VOLUME RECOMBINATION IN THE ASDEX UPGRADE DIVERTOR

U. Wenzel[1], K. Behringer, A. Carlson, K. Schmidtmann and ASDEX Upgrade team

Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching and Berlin[1]

1. Introduction

Consider the divertor plasma in front of the target plates. Net recombination occurs in the divertor plasma when the recombination rate exceeds the ionisation rate. This happens at low electron temperature because ionization and recombination rates of hydrogen are anti-correlated functions of the temperature. Moreover, when three-body recombination begins to dominate, the recombination rate is strongly enhanced for sufficient large electron densities by the linear dependence of the rate coefficient on the electron density. Spectroscopic evidence for reaching the recombination dominated regime results mainly from the observation of the Balmer series. Here we analyze a discharge with density ramp-up in divertor configuration I. Fig. 1 shows spectra measured with a scanning mirror spectrometer. At 1.43 s the line of sight sampled the inboard divertor. The outboard divertor was scanned at 1.60 s (during the forward movement of the mirror) and at 1.67 s (when the mirror moved back). In the inboard divertor the Balmer series is observed up to $n = 11$. The levels of hydrogen are occupied by recombination as found from an analysis of the intensity ratio of the series terms. In the outer divertor the Balmer series is only very weak at 1.6 s, but recombination becomes stronger with increasing density as indicated by the spectrum at 1.67 s.

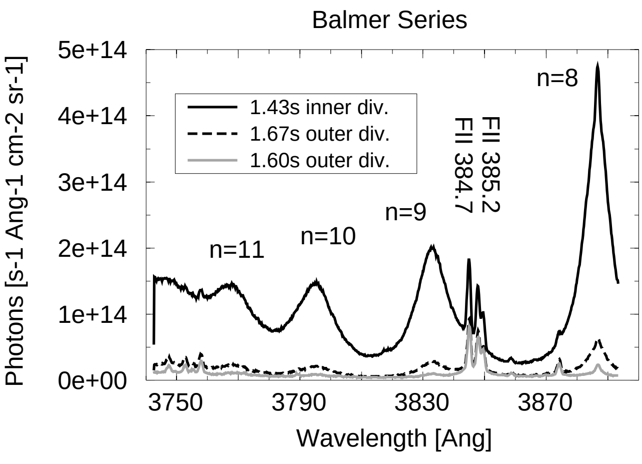

Fig. 1: Spectra of the Balmer series in the inboard and outboard divertor

2. Conditions for net recombination

For the determination of the net recombination rate the collisional-radiative model contained in the ADAS program was applied. The opacity of the Lyman series was taken into account by additional routines [1]. Fig. 2 shows the net recombination rate as a function of the temperature calculated for an electron density of $3 \cdot 10^{20}\,\mathrm{m}^{-3}$ and a neutral density of $2 \cdot 10^{19}\,\mathrm{m}^{-3}$. The neutral density was estimated from a measurement of the opacity of the L_β line. For that

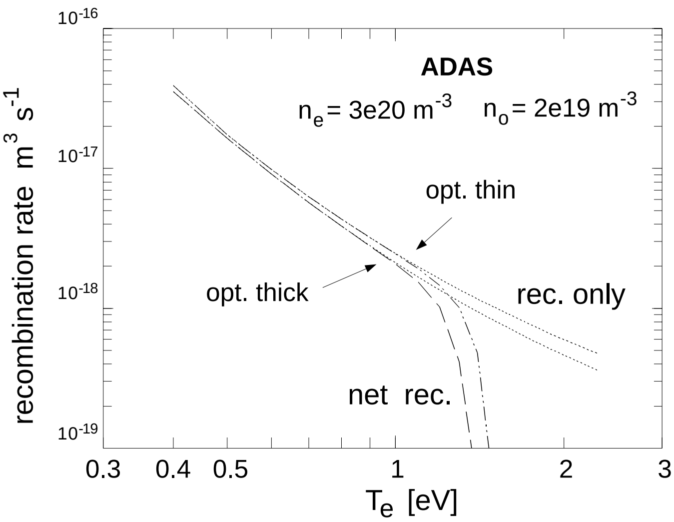

Fig. 2: Recombination rate coefficients (including net rates) for optically thin and thick conditions

purpose H_α and L_β were simultaneously observed with the scanning spectrometer. At high line-averaged density, deviations of the proportionality of both signals were found up to a factor of 0.5. Assuming opacity effects as the reason, we get the density value given above. Fig. 2 shows significant net recombination with rates of $10^{-18}\,\mathrm{m}^3 s^{-1}$ for electron temperatures below 1.3 eV. Optically thick conditions result to a shift of net recombination to lower temperatures; in our case to 1.1 eV. Due to self absorption, the $n = 2$ is more fully occupied, which enhances the ionization and reduces the recombination rate. For $T_e \rightarrow 0$ the two curves converge. Radiative decay of the $n = 2$ level becomes more and more important in comparison to collisional coupling to the level $n = 3$.

3. Plasma parameter in the recombining region

For a quantitative description of the volume recombination, knowledge of the plasma parameters is necessary. When the continuum and the series emission of hydrogen can be measured, a variety of methods exist to evaluate the plasma parameters. Line broadening of the Balmer series terms is mainly due to the Stark effect. Fig. 3 shows the density profile in the inboard divertor obtained from the Stark widths with the maximum density at 1.43 s. For this time point the electron temperature was $0.8 \pm 0.1 eV$. This value

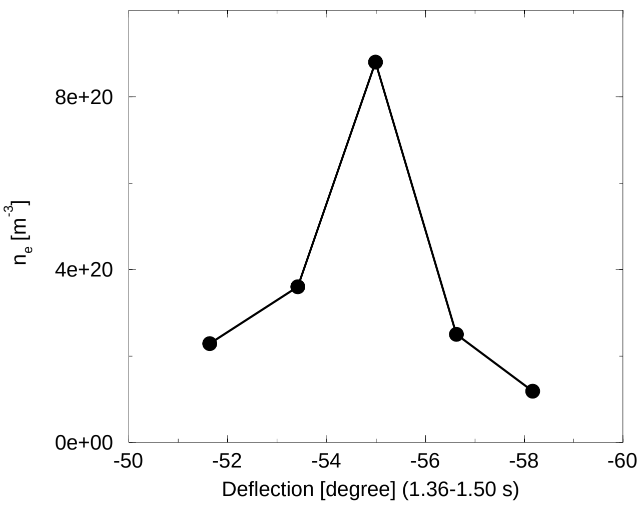

Fig. 3: Profile of the electron density determined from the Stark widths of the Balmer series term n = 8

was determined by an analysis of the spectral dependence of the Lyman continuum. Finally, the volume of the recombination zone was found to be to $0.08m^3$. The width results from the density profile shown in Fig. 3. The length was determined by a comparison of the absolute intensity of a Balmer series term with a value calculated on the basis of the known plasma parameters.

4. Target vs. volume sink

To be significant, volume recombination must be comparable to the target sink of the plasma ions. In ASDEX Upgrade particle fluxes to the divertor targets are measured by Langmuir probes. Fig. 4 shows the temporal evolution for the discharge under consideration. In the inner divertor the flux decreases continuously from an initial value of $3 \cdot 10^{22}\,\mathrm{s}^{-1}$. In the outer divertor the flux first increases during the ramp-up. At 1.5 s the flux saturates followed by a decrease (roll-over).

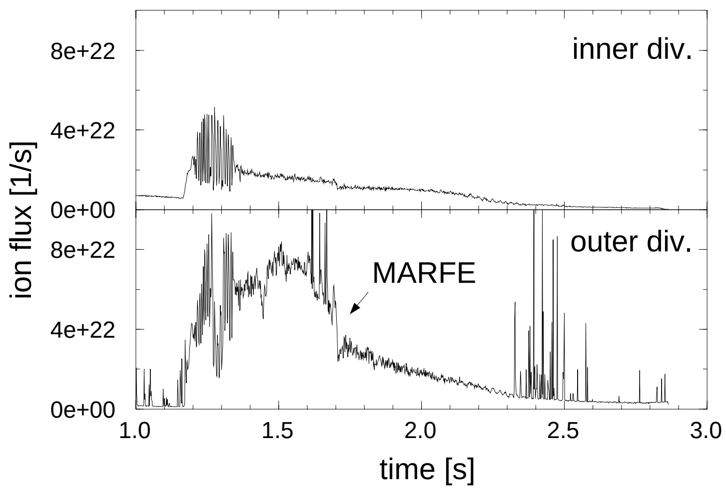

Fig. 4: Plasma fluxes to the inner and outer divertor target measured with Langmuir probes

What temperature is necessary for equal volume and target recombination? Consider now the inner divertor at 1.43 s when the flux amounts to $2 \cdot 10^{22}\,\mathrm{s}^{-1}$. The volume recombination rate is given by $\Gamma_{vol} = \xi_{rec} n_e n_i V_{rec}$. Evaluating this expression for the mean value $n_e = 4 \cdot 10^{20}\,\mathrm{m}^{-3}$ in the volume $V_{rec} = 0.08\,\mathrm{m}^3$, we obtain for the recombination rate coefficient $\xi_{rec} = 2 \cdot 10^{18}\,\mathrm{m}^3\,\mathrm{s}^{-1}$. Fig. 2 shows that net recombination has this value at 1 eV with only minor modication by the effect of opacity. From the analysis of the spectral dependence of the Lyman continuum we found a lower value (0.8 eV), i.e., the volume sink exceeds the target sink by a factor of 2 (see Fig. 2). At the same time in the outer divertor volume recombination is weak as indicated by the spectrum at 1.6 s in Fig. 1. Note that the asymmetry in particle flux, e.g., at 1.5 s the ratio in-out is 1:4, is correlated with the asymmetry in volume recombination. This gives a qualitative explanation for the different temporal dependencies of the target plate fluxes in the inboard and outboard divertor.

5. Detachment and volume recombination

In [2] the degree of detachment (DOD) was introduced to characterize divertor detachment. This concept assumes a quadratic dependence of the divertor density on the midplane density. Deviation from this relation is expressed as a DOD factor. It takes on values greater than one with the saturation of the flux.

The question arises whether volume recombination triggers the saturation. A quantitative analysis, i.e., the measurement of the temperature by passive spectroscopy in the outboard divertor, is impossible because the spectrum recorded later at 1.6 s does not allow the evaluation of neither density nor temperature. Signatures of recombination are observed but from a rough scaling net recombination rates are expected to be at least one order of magnitude below the target sink. From this observation we conclude that volume recombination is not responsible for the roll-over. Previous modelling studies show that below 5 eV the saturation can be caused by a lack of energy necessary to ionize the neutral hydrogen. Additional energy losses by impurity radiation in front of the gas target increase this effect [3, 4].

In the outer divertor volume recombination is only significant after the formation of a X-point marfe at 1.7 s. This transition occurs rapidly as indicated by the jump in the particle flux in the outer divertor. After the transition we observe now strong net recombination in three regions: in the high density, low temperature core of the marfe and in both divertors. During the transition in the outer divertor the temperature drops below the treshold for net recombination, i.e., the temperature asymmetry between the divertor legs is reduced by the X-point marfe. The H_α signal from the divertor doubles at the transition because of the increased occupation of the level with $n = 3$ by recombination. Therefore, the drop in the probe signal at 1.7 s may be qualitatively explained by the sudden onset of volume net recombination. After marfe formation the particle flux further decreases by a continuous growing volume recombination rate.

References

[1] Behringer K.: “The influence of opacity on hydrogen line emission and ionization balance in high density divertor plasma.” IPP Report 10/5, Max-Planck Institut für Plasmaphysik, Garching 1997

[2] Loarte A. et al.: “Plasma Detachment in JET Mark I Divertor Experiments.” JET Report JET–P(97)03, Abingdom 1997

[3] Borras K. et al.: Nucl. Mater. **241–243** (1997) 250

[4] Kastalewicz H. et al.: “B2–Eirene density and energy scans for ASDEX Upgrade shots.” *This Conference.*