Interpretation of the Carbon Line Emission in the ASDEX-Upgrade Divertor

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1 Introduction

Spectroscopic observation of plasma facing structures in a fusion device allows the estimation of the released particle flux. In ASDEX Upgrade the visible emission of CII at 658 nm was previously used for a quantitative determination of the carbon influx from the outer divertor target [1].
For a homogeneous plasma (constant T_e) the particle influx is given by

$$\Gamma = 4\pi \frac{S}{XB} I$$

where S and X are ionization and excitation rate coefficients, B is the branching ratio and I is the measured intensity (in $photons/m^{-2}sr^{-1}s^{-1}$). In general, the quantity S/X is a strong function of the electron temperature typical for divertor plasmas (below 20eV) and has to be known to evaluate the fluxes [2]. Moreover, if there are temperature gradients in the divertor the above equation only holds for an average but unknown temperature T_{eff}.
In [1] the plasma parameters determined by an in-vessel probe in the outer divertor at fixed position were used for the evaluation of the flux. Here, we apply a line ratio method for an estimation of the electron temperature at the position of the radiating species and discuss the limitations of the method due to temperature gradients.

2 Carbon emission in the divertor

A scanning spectrometer for the VUV and visible range was used for spectroscopic studies of the divertor radiation [3]. Its schematic arrangement on ASDEX Upgrade is shown in Fig. 1. Because the targets are observed nearly in normal direction the measured intensity is proportional to the particle flux.
Carbon line emission profiles are given in Fig. 2. For CII the emission of the resonance line at 135.5 nm is compared to the visible line at 658.3 nm (ohmic discharge with ion grad B drift toward the X-point). CIII emission at 465 nm and 97.7 nm is also shown for a neutral beam heated discharge. The emission profiles of both species in the visible differ from the VUV emission. Typically, the line ratio I_{vis}/I_{vuv} is much greater in the outer divertor which can only be explained by an in-out temperature asymmetry. In the inner divertor the temperature must be so low that the high lying initial level of the visible line is not as efficiently populated as the lower lying level of the VUV line. For an evaluation of the particle flux this asymmetry must

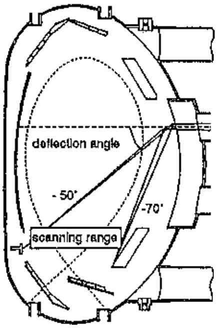

Figure 1: Schematic arrangement of the scanning spectrometer for the VUV and visible range used for divertor studies. Carbon emission will be plotted over the deflection angle.

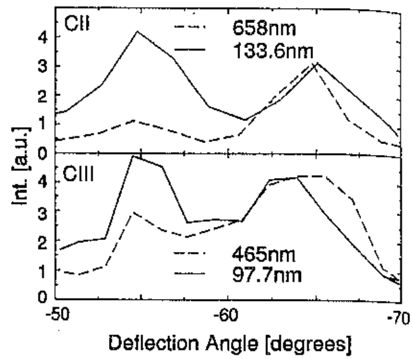

Figure 2: Carbon emission in an ohmic (CII) and neutral beam heated discharge (CIII) in the visible and VUV spectral range. Emission of the VUV resonance lines is nearly symmetric whereas the emission in the visible dominates in the outer divertor.

be taken into account. Without knowledge of the temperature one can only say that the visible emission profile is a better representation of the relative carbon influx than that in the VUV. In Fig. 3 the CII and CIV emission in an ohmic discharge is shown. At 2.0 s the gas valve was closed leading to a reduction of the plasma flux to the targets. The divertor density decreases, followed by an increase of the temperature. In the outer divertor both intensities decrease as expected. In the inner one, however, the CII emission decreases whereas the CIV emission rises. Here the temperature dependence of the ratio S/X is essential for a correct interpretation.

3 Electron temperatures determined by the line ratio method

The line ratio method was already applied to determine the electron temperature in the divertor of the DIII-D tokamak [4]. The chosen carbon lines at distant wavelengths in the VUV, however, require an absolute calibration of the spectrometer. We use instead closely neighbouring lines of CII at 80.7 nm (quartet system) and 85.8 nm (doublet system) which can be quantitatively analyzed without a calibration. The line ratio was calculated with a collisional-radiative model [5]. In this model all metastable levels of carbon were taken into account. The temperature dependence shown in Fig. 4 results mainly from the energy separation of 5.3 eV of the metastable and ground term of CII which are the initial states to populate the upper levels of the transitions at 80.7 nm and 85.8 nm, respectively. Temperatures determined in this way characterize the region where CII emission is maximal along the line of sight (T_{emis}).

The investigation of the ohmic discharge described above showed clearly the assumed asymmetry. A value of $T_e = 5\,eV$ in the inner divertor and 12 eV in the outer divertor is found. After closure of the gas valve this asymmetry is reduced. Now the inner divertor temperature rises to 9 eV which is the reason for the observed increase of the CIV signal (see Fig. 3).

A lower temperature with subsequent detachment in the inner divertor is also found in other divertor tokamaks (DIII-D, ALCATOR C-Mod) and can be explained by a preferential energy input into the outer part of the sol [6]. Symmetry returns when both divertors (inner and outer) are detached. As an example we consider a neutral beam heated discharge (#7743) with two density plateaus. At a density of $5 \cdot 10^{19}\,m^{-3}$ we find $T_{in} = 5\,eV$ and $T_{out} = 10\,eV$. When the density is increased up to $8 \cdot 10^{19}\,m^{-3}$ the outer divertor detaches too and T_{emis} is 8 eV in both divertors. CII radiates now in a greater distance from the plates.
Such an asymmetrically detached divertor was found in the 2D-modeling with the B2-Eirene code. Fig. 5 shows the isolines of the electron temperature in steps of 1 eV together with the isolines of the total CII emission for a 3.5 MW neutral beam heated discharge. In the inner divertor CII emission peaks at 4 eV and in the outer at 8 eV which is near to the temperatures found by the line ratio method.

4 Carbon flux ratios

We consider the symmetrical emission profiles in the VUV. When taking into account the temperature dependence of S/X we arrive at a flux ratio (inside - outside) in the detached phase of 1 : 60 and after closing the valve of 1 : 1 for the ohmic discharge discussed above. Visible emission shows an asymmetrical influx already directly. A quantitative evaluation with the proper ratio of S/X results in the same ratio as above.
With the strong temperature gradient and the low temperatures in the inner divertor a problem arises. If the ionization length is comparable to the temperature gradient length we have $T_{eff} > T_{emis}$. A higher value of the temperature value results in a greater S/X and therefore reduces the flux asymmetry. A quantitative evaluation is then impossible without modeling the temperature gradient. The flux asymmetry, however, remains in any case. One can state that the electron temperature has a great influence on the carbon erosion indicating the role of physical sputtering.

5 Summary

Electron temperatures in the divertor have been estimated using the line ratio method. Asymmetries were found with temperatures as low as 5 eV in the inner divertor resulting in an asymmetrical carbon influx from the target plates. B2 - Eirene modeling of the divertor confirms the temperatures found as well as the observed inside - outside asymmetry.

References

[1] Field, A.R., Garcia-Rosales, C., Lieder G. et al., Nucl. Fusion 36(1996), 119.

[2] Behringer, K., Summers, H. P., Denne, B. et al., Plasma Phys. Control. Fusion 31(1989), 2059.

[3] Field, A.R., Fink, J., Dux, R. et al., Rev. Sci. Instrum. 66(1995), 5433.

[4] Isler, R., to be published in Fusion Eng. and Design

[5] Napiontek, B., degree thesis, submitted to Humboldt University, Berlin, 1996

[6] Harbour, P.J., Contrib. Plasma Phys. 28(1988), 417.

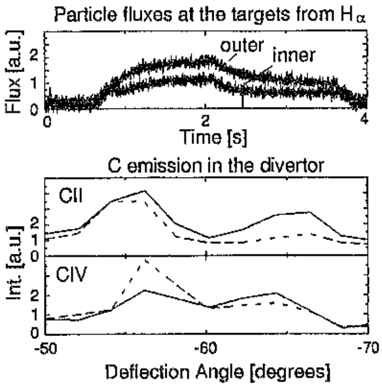

Figure 3: Comparison of the CII and CIV emission in two phases of the standard discharge: solid line - before closure, and dashed line - after closure of the gas valve. Note the opposite behaviour of CII and CIV emission in the inner divertor.

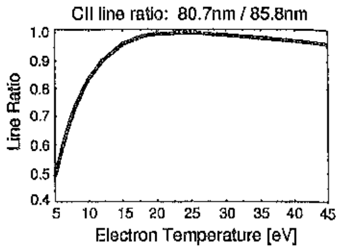

Figure 4: CII line ratio of 80.7 nm (quartet system) and 85.8 nm (doublet system) as a function of the electron temperature. The energy of the initial levels is 20.6 and 14.4 eV, respectively.

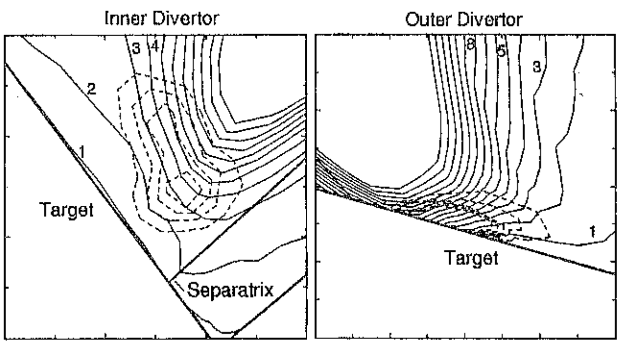

Figure 5: Typical asymmetrical divertor detachment obtained from B2 Eirene code calculations for 3.5 MW input power and $n_e = 4 \cdot 10^{19}\,m^{-3}$. In the inner divertor (left) the CII radiation zone (broken contour lines) is well separated from the plates. The maximum appears at 4 eV (full lines). In the outer divertor (right) this zone is attached to the plate. Higher temperature regions where the T_e contours are less inclined with respect to the lines of sight of the spectrometer contribute preferentially to the measured intensity (8 eV).