*27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol.* **24B** *(2000) 1192 -1195*

# Recombining plasmas in the ASDEX Upgrade divertor and the divertor simulator NAGDIS-II

U. Wenzel*, R. Pugno, K. Schmidtmann, N. Hattori+, D. Nishijima+,
N. Ohno+, S. Takamura+, Y. Uesugi
*Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching and Berlin(*)*
*+ Department of Energy Engineering and Science, Graduate School of Engineering, Nagoya University*

In the last years dense recombining plasmas were obtained in the tokamak divertors of ALCATOR C-Mod, ASDEX Upgrade, DIII-D and JET. Also in a linear device, the Nagoya divertor simulator NAGDIS-II, a recombining plasma was found. In the following it is compared with that of a tokamak divertor (ASDEX Upgrade) to find out whether the essential physical mechanisms are the same.

In the standard configuration of ASDEX Upgrade (single X-point at bottom, ion grad B drift toward the X-point) the inner divertor is the colder one. As a consequence the plasma is frequently recombining. We consider a neutral beam heated discharge with the following parameters: current 1 MA, magnetic field -2.5 T, line-averaged density $9 * 10^{19} m^{-3}$, beam power 7 MW [1]. The filling gas was hydrogen. Fig. 1 shows the plasma parameters of the inner divertor measured by spectroscopic techniques. In the recombining plasma we observe the Balmer series up to series terms with n = 11. The electron density was obtained from the absolute intensity of the Balmer continuum and the electron temperature from a Boltzmann plot of Balmer series terms. All quantities are averaged over a line-of-sight. They are plotted over the poloidal distance from the target to the crossing point of the line-of-sight with the separatrix.

The temperature profile obtained in this way is flat with $T_e = 0.27\,eV$. The maximum electron density is $n_e = 8 \times 10^{20} m^{-3}$. For these parameters the 3-body recombination rate $K_{3by}$ is very large, since it scales as $K_{3by} \propto n_e T_e^{-9/2}$. Due to the volume recombination the electron density decays toward the target plate. Note that the plasma in the outer divertor is ionising at the same time. Here the plasma recombines mainly at the target.

Consider now a recombining plasma obtained in the Nagoya divertor simulator NAGDIS-II [2]. The necessary high plasma densities in the ion source can be only produced in helium. At high neutral pressure in the simulator chamber the plasma is extinguished in the volume in front of the end plate (downstream). Here we observe the signatures of volume recombination: series terms of the $2^3$P – $n^3$D transition of HeI up to n = 20 and the corresponding $2^3P$-free transition. Using these spectra the plasma parameters were

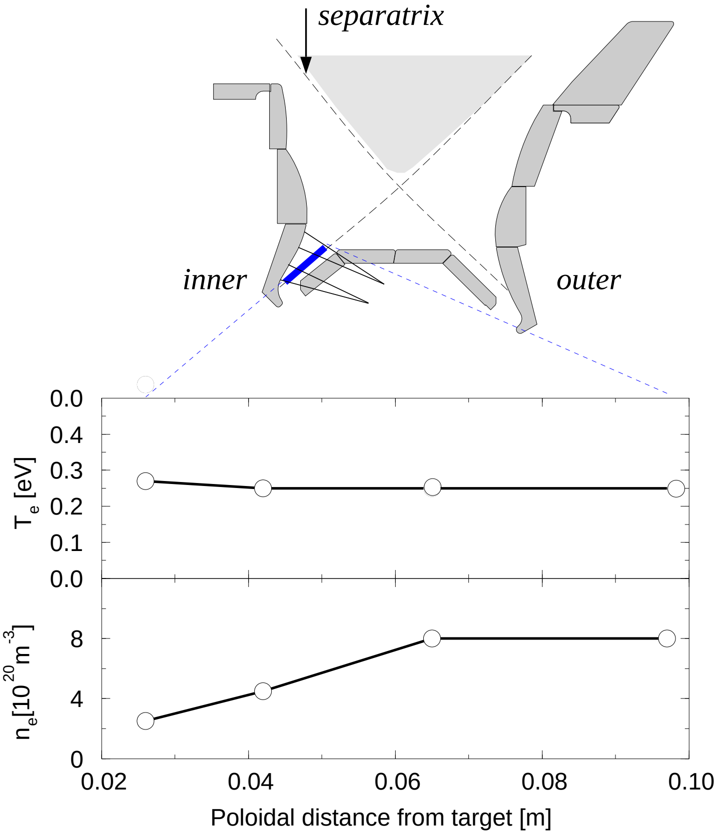

Figure 1: Electron density and temperature profiles of a strongly recombining plasma in the inner divertor of ASDEX Upgrade

evaluated (Fig. 2). The electron temperature was obtained from the spectral resolved continuum emission and the electron density from the absolute value of the continuum emission. When the neutral pressure is increased, the recombining region grows in longitudinal direction. Since our line-of-sight is fixed, we sample the recombining region at different longitudinal positions. In this sense Fig. 2 represents longitudinal profiles but with different values of the neutral pressure for every point.

The temperature profile obtained in this way is rather flat with a minimum of $T_e = 0.12\,eV$. In principle, there could be a stronger variation of $T_e$ which is exactly canceled by the influence of neutral pressure. This is, however, not very likely since the temperature profile in the recombining divertor plasma of ASDEX Upgrade is also flat. The electron density shows a maximum of $2 * 10^{19} m^{-3}$ and decreases toward the end plate.

First we note that the spatial profiles of the plasma parameters are very similar in both devices. The temperature profiles are flat and the electron densities decay toward the target plates. We do not observe a maximum of the electron density in ASDEX Upgrade but this could be due to the limited spatial resolution number (only 4 lines-of-sight). The absolute values, however, are different. In the helium plasma of NAGDIS-II the temperature is only one half compared to the hydrogen plasma in ASDEX Upgrade. The electron density is more than a magnitude lower than in ASDEX Upgrade (factor 40). The latter is clearly due to the limited plasma pressure of the ion source in NAGDIS-II.

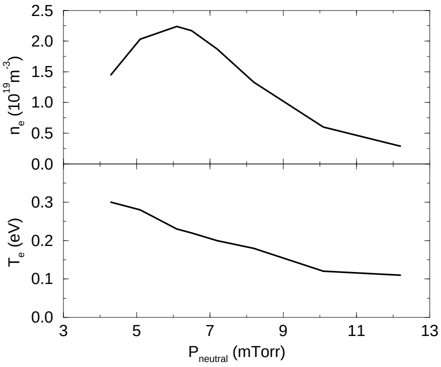

Figure 2: Plasma parameters in front of the end plate in NAGDIS-II as obtained from the continuum emission of neutral helium.

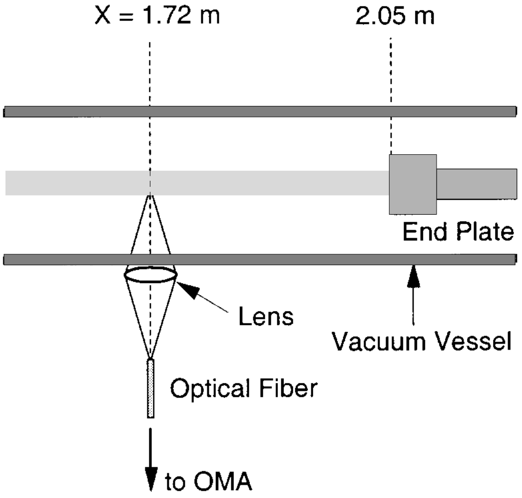

Figure 3: Schematic view of the spectroscopic measurement in the downstream region of the linear divertor plasma simulator NAGDIS-II.

Dense recombing plasma solutions were obtained from the fluid equations. For ASDEX Upgrade volume recombination was predicted using the B2-EIRENE code. Afterwards the spectroscopic results were obtained (Fig. 1). Fig. 2 shows a simulation of the recombining plasma in NAGDIS-II carried out with the B2 code. The essential features are reproduced: the moderate decrease of the electron temperature and the maximum of the electron density at 8 mTorr. The corresponding electron temperature is about 0.5 eV. The increase of the density is due to a slowing down of the plasma flow. For temperatures below 0.5 eV the density decays due to the volume recombination.
Can simpler models describe both experiments? In Ref. [3] a model for the cooling of the plasma was proposed. The ions are thermalized by neutral collisions with frequency $\nu_{iN}$, so that $T_N = T_i$. The electrons with $T_e > T_i$ loose their energy by electron-ion collisions with frequency $\nu = (m/M)\nu_{ei}$. Fig. 5 shows schematically the longitudinal profiles of electron temperature and pressure. They were obtained in asymptotic approximation. For $T > T_*$ electron energy removal via electron-ion collisions is very efficient causing the temperature decrease (recombination front). Volume recombination can be neglected. Therefore the plasma flux remains constant and the pressure is a linear function of the spatial coordinate (due to the used diffusive approximation). For $T \leq T_*$ 3-body recombination becomes strong since $\nu_{3by} \propto T^{-\frac{9}{2}}$. Due to the volume recombination the electron density decreases. At low density the efficiency of Coulomb collisions is low so that the electron temperature varies only slowly.
The plasma in the described experiments is in the range with $T \leq T_*$ since we observe

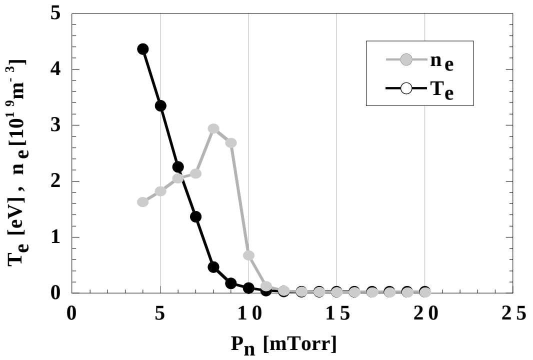

Figure 4: Simulation of the plasma parameters in NAGDIS-II in dependence on the neutral pressure.

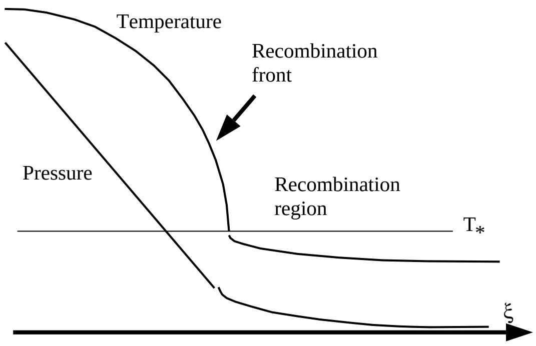

Figure 5: Schematical spatial profiles of the electron temperature and pressure in the region of a recombining plasma according to Ref. [3].

flat temperature profiles and an electron density decay. The experimental value of the temperature should be equal to the temperature in the transition range $T_*$. For helium and a neutral pressure of 10 mTorr $T_* = 0.15eV$ is estimated in Ref. [3] in good agreement with the experimental value obtained in NAGDIS-II (see Fig. 2). For ASDEX Upgrade the model fails. In the ASDEX Upgrade divertor we have hydrogen gas. An ionisation manometer below the roof baffle (Fig. 1) measures a neutral pressure of about 15mTorr. With the scaling of the transition temperature of $T_* \propto NM^{\frac{3}{2}}$ (assuming a constant rate $K_{iN}$) we find for hydrogen $T_* = 0.02\,eV$ which is an order of magnitude below the observed value.

In summary, recombining plasmas in the divertor of ASDEX Upgrade and the divertor simulator are similar despite the different electron density range. Flat electron temperature profiles are found in both devices. The electron densities decay towards the target due to the strong 3-body recombination. Thus, the plasma in the divertor simulator is well suited to study some problems of a tokamak divertor as the complicated response of the $H_\alpha$ emission to ELMs or the enhanced fluctuation level in recombining plasmas.

# References

[1] WENZEL, U. et al., J. Nucl. Mater. **266–269** (1999) 1252.

[2] EZUMI, N. et al., in *Proc. of the 24th EPS Conference on Controlled Fusion and Plasma Physics, Berchtesgaden*, volume 21A, part III, pages 1225–1228, 1997.

[3] KRASHENINNIKOV, S. et al., Phys. Plasmas **4** (1997) 1638.