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 (Eᵣ) [6]. Detailed measurements in the SOL allow to benchmark and improve the fluid codes.

Experimental setup and discharges

At ASDEX Upgrade we performed measurements of the parallel flow using a reciprocating probe. The probe is located about 30cm 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 – 1.5kHz and the data sampled with 2MHz. The probe characteristics were analysed as described in [7] to determine the floating potential Vᵦ, electron density nₑ and temperature Tₑ. The Mach number of the parallel flow was determined by Hutchinson’s formula

\[ M = \frac{0.43}{\ln\left(\frac{j_+}{j_-}\right)} \]

[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 \(< -100\, \text{V}\).

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 \(I_p = 1\, \text{MA}\) and the toroidal magnetic field \(B_t = -2.0\, \text{T}\). 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 pro-
files 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.

**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 $\leq 5$ 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. 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.

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 $\Delta V$ in front of the divertor while $\Delta V$ 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 $R - R_{sep} \approx 0.005$ 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

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

with the ion sound velocity $c_s$, minor and major radius $r$ and $R$, poloidal angle $\theta$, poloidal B-field.
$B_{\text{pol}}$, and the ion pressure $p_i$. We assume $T_e = T_i$. Most probably this assumption overestimates $M_{PS}$ since $\nabla p_i$ is expected to be more flat than $\nabla p_e$. 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]:

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

(2)

with the elongation $\kappa$. 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 $R - R_{sep} > 5$ mm are most likely caused by measurement errors, so that $M_{PS}$ and $M_C$ are almost constant at $\approx 0.1$ 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 $R - R_{sep} > 1$ 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 $\approx 0.2$ 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.

References