Parallel plasma flow and radial electric field in the scrape-off layer of ASDEX Upgrade

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Introduction

In the scrape-off layer (SOL) of numerous tokamaks a strong parallel plasma flow has been observed [1]-[5]. This parallel plasma flow is an important component in SOL physics influencing the deuterium and impurity transport. In several experiments it was shown that the Pfirsch-Schlüter (PS) ion flow (together with the toroidal rotation) can cause a substantial fraction of the measured parallel plasma flow [1, 3, 4]. So far the parallel flow can be investigated only experimentally since common fluid codes like SOLPS and EDGE2D underestimate the flow by a factor of 3-10. This might be related to an underestimation of the radial electric field (E_r) [6]. Detailed measurements in the SOL allow to benchmark and improve the fluid codes.

Experimental setup and discharges

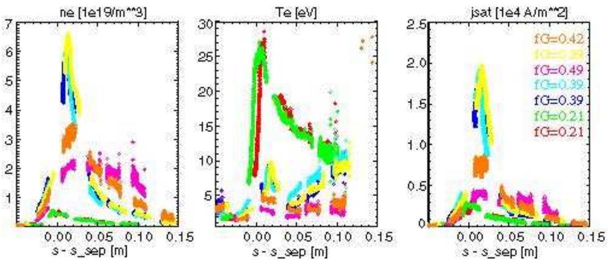

Figure 1: Plasma parameters for several densities at the outer divertor equipped with C tiles.

At ASDEX Upgrade we performed measurements of the parallel flow using a reciprocating probe. The probe is located about 30 cm above torus midplane [5]. The probe head consists of ten pins which were mounted in plane with the surface allowing for high heat fluxes onto the probe. The surface of the probe head is tilted by 14 deg with respect to the toroidal direction, housing five pins on each side. The presented measurements were made with a pair of swept single probes facing opposite directions. The probes were swept with $1.3-1.5$ kHz and the data sampled with 2 MHz. The probe characteristics were analysed as described in [7] to determine the floating potential V_{fl}, electron density n_e and temperature T_e. The Mach number of the parallel flow was determined by Hutchinson's formula $M = 0.43 ln(j_+/j_-)$ [8]. The saturation currents j_+ (facing counter-current), and j_- (co-current) are taken from the single probe measurement by choosing the data with a bias voltage of < -100 V.

In a series of ohmic discharges the density was varied with Greenwald fractions of $f_{GW} = 0.21, 0.39, 0.42, 0.49$. The plasma current was $I_p = 1$ MA and the toroidal magnetic field $B_t = -2.0$ T. Thus the $B \times \nabla B$ drift direction was towards the active lower divertor. The parallel plasma flow (transport) might be related to the plasma in the divertor (energy and ion sink). Figures 1 and 2 show the plasma parameters in front of the divertor determined from flush mounted Langmuir probes. To gain a better radial resolution strike point scans were performed. The profiles are shown over the distance to the separatrix along the target. For $f_{GW} = 0.21$ the inner target is not yet detached while the outer divertor is fully attached showing rather high T_e up to 25 eV. At $f_{GW} = 0.39$ the ion saturation current j_{sat} and the density in the outer divertor is still increasing. The reduced T_e close to the separatrix indicates a beginning power detachment while in the SOL wing T_e is still unchanged. The inner divertor is already fully detached and cold. At $f_{GW} = 0.42$ the density just started to decrease in the outer divertor (ion flux detachment) and the n_e profile broadens. With $f_{GW} = 0.49$ the outer divertor is detached and cold, $T_e < 5$ eV.

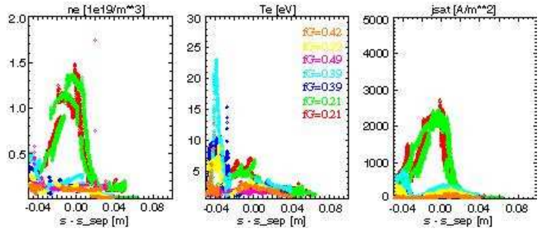

Figure 2: Plasma parameter for several densities at the inner divertor.

Measurements at the midplane

Comparing the data taken during the inward and outward motion of the probe some deviations occur. V_{fl}, j_{sat}, T_e and n_e profiles taken during the outward motion are in several cases virtually shifted by ≤ 5 mm inward compared to the inward motion profile. An increased electron emission due to a heating of the probe can e.g. reduce the potential but is expected to cause a jump from V_{fl} to the plasma potential V_{pl} rather than a moderate increase in the potential [9]. The influence of electron emission on j_{sat} is expected to be smaller than on V_{fl} in contradiction to the measurements. Thus, the reason for this virtual shift is not clear. Since the differences of the measurements during the inward and outward motion of the probe are of the order of the data scatter we use for further analysis averaged values not distinguishing between outward and inward motion. The radial profiles were binned with a box of 1 mm.

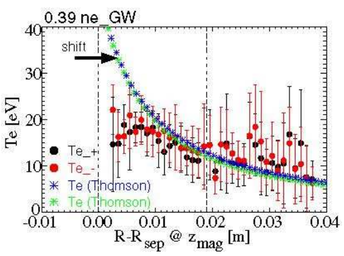

Figure 3: Average temperature profile for the discharges at $f_{GW} = 0.39$ in comparison with a T_e fit from the Thomson scattering system for two of these discharges mapped to the distance to the separatrix at midplane.

The pins facing in counter-current direction detected a higher V_{fl}, j_{sat}, and n_e than the opposite pin. The temperature is the same on both sides of the probe as indicated in black and red in fig. 3). The error bars correspond to the standard deviation of the binned data. The left vertical line shows the separatrix position while the right one indicates the innermost point outside of which we expect the measurements to be influenced by neighbouring limiters. For a further analysis the mean values of co- and counter-current pin were used for V_{fl} and n_e. In the low density case the probe was kept at a rather large distance to the separatrix. In all other cases the temperature determined from the probe characteristics is rather low at the separatrix, about 20 eV. In comparison a fitted T_e profile from the edge Thomson scattering (TS) diagnostic is shown. With the ansatz of a Bohm like transport which delivered the best fit results for the SOL the power balance was used to correct the separatrix position for the T_e profile from TS. These shifted profiles are shown in figure 3 where the black arrow indicates the shift which is consistent with earlier observations. Close to the separatrix the Langmuir probes obviously underestimate the electron temperature at least in medium to high density discharges. A possible explanation for this observation is given by the fact that the TS diagnostic is more sensitive to bulk electrons while the Langmuir probes are sensitive to the Maxwellian tail. Possibly a loss of fast electrons in the SOL causes the T_e underestimation of the probes.

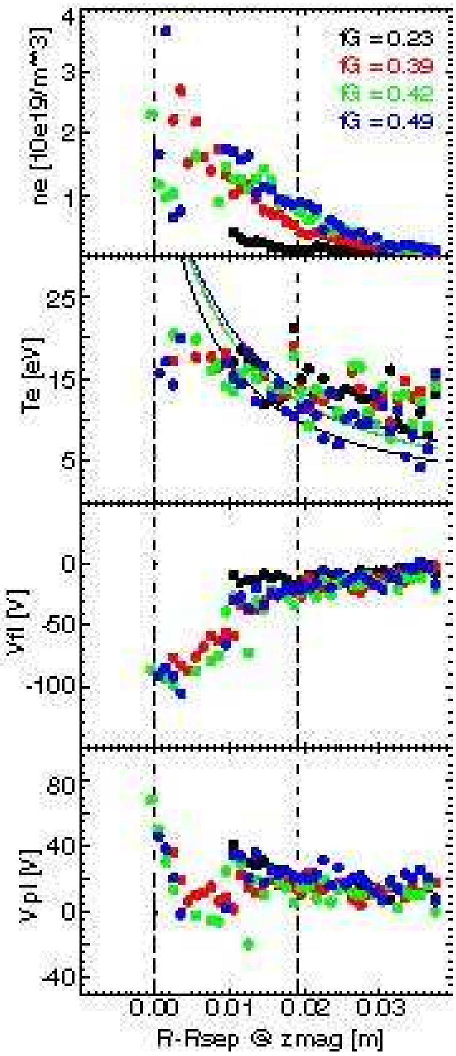

Figure 4: SOL profiles for a density scan mapped onto $R - R_{sep}$ at the midplane. Probe data are shown as dots, TS data as lines.

In figure 4 n_e, T_e, V_{fl} and V_{pl} are plotted over $R - R_{sep}$ mapped onto the midplane. From $f_{GW} = 0.39$ to 0.49 the SOL density increases only slightly. T_e from the probes and TS is rather similar for all n_e. V_{fl} is strongly decreasing towards the separatrix for $f_{GW} \geq 0.39$. The strong V_{fl} decrease at medium densities can be explained by the divertor detachment. V_{fl} is measured with respect to the divertor potential. Therefore a decrease of $T_{e,div}$ causes a reduced potential drop ΔV in front of the divertor while ΔV at the midplane probes stays unchanged. V_{pl} is determined from V_{fl} and T_e with $V_{pl} = V_{fl} + 3.1T_e$ [9] using the T_e from TS. The profile is rather flat but then increases strongly towards the separatrix. The dip at $R - R_{sep} \approx 0.005\,\mathrm{m}$ is most probably a measurement error ($E_r < 0$ cannot be expected). In fig. 5 the measured flow profiles are shown (dots). At low density there is a large parallel flow from the outer midplane towards the magnetic high field side (HFS) indicated by the positive sign. The peak value reached in the measurement is 0.6. The behaviour closer to the separatrix is unknown. The shape of the flow profiles at higher densities follows closely the profile shape of V_{pl} although the dip ($M \approx 0.2$) is shifted a few mm outward. At medium densities there is still the slight tendency of decreasing M with increasing n_e. Over the last cm towards the separatrix M strongly increases reaching $M = 0.5 - 0.6$.

Good agreement between measured parallel and calculated Pfirsch-Schlüter flow was reported in [1, 4]. To determine the Pfirsch-Schlüter flow the n_e, T_e profiles shown in figure 4 were fitted exponentially to calculate the gradients. $E_r = -\nabla_r V_{pl}$ was determined from a polynom fit to V_{pl}. In cylindrical approximation the parallel M_{PS} can be expressed by

$$M_{PS} = \frac{2r}{RB_{pol}} \frac{cos(\theta)}{c_s} \left(E_r - \frac{\nabla p_i}{en_e} \right) \quad (1)$$

with the ion sound velocity c_s, minor and major radius r and R, poloidal angle θ, poloidal B-field

B_{pol}, and the ion pressure p_i. We assume $T_e = T_i$. Most probably this assumption overestimates M_{PS} since ∇p_i is expected to be more flat than ∇p_e. A more complete expression for the parallel flow taking into account the ellipticity of the geometry and a 'return parallel flow' caused by the $E \times B$ drift was derived in [10]:

$$M_C = \frac{E_r}{c_s B_{pol}} - \frac{2r}{c_s R} \frac{B}{B_{pol}} \frac{\nabla p_i}{e n_e B} \left(1 + \frac{\tan^2 \theta}{\kappa^2}\right)^{-0.5} \quad (2)$$

with the elongation κ. In figure 5 the comparison of the measured flow (dots) with the PS flow in cylindrical geometry (broken line) and M_C (solid line) is shown. M_C is larger than M_{PS}. The wiggles at $R - R_{sep} > 5\,\mathrm{mm}$ are most likely caused by measurement errors, so that M_{PS} and M_C are almost constant at ≈ 0.1 for $f_{GW} \geq 0.39$ which is less than the measured flow in this region of $M \geq 0.2$. Towards R_{sep} both M_{PS} and M_C are strongly rising and can account for the measured flow. This rise is caused by a strong increase of E_r. At low densities where the measurement is available for $R - R_{sep} > 1\,\mathrm{cm}$ only $M_{PS} \leq 0.15$, $M_C \leq 0.25$ are much lower than the measured $M \approx 0.6$.

Conclusions

The Langmuir probes underestimate T_e significantly when approaching the separatrix. The measurements show a strong parallel flow in the SOL towards the HFS. At low n_e there is a large flow in the outer SOL. When the outer divertor shows partial detachment a strong flow of 0.6 was observed at R_{sep} decreasing over 5 mm to ≈ 0.2 where it is rising again. Close to the separatrix the PS and 'return flow' can cause the observed flow but further outside there has to be a large additional contribution like e.g. a transport related flow. Possibly there exists a connection of parallel flow and divertor detachment.

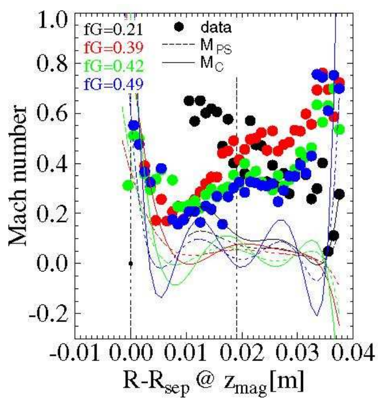

Figure 5: Mach number profiles for different n_e. Showing the data (dots), the PS flow M_{PS} (broken line) and M_C (solid line).

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