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Studies of the poloidal temperature asymmetry in the scrape-off layer of ASDEX Upgrade

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1 Introduction

A common feature of a divertor tokamak is a temperature in-out asymmetry: one divertor leg is cold (and, thus, high-recycling and detached) whereas the other one is warmer. On Alcator C-Mod it was shown that the position of the cold leg depends on the direction of the toroidal magnetic field [1] which points to the importance of $E \times B$ drift effects (Fig. 1). Up to now the poloidal $E \times B$ drift was assumed to directly cause the asymmetry by driving the energy away from the cold end. However, very large imbalances, as observed at low density, could not be modelled in this way.

The experimental observations can be explained by the mechanism of symmetry breaking. Asymmetric temperature profiles may occur after a bifurcative transition of the longitudinal temperature profile as demonstrated by one- dimensional modeling [2]. In these models the symmetry is, however, spontaneously broken, i.e no direction is preferred. We study this type of bifurcation in the plasma edge of ASDEX Upgrade using the 2D Braams - Eirene model. In this model the symmetry is already broken by geometry effects without the inclusion of the E×B drift. By a systematic experimental study of the position of the cold divertor leg for discharges with upper and lower single null we investigate the influence of the geometry effect as well as the E×B drift. The described experiments and first modeling results with drift terms point to the radial E×B drift as the leading symmetry breaking mechanism.

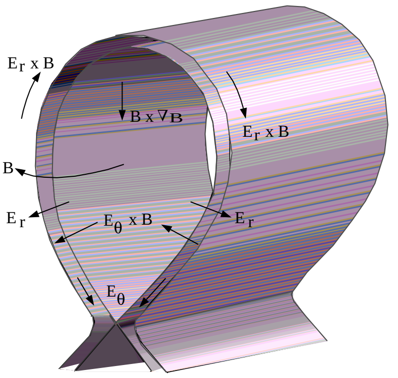

Figure 1: *Flux surfaces and the E×B drifts with a negative toroidal magnetic field (the normal field direction in ASDEX Upgrade)*

2 Temperature asymmetry in the standard configuration

In the standard configuration of ASDEX Upgrade (negative toroidal field, X-point at bottom, Fig. 1) the inner divertor is the colder one. Spectroscopy confirms an observation from ALCATOR C-Mod that temperature imbalance is largest at the lowest line-averaged density available ($5 \times 10^{19}\mathrm{m}^{-3}$ in the ALCATOR C-Mod). Figure 2 shows the change of the CIII emission at 297 nm ($^1\mathrm{D} \rightarrow {}^1\mathrm{P}°$) in a discharge with decaying plasma density. The radiation was sampled with a scanning mirror spectrometer in an Ohmic helium discharge in which the gas valve was closed at 2.1 s. When the line of sight crosses the

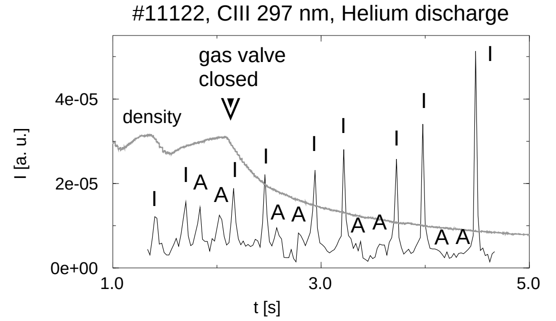

Figure 2: *Radiative pattern of CIII emission at 297nm in the divertor with a lower single null. The intensity trace was recorded with a scanning mirror spectrometer. The peak from the inner divertor is signed with I and from the outer divertor with A. Also shown is the line-averaged density which goes down after 2.1 s because the gas valve was closed. With decreasing density the initially symmetric emission pattern becomes asymmetric.*

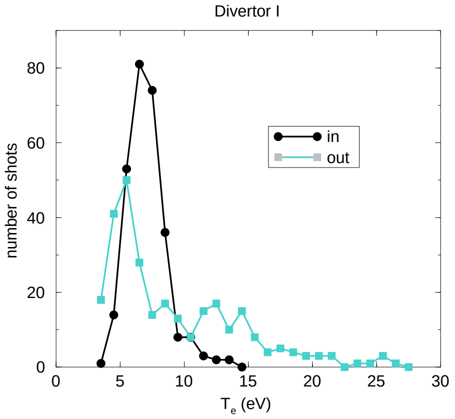

Figure 3: *Distributions of average divertor temperatures for discharges in the range #8000-#8499 (divertor I). In the inboard divertor (black line) it is peaked around 6-7 eV while in the outboard divertor (gray line) the distribution is much broader.*

inner or outer divertor an emission peak is measured. At medium density the emission is almost in-out symmetric. At lower density the intensity rises inboard but vanishes outboard. As a result the emission is strongly in-out asymmetric. Because the measured line intensity is very sensitive to the temperature (the ratio of the ionisation to the excitation rate is approximately a linear function of the temperature) this indicates a strong in-out asymmetry of the electron temperature.

Next we investigate the distributions of T_e in both divertor legs. Fig. 3 shows the number of discharges having a fixed divertor temperature. We analyzed all 288 discharges in the range #8000-#8499 (divertor I) for which Langmuir data was present. To obtain one value of T_e representative for the discharge, the data was first spatially integrated and then averaged in time. From these values, histograms with a resolution of 1 eV were constructed. As Fig. 3 shows, the distributions exhibit significant differences. In the inboard divertor the mean temperature is 7 eV. The variance is small (2.4 eV^2), i.e. T_e is only weakly dependent on the discharge conditions. In the outer divertor the mean value is 9.2 eV. The variance, however, is ten times greater (26.4 eV^2). Different discharge conditions (i.e. variations of power input and density) are reflected by a varying T_e in the outer divertor.

3 Numerical modeling of the edge plasma

Numerical simulation (without E×B drifts) of the edge plasma over a wide range of densities helped us to understand the appearance of the asymmetric T_e profiles. In Fig. 4 the results are shown for an input power of 3 MW and a constant diffusion coefficient of 0.2 m^2s. All plasma parameters are the maximum values at the target plates. At very low density (not routinely accessible in ASDEX Upgrade) electron temperature and pressure are almost in-out symmetric. At higher density a transition occurs from the high temperature divertor state to the low temperature one. In the inner divertor the electron temperature drops from 40 eV to 2 eV (detached) while in the outer the temperature is 15 eV (attached). After that the outer divertor cools down more gradually with further increasing density. The transition is related to a bifurcation point of the plasma solution. It is a consequence of the particular characteristic of the impurity radiation function (which has a negative derivative for carbon below 40 eV) and the non-linearity of the heat

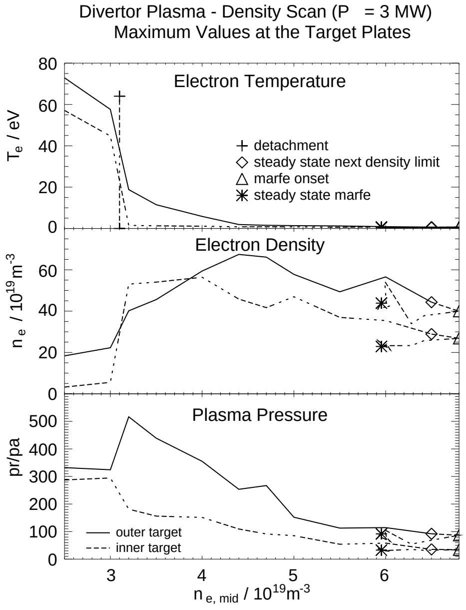

Figure 4: *Plasma parameters (maximum values at the target) for a density scan in the B2-Eirene model (solid lines - outer divertor, dotted lines - inner divertor). At the density* $3 * 10^{19} m^{-3}$ *the inner divertor detaches while the outer cools down more gradually. After the transition the divertor plasma exhibits a great in-out asymmetry of the temperature and of the plasma pressure.*

flux. Detachment may occur when both conditions are fulfilled, i.e. the temperature is below 40 eV. A small initial asymmetry as present in Fig. 4 is amplified by the bifurcation. Therefore, the cold divertor leg is at this end where the bifurcation temperature is reached. By the drop of the temperature less power can be transferred through the sheath at the cold target. As a consequence, the partition of the power into the both flux tubes becomes asymmetric and thus the divertor temperature, too.

The numerical simulation reflects the main experimental observations:

- T_e is constant in the inner divertor. Variation of the energy input influences mainly the temperature in the outer divertor. In the inner divertor the measured values are, however, a factor of three above those predicted by the B2-Eirene model. As the probe measurements are uncertain owing to kinetic and resistive effects at low T_e, we consider them to give an upper limit.
- The T_e asymmetry is largest at low density (Fig. 2). However, we do not reach the bifurcation point even at a density of 8×10^{18}m^{-3}, but the large imbalances are a sign that the bifurcation point cannot be far away.

In the real tokamak two effects compete breaking the initial symmetry: (i) the outboard dominance of thermal transport in the core results in a higher resistance for heat conduction to the inner divertor leg with respect to the outer leg and (ii) E×B drift effects due to radial and poloidal electric fields. Only the first effect is included in the B2-Eirene model. The cold leg is thus predicted to occur always far away from the energy source (i.e. inboard) for the X-point at bottom or on top. In the following section this prediction is checked by an experimental study of the position of the cold leg for discharges with an upper X-point.

4 Temperature asymmetry with X-point on top

By means of spectroscopy we were able to determine the temperature differences between the legs in the high and low density case. At very high densities we observe the Balmer series emission with high quantum numbers due to volume recombination which indicates an electron temperature of about 1 eV (in standard configuration the Balmer emission appears first inboard [3]). At low density we use the typical line emission pattern of intrinsic impurities to detect temperature differences.

For the upper X-point and low density ($4 \times 10^{19} m^{-3}$ with neutral beam heating) we sampled a silicon line at 254.1 nm with the scanning mirror spectrometer. The emission pattern is asymmetric as expected with the emission from the outer divertor, i.e. the low temperature leg is now localized outboard. The same is true at high densities as demonstrated in Fig. 5. The left figure shows the Balmer line with n=7 during density ramp-up which alos appears first outboard contrary to the case with the X-point at bottom. In discharges with positiv directed magnetic field the asymmetry reverses (Fig. 5 right). In summary, the low temperature divertor forms always in front of that target from which the poloidal E×B velocity points away assuming an outwards directed radial electric field.

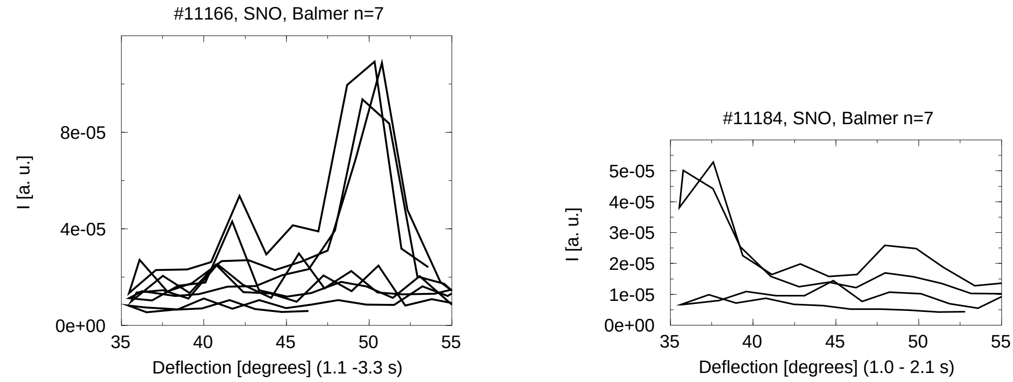

Figure 5: *Comparison of the Balmer line n=7 with an upper X-point for both direction of the toroidal magnetic field. The density was ramped up to the density limit. The Balmer line emission sets in at divertor temperatures below 1eV when volume recombination becomes dominant. It is first observed outboard with normal field (left) and inboard with reversed field (right).*

5 Discussion and conclusions

Our experiments clearly demonstrate that the E×B drift dominates over the effect of a long connection length. In [1] the poloidal drift (see Fig. 1) was identified as the probable candidate to explain the observed asymmetries by driving the energy away from the cold end. However, a preliminary numerical simulation using the B2-Eirene model with the inclusion of the drift terms showed only a significant influence of the direction of the magnetic field when the impurity radiation was considered [4]. Therefore we consider the radial E×B drift to explain the observed asymmetry. It drives electrons and impurity ions in the same direction either inboard (for a lower single null, see Fig. 1) or outboard (for an upper single null). The resulting asymmetric radiation losses cause an asymmetry in the temperature: the divertor leg with the higher radiative losses reaches first the bifurcation point and forms the stable low temperature end of the scrape-off layer.

In summary, it is not the direct action of the poloidal E×B drift which causes the asymmetry. The small effect of the radial E×B drift breaks the symmetry and the asymmetric solution is due to the nonlinearities of the heat conduction and impurity radiation.

References

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