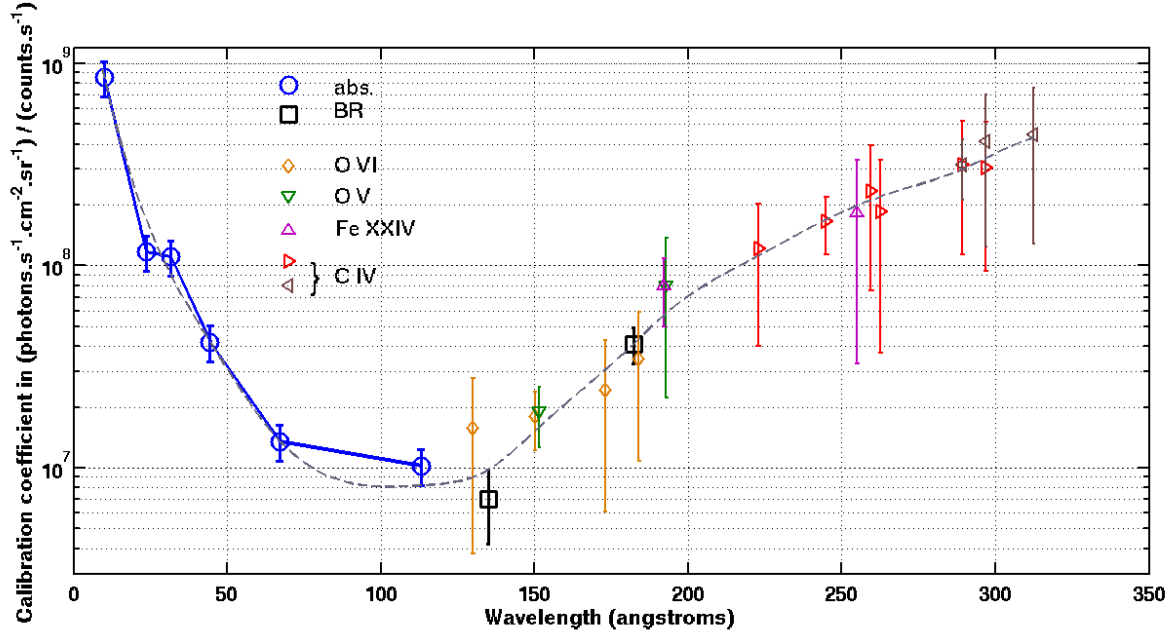
375  
376 **Figure 4:** *Poloidal cross section (solid line) of the tokamak vessel, (dashed-dotted*  
377 *line) of the plasma last closed flux surface and (dashed line) of the extreme positions of the*  
378 *line of sight.*

379  
380 Both the spectral line shapes and the radial profiles were used to reject blended lines.  
381 In the case of the Fe XXIV lines, observed to be blended in [5], the analysis of the radial  
382 brightness profiles allows to distinguish them from blended light species lines.

383 The calibration coefficients obtained with this method have been added to the results  
384 obtained in Section 2.2. The overall calibration curve is shown in **Fig. 5**. It shows a broad  
385 minimum (corresponding to a maximum in sensitivity) around 100 Å over a range of about 70  
386 Å. The spectrometer sensitivity decreases steeply on both sides, although in the long  
387 wavelength direction the slope tends to become lower. This indicates that with the same  
388 grating a modified spectrometer with a longer mechanical range for the detector would be  
389 sensitive enough to provide information over a broader wavelength range. This has been done  
390 for the Schwob-Fraenkel spectrometer installed on the Berlin EBIT experiment [14, 15]. On  
391 the contrary, in the short wavelength direction the slope is steeper and steeper. This indicates  
392 that extending the mechanical range to shorter wavelengths would not provide additional  
393 useful information below 10 Å.

394





395

396 **Figure 5:** Absolute brightness calibration in lab (solid line with  $\circ$ ), calibration transfer using  
 397 the branching ratio method ( $\square$ ) and relative calibration using the CRM of line ratios with  
 398 plasma (the symbols are explained on the figure). The grey dashed line is a spline among the  
 399 points and is adopted as the final calibration curve.

400

#### 401 4.2. Uncertainties

402

403 In the wavelength range absolutely calibrated with the ultrasoft-X ray source (9.9 -  
 404 113 Å), the main uncertainty is that associated with the spectral line intensities measured with  
 405 the spectrometer. It is mostly due to the uncertainty on the background estimate, which can be  
 406 difficult for the weaker lines of the calibration source. The uncertainty on these intensities is  
 407 at maximum 10% (it can be as low as 5% for the stronger lines). In addition, we estimate an  
 408 uncertainty of 10% to take account of the geometric aperture uncertainty. The uncertainty on  
 409 the proportional gas counter measurements is negligible compared to those associated with  
 410 the spectrometer measurements. We have thus a global uncertainty of 20% for the calibration  
 411 coefficients up to 113 Å.

412

413 For the calibration points using the branching ratio method, we must take into account  
 414 the time fluctuations of the two spectral line intensities used for each point. These fluctuations  
 415 are not negligible even during the stationary phase of the plasma. They are actually much  
 416 larger than the statistical error (which is the square root of the time average signal if a Poisson  
 417 distribution is assumed). The total uncertainty is thus estimated to 40% at 134.9 Å and 32% at  
 182.2 Å.

418 For the CRM calibration method, a part of the uncertainty associated with the  
 419 reference line (at wavelength  $\lambda_0$ ) of a given line group is determined from the time fluctuation  
 420 of the measured signal as discussed in the previous paragraph. To this fluctuation uncertainty,  
 421 an uncertainty of 30% is added, corresponding to the interpolation of this reference line  
 422 between two already calibrated wavelengths. For any other line (wavelength  $\lambda$ ) of the group,  
 423 the uncertainty is deduced from **Eq. 17**:

424

$$425 \quad \frac{\Delta K(\lambda)}{K(\lambda)} = \frac{\Delta K(\lambda_0)}{K(\lambda_0)} + \frac{\Delta \left( \frac{PEC(\lambda)}{PEC(\lambda_0)} \right)}{\frac{PEC(\lambda)}{PEC(\lambda_0)}} + \frac{\Delta N^m(\lambda)}{N^m(\lambda)} + \frac{\Delta N^m(\lambda_0)}{N^m(\lambda_0)} \quad (18)$$

426

427 The relative uncertainties on the signals  $N^m(\lambda)$  and  $N^m(\lambda_0)$  are calculated from the time  
 428 fluctuations of the measurements, as said above. The uncertainty on the PECs themselves is  
 429 difficult to assess and not always available in the literature. It seems that a global value of  
 430 30% for all PEC ratios reflects satisfactorily both the accuracy of the atomic physics  
 431 calculations and the residual PEC ratio dependence on  $T_e^{em}$  (see above the discussion about  
 432 **Eq. 15**).

433

434 For a practical purpose, a curve has been fitted on the points in **Fig. 5**. The most  
 435 satisfactory result was obtained with a spline. Below 120 Å the 20% uncertainty estimated for  
 436 the absolute calibration points can be retained. Between 120 and 180 Å, where line intensity  
 437 branching ratios were available, an uncertainty of about 35% is estimated. Above this  
 438 wavelength, a value of 50% reflects satisfactorily the spreading and uncertainties of the  
 439 relative calibration points. In this range, the uncertainty might be an underestimate of the  
 440 actual uncertainty due to the use of the CRM, for which the uncertainties are not well known.

441

442

443

#### 444 **5. Spatial variations of the detector response**

445

446 The tolerances of the spectrometer design and realisation are very tight, so that most  
 447 mechanical pieces are positioned to less than 25 µm. Nevertheless, the response of the  
 448 detector assembly along its length (i. e. along the wavelength direction) is not perfectly

449 uniform. It can be due to several reasons such as the small inhomogeneities of the  
 450 multichannel plate and phosphor screen responses, the transmission of the fiber optics bundle  
 451 or the quantum efficiency dependence on the photon incidence angle on the MCP input face.

452 As the non-uniformity and the spatial variation of the detector response play a role in  
 453 the estimate of the spectral line absolute brightnesses, it has been measured for the LW  
 454 assembly. The simplest way of doing this measurement is to select a spectral range containing  
 455 well isolated spectral lines and perform several measurements, moving the detector by small  
 456 position shifts between measurements in such a way that the spectral lines would strike  
 457 different parts of the MCP.

458 Due to programme constraints, this method could not be applied in the spectroscopy  
 459 laboratory. Therefore we have used the same series of identical discharges on the Tore Supra  
 460 tokamak as for the calibration. During this series, the detectors were moved in a limited  
 461 number of positions. As a result of this procedure, many spectral lines could be measured at a  
 462 few positions on the detector. By comparing the spectrometer measurements of a given  
 463 spectral line in the various positions and synthetising the results for all lines, we were able to  
 464 deduce the non-uniformity and spatial variation of the detector assembly response. The list of  
 465 the lines used for this procedure is given in **Table 5**.

466

Wavelength (Å)	Emitter
129.9	O VI
132.9	Fe XXIII
134.9	C VI 2-4 (+ Ly $\alpha$ 4 <sup>th</sup> order)
135.8	Fe XXII
238.5	O IV, C IV
241.5	C V (40.3 Å 6 <sup>th</sup> order)
244.9	C IV
281.9	C V
284.1	Fe XV
289.2	C IV
292.0, 291.3	Ni XVIII, C III

467

468 **Table 5:** *List of spectral lines and corresponding emitters for the evaluation of the non-*  
 469 *uniformity and spatial variation of the detector response.*

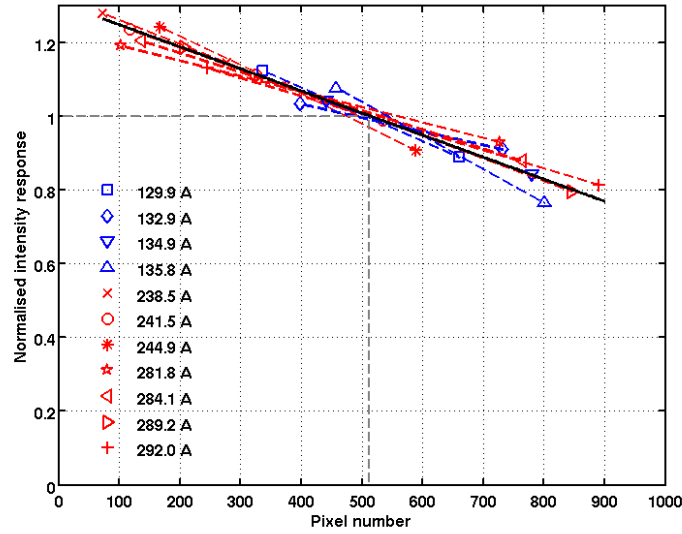
470

471 The synthesis of all these measurements is presented on **Fig. 6**. The results show that  
472 the intensity response is a decreasing function of the spectral line position in the direction of  
473 increasing pixel number (corresponding to increasing wavelengths) on the MCP detector in  
474 the useful range (between pixels 70 and 900 for the LW detector). The measurements show  
475 that the response at both ends of the detector (below pixel 70 and above pixel 900) is  
476 substantially degraded with respect to the major part of the detector range. This is due to the  
477 fact that the size of the PDA is slightly larger than the fiber optics bundle size. One notices  
478 that the unuseful portion on the large pixel number extremity is wider than that on the small  
479 pixel number extremity. This indicates that the bundle is not perfectly centred on the  
480 photodiode array. Both ends of the detector have thus been excluded from the study.

481 A straight line has been fitted to the data and the correction factor curve thus obtained  
482 has been normalised so that it is 1 in the middle of the detector (pixel 512 here). The  
483 spreading of the points around a given position and wavelength in **Fig. 6** indicates that the  
484 measurement fluctuations are dominant over the spatial inhomogeneities along the detector.  
485 The response decrease along the detector seems to be mostly related to the varying response  
486 of the MCP with the photon incidence angle. Indeed it is known that the MCP quantum  
487 efficiency decreases as the incoming photon angle with the grating plane becomes more  
488 grazing.

489 In **Fig. 6**, the average slope for the group of lines around 130 Å does not show a  
490 significant difference with that for the group in the range 240-292 Å (it would correspond to a  
491 response difference of less than 3%). Therefore we can consider that the wavelength  
492 dependence of the detector response spatial variation can be neglected. As no data in the short  
493 (10-70 Å) wavelength range are available for this calibration campaign, the average decrease  
494 of **Fig. 6** was used to correct all the line intensity measurements performed for the Manson  
495 source and the branching ratio methods (**Figure 5** includes these corrections.) As the intensity  
496 response curve introduces a maximum correction of about 20%, which is small compared  
497 with the global uncertainty estimated in Section 4.2, it was not necessary to make this  
498 correction for the CRM calibration above 200 Å.

499



500

501 **Figure 6:** Intensity response of the LW detector assembly as a function of the line position on  
 502 the detector (measured in pixels). Each symbol represents a different spectral line (see list on  
 503 Table 4). Dashed line: final correction factor.

504

## 505 **6. Summary and conclusion**

506 The grazing incidence spectrometer operated on Tore Supra with a 600g/mm grating  
 507 blazed at  $1.5^\circ$  has been absolutely calibrated over most of its wavelength coverage, i. e. 9.9-  
 508 312 Å. For the lower part of this domain (9.9-113 Å) we have used an ultrasoft-X ray source  
 509 calibrated against a gas flow proportional counter set up with a 100% efficiency. For the rest  
 510 of the wavelength domain we have used the branching ratio method for absolute calibration  
 511 transfer and collisional-radiative modelling of line intensity ratios for relative calibration.

512 The results show that the spectrometer sensitivity has improved with respect to the  
 513 previous setup thanks to the new grating and the double multichannel plates in chevron  
 514 configuration. The spectrometer is most sensitive in the 50-200 Å range, with a steep decrease  
 515 below 50 Å. On the long wavelength side the sensitivity decrease is not as steep. In fact, after  
 516 the present calibration procedure we have exchanged the 600 g/mm grating with a 300 g/mm  
 517 one and obtained useful measurements up to 680 Å.

518 The uncertainties have been calculated for each individual calibration wavelength. Due  
 519 to the variety of methods used for the whole wavelength range, it is not straightforward to  
 520 determine a precise global uncertainty. We estimate a 20% uncertainty below 120 Å, where  
 521 direct absolute calibration was obtained with the ultrasoft-X ray source, and 35% in the range  
 522 120-180 Å where the line branching ratio method was used. In the range above 180 Å where  
 523 only the relative calibration procedure (collisional-radiative modelling of line intensity ratios)

524 was available, the uncertainty is estimated to 50% or even more. This reflects the larger  
525 uncertainties and the spreading of the individual calibration points in the LW range.

526

527

528

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