Available online at www.sciencedirect.com

ScienceDirect

Journal of Nuclear Materials 363–365 (2007) 605–610

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Deuterium plasma flow in the scrape-off layer of ASDEX Upgrade

H.W. Müller [a,*], V. Bobkov [a], A. Herrmann [a], M. Maraschek [a], J. Neuhauser [a], V. Rohde [a], A. Schmid [a], M. Tsalas [b], ASDEX Upgrade Team [a]

[a] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany*
[b] *NCRS Demokritos, Institute of Nuclear Technology – Rad. Prot., Attica, Greece*

Abstract

Measurements of the plasma flow parallel to the magnetic field in the scrape-off layer (SOL) of ASDEX Upgrade were performed using Mach probes. The parallel flow was studied at various densities in L- and H-mode discharges with lower and upper single null configuration applying normal and reversed toroidal field. Two reciprocating probes allow for flow measurements in the outer midplane and in front of the lower divertor, slightly below the X-point, covering the inner and outer divertor leg. Strong parallel flows were observed with Mach numbers of up to 0.6 in the outer midplane and even larger than 1.0 above the divertor. Such a flow can connect the particle loss of the confined plasma predominantly happening on the torus outside to the strong recycling observed at the torus inside. The plasma flow varies with plasma density and ion drift direction.

PACS: 52.25.−b; 52.30.−q; 52.55.Fa

Keywords: ASDEX Upgrade; Edge plasma; Plasma flow; Probes; Divertor plasma

1. Introduction

Strong flows have been observed in the scrape-off layer (SOL) of tokamaks, e.g. [1–3] and references therein. It is thought that the parallel plasma flow plays an important role for the particle transport in the SOL. Experiments and modelling efforts have shown that the particle loss from the confined plasma predominantly takes place at the magnetic low field side (LFS) driven, e.g. by filamentary transport and ballooning modes [4–7]. Nevertheless a strong deuterium and carbon recycling was observed at the inner heat shield of ASDEX Upgrade [8]. A possible mechanism to bring the particles from the LFS to the high field side (HFS) is a plasma flow in the SOL parallel to the magnetic field which also could be linked to divertor power asymmetries or be related to impurity migration and carbon deposition. Many driving forces might be related to the plasma flow like poloidal asymmetries of the pressure, poloidal and toroidal plasma rotation or cross-field drifts ($\vec{B} \times \nabla B$, $\vec{E} \times \vec{B}$). Due

* Corresponding author.
E-mail address: Hans.Werner.Mueller@ipp.mpg.de (H.W. Müller).

doi:10.1016/j.jnucmat.2006.12.054

to the number of possibly involved mechanisms and supposed importance for transport the plasma flow is thought to be a key element modelling and understanding the SOL transport. Since modelling the plasma flow with cross-field drifts included is still a challenge for the codes [2,3] flow measurements in well diagnosed SOL plasmas are of great importance, but rather rare for H-mode discharges.

2. Experimental setup

ASDEX Upgrade [9] has good diagnostic capabilities for SOL studies. The measurements presented in this paper were performed by Langmuir probes. The divertors in ASDEX Upgrade are equipped with a poloidal array of flush mounted Langmuir probes (thick black dots in Fig. 1) which are usually operated as triple probes. Additionally there are two fast reciprocating probes, one located in the outer midplane (MEM) [10], see Fig. 1, and another at the X-point of the lower divertor (LPS) [11]. Both probes perform their strokes in the 100 ms range. The midplane system samples the data with 2 MHz, while the X-point probe collects the data with 500 kHz. The X-point probe was equipped with three pin tips, where two were acting as a Mach probe, measuring the toroidal Mach number and the third one was operated as single (swept) probe. The midplane system used probe heads with 10 in-plane pins, 5 in each toroidal direction [12]. During the experiments presented here two pins located on opposite sides were operated as single probes. The ion saturation branch of the swept probes (voltage < -100 V) is used for calculating the Mach number. These saturation currents are thought to emerge from currents essentially parallel to the magnetic field B since $c_s/v_{\perp,d} \gg B_t/B_p$, with ion sound speed c_s, cross-field velocity due to drifts $v_{\perp,d}$ and toroidal and poloidal field B_t, B_p. This allows to deduce the Mach number of the parallel plasma flow using Hutchinson's formula $M = 0.43\ln(j_+/j_-)$ [13], where j_+ is the saturation current parallel to B and in co-current direction with respect to the plasma current I_p and j_- the saturation current in opposite direction.

3. Plasma flow in ohmic discharges

Two ohmic discharges (#21305, #21326) with $B_t = -2\ T$, $I_p = 1$ MA and $q_{95} = 3.3$ were performed including a strike point sweep to get good profiles from the Langmuir probes in the lower divertor. The ion $\vec{B} \times \nabla B$ drift points towards the active divertor. The plasma shape is shown in Fig. 1 on the left. In #21305 the density was $n_e = 2.8 \times 10^{19}\ m^{-3}$ corresponding to a Greenwald

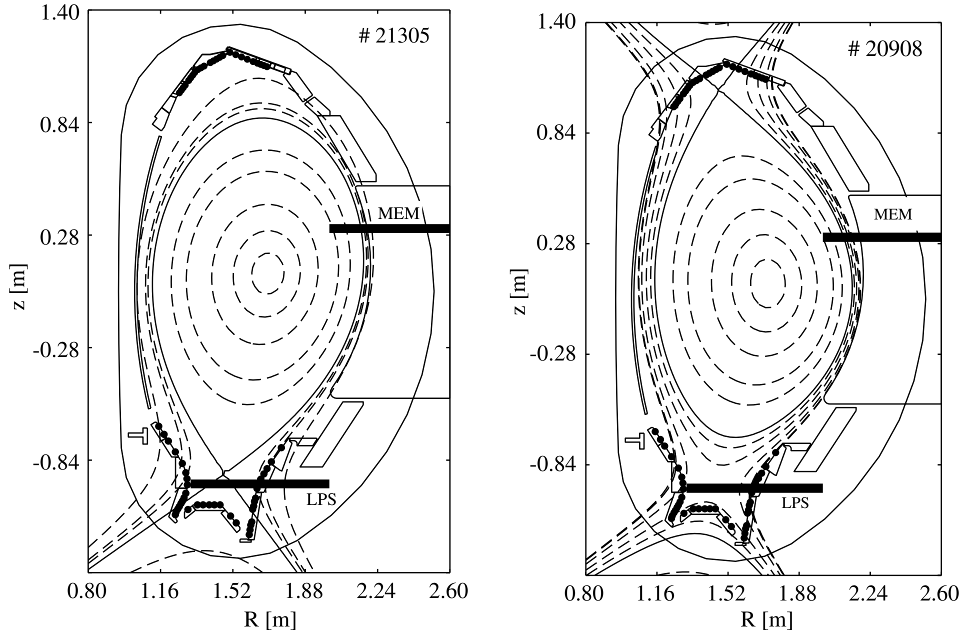

Fig. 1. Poloidal cross section of ASDEX Upgrade showing the reciprocating probes MEM and LPS with the plasma shape of the discharges #21305 and #20908.

fraction of $f_{GW} = 0.2$. Here the outer divertor was fully attached and the inner divertor not yet detached. For #21326 the density was increased to $n_e = 5.5 \times 10^{19}\ m^{-3}$ or $n_e = 0.43 n_{GW}$. This caused a detachment of the inner divertor while the outer divertor just started to detach. The ion saturation current in the outer divertor already decreased during the discharge while the line averaged density stayed constant.

Fig. 2 shows the Mach numbers of the parallel flow measured by the probe at the LFS mapped to the outer midplane for #21305 (solid circles) and #21326 (open triangles). For distances to the separatrix beyond the solid vertical black line the measurement might already be influenced by in-vessel structures. The collection length of the Langmuir probe is $L_{col} \sim 0.4$ m. We assume that for a connection length $L_c \sim 10 \times L_{coll}$ the flow measurement is not disturbed by structures intersecting the flux tube onto the probe. With both sides of the probe connected to the divertor ($R - R_{sep} < 0.022$ m, in front of the solid vertical line) there is a minimum of $M \approx 0.25$ in the low density case. Towards the separatrix follows a strong rise of M reaching a maximum of $M \approx 0.6$ at the innermost point of the stroke, 5 mm outside the separatrix (broken vertical line). The uncertainty of the probe position relative to the separatrix is in the range of ∼5 mm. The positive M corresponds to a plasma flow in co-current direction assuming a flow parallel B towards the HFS and inner divertor. This flow from the outer midplane towards the inner divertor in the given configuration has also been observed at various other tokamaks [1–3]. It is unclear, if closer to the separatrix M will decrease again as e.g., in JET. The observed flow is already a candidate for

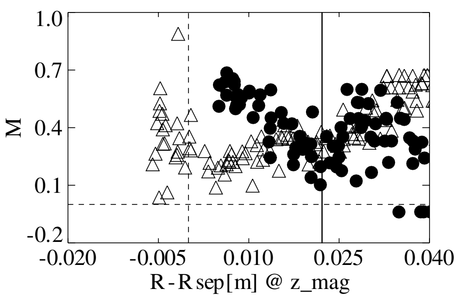

Fig. 2. Parallel flow in ohmic discharges at the MEM position mapped to the outer midplane. The filled circles indicate the low density case, the open triangles the Mach number at $n_e = 0.43 n_{GW}$. The flow is directed towards the inner divertor ($M > 0$).

a strong particle transport from LFS to HFS. Previous measurements at ASDEX Upgrade and JET have shown that the parallel flow in the outer midplane is quite similar for NBI heated H-mode and L-mode/ohmic plasmas [3,12]. Increasing the density to $n_e = 0.43 n_{GW}$ keeps the parallel flow in the outer region unaffected. Further towards the separatrix the flow decreases to $M \approx 0.15$ just outside the separatrix, but the direction stays unchanged. Inside the separatrix the flow increases again to $M \approx 0.4$. So, the density strongly affects the parallel flow in the SOL as also reported from other experiments [1–3].

In Fig. 3, the electron pressure ($p_e = n_e k_B T_e$, Boltzmann factor k_B and electron temperature T_e) profiles are shown. In the low density case the pressure profile of the X-point probe (LPS) is identical at LFS and HFS, even in a range where a strong parallel flow was detected at the outer midplane. Also the profile from the outer divertor probes agrees (although there is an uncertainty due to possibly eroded tips at the LPS probe). The pressure profiles determined from the midplane probe, facing co- and counter-current, are about the same, but show a strong scatter. Only at the inner divertor the pressure is somewhat reduced, maybe due to a beginning detachment. So, there is no clear poloidal variation of the pressure profile detected, which could cause the observed strong plasma flow. At higher density (#21326) the inner divertor is completely detached and the pressure very low. The pressure in the outer divertor rose only slightly with the density increment compared to the pressure increase at the X-point probe. The pressure profiles at the X-point again agree for HFS and LFS.

The flows at the X-point probe in front of the divertor are shown in Fig. 4 compared to the MEM flows at the LFS. The flow in front of the divertor is always directed towards the closest divertor, $M > 0$ at the inner divertor, $M < 0$ at the outer one. For low densities the flow is subsonic and decreasing from outside towards the separatrix, where M even gets close to 0 in the outer divertor. Since the parallel flow at the outer midplane is towards the HFS there must be a stagnation point at the LSF between divertor and the MEM position. At higher line averaged density the flow is decreased in the outer part of the divertors, but larger close to the separatrix, the peak value in the inner divertor is even $M \approx 1.6$, while the parallel flow at the outer midplane is reduced close to the separatrix ($R - R_{sep} < 1.5$ cm). The stagnation point remains

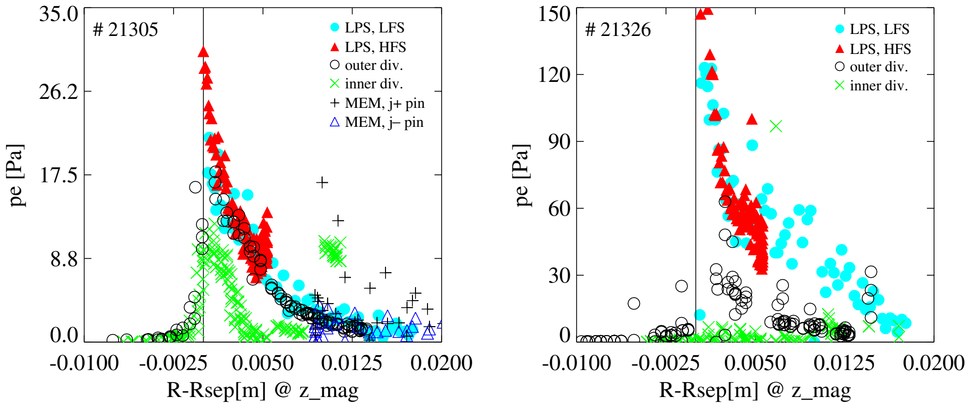

Fig. 3. Electron pressure profiles at the position of the LPS probe and the divertor probes mapped to the outer midplane. MEM probe measurements are available for #21305 only. The left hand side shows the low density ($f_{GW} = 0.2$) discharge #21305, the right picture #21326 which was at $f_{GW} = 0.43$.

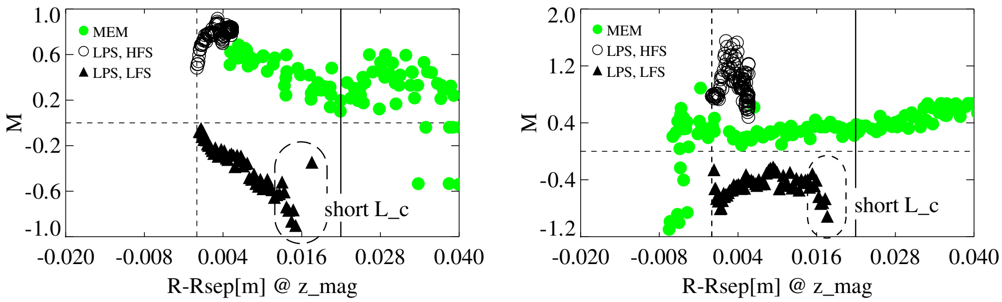

Fig. 4. Comparison of toroidal flow at the LPS position and parallel flow at the main chamber LFS mapped to the outer midplane for #21305 at $f_{GW} = 0.2$ (left) and #21326 at $f_{GW} = 0.43$ (right).

between outer divertor and outer midplane. The reduced Mach number in the outer midplane might indicate that the stagnation point is closer to the MEM position. At low density the Mach numbers in the outer midplane and in front of the inner divertor are in the same range while at higher density the Mach number increases strongly towards the inner divertor.

4. Parallel plasma flow in upper single null H-mode

The shape of the H-mode discharges in upper single null (USN) configuration is shown in Fig. 1 (right). The USN allows to change the direction of B_t and helicity on a shot to shot base due to flat divertor targets. All discharges were performed with $I_p = 0.8$ MA, $|B_t| = 2$ T, $q_{95} = 4.2$, two densities $n_e = 6.6 \times 10^{19}$ m^{-3} and $n_e = 8.0 \times 10^{19}$ m^{-3} corresponding to $f_{GW} = 0.65$ and $f_{GW} = 0.8$, NBI and ICRH heating of $P_{NBI} = 5$ MW and 2–2.5 MW.

Fig. 5 shows the parallel flow measured at the outer midplane in different scenarios (two densities $f_{GW} = 0.65$, $f_{GW} = 0.8$ and $B_t = +2$ *T*, $B_t = -2$ *T*). Different symbols in one graph indicate data from different discharges with identical parameters (up to three discharges and five strokes included). The flow profiles agree well although the discharges were performed in two campaigns with different probe heads. So, the results are robust. For $B_t = +2$ *T* the ion $\vec{B} \times \nabla B$ drift is towards the active divertor. $M > 0$ indicates a parallel flow directed towards the HFS and inner divertor. The vertical solid line represents the innermost position which is likely affected by a short L_c to the tip measuring j_-, the broken one the outermost position where this tip is connected $\| B$ to the inner upper divertor. In between the two lines the tip is connected to the outer lower divertor. For $n_e = 0.65 n_{GW}$ the flow is away from the upper outer divertor and radially increasing towards the separatrix. The situation corresponds to the LSN discharges. However, M

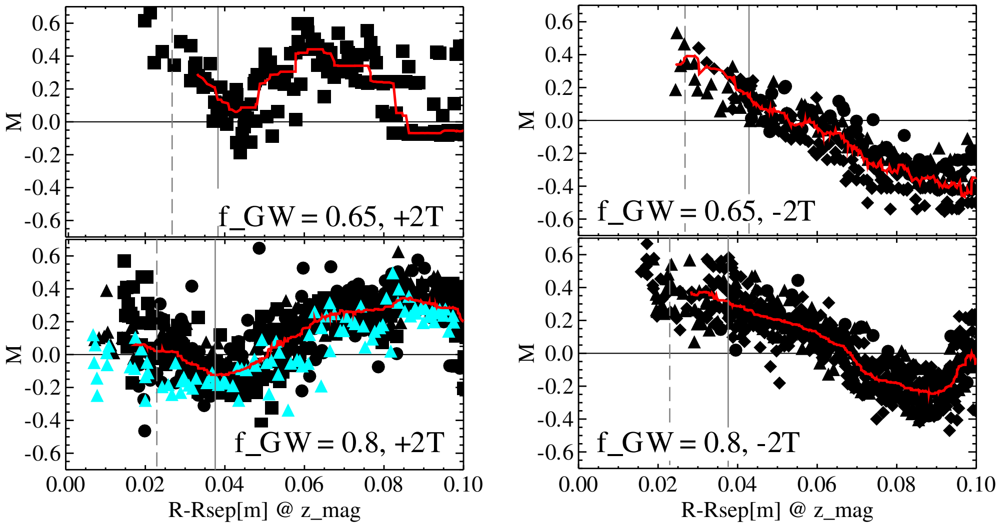

Fig. 5. Parallel flow from MEM probe for USN discharges with ion $\vec{B} \times \nabla B$ drift towards active divertor ($+2T$) and away ($-2T$). Different symbols correspond to different discharges. The red lines indicate an averaged value for the complete data set. For $f_{GW} = 0.8$, $B_t = +2T$ a single stroke is highlighted. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

is surprisingly high for $f_{GW} = 0.65$ (compare Fig. 2). Possibly the degree of detachment is of importance. The upper divertor is much more open than the lower one and hence the plasma flow might be higher than in LSN configuration at the same density. With increasing the density to $n_e = 0.8n_{GW}$ the parallel flow is again decreased. Close to the separatrix the direction of the flow remains in co-current direction. Where the j_+ pin is connected to the lower outer divertor and extending into the limiter shadow occurs a flow reversal. A single stroke showing this quite clear is highlighted in Fig. 5. Since the absolute value of M is rather small and some strokes show this only very weak a more detailed study is required to exclude artefacts (e.g., offsets in the measurement).

When B_t is changed to $-2\ T$ the ion $\vec{B} \times \nabla B$ drift is away from the active divertor and $M > 0$ indicates a parallel flow towards the upper outer divertor. Then the tip measuring j_+ is the first affected by a short L_c and connected to the inner divertor for positions close to the separatrix. The parallel plasma flow is in co-current direction, but now towards the upper outer divertor (changed helicity). For $f_{GW} = 0.65$ the plasma flow agrees quite well with the $+2\ T$ case, the Mach number and the slope are about the same outside the limiter shadow. But this time the particle flux is into the upper outer. After the density increment to $n_e = 0.8n_{GW}$ the flow is not decreasing. Possibly the flow is not decreasing with the density increment since this time the flow in the outer midplane is already directed towards the closest divertor.

5. Conclusions

In a wide range of plasma parameters strong plasma flows are measured in the SOL. Since the estimated $c_s/v_{\perp,d} \gg B_t/B_p$ these flows are essentially parallel B. In LSN discharges with ion $\vec{B} \times \nabla B$ drift towards the active divertor close to the divertor targets the flow is directed to the target and can reach supersonic values. The flow at the main chamber LFS is directed to the HFS for the ion $\vec{B} \times \nabla B$ drift to the active divertor and low to medium densities. Therefore it is a candidate for a strong particle transport in the SOL. At high density $f_{GW} = 0.8$ the outer region of the scrape-off layer showed a flow reversal while the region close to the separatrix still remains in co-current direction. The density, possibly via the divertor detachment, is an important player for the flow. The behaviour at high density with ion $\vec{B} \times \nabla B$ drift to the active divertor has to be investigated in more detail to exclude artefacts. When the ion drift is away from the active divertor the plasma flow in the main chamber LFS remains in co-current direction which is towards the upper outer divertor in the studied USN configuration. Hence the cross-field drifts play an important role for the plasma flow. At low densities high Mach numbers occur but no strong poloidal variation in the static pressure was detected.

References

[1] N. Asakura et al., Nucl. Fusion 39 (1999) 1983.
[2] B. LaBombard et al., Nucl. Fusion 44 (2004) 1047.
[3] S.K. Erents et al., Plasma Phys. Control. Fusion 46 (2004) 1757.
[4] S. Krasheninnikov, Phys. Lett. A 283 (2001) 368.
[5] J. Neuhauser et al., Plasma Phys. Control. Fusion 44 (2002) 855.
[6] W. Suttrop et al., Plasma Phys. Control. Fusion 42 (2000) A97.
[7] S. Saarelma et al., Nucl. Fusion 43 (2003) 262.
[8] A. Kallenbach et al., Nucl. Fusion 43 (2003) 573.
[9] A. Herrmann et al., Fusion Sci. Technol. 44 (2003) 569.
[10] V. Rohde et al., ECA 20C (EPS 1996) d040.
[11] N. Tsois et al., J. Nucl. Mater. 269 (1999) 1230.
[12] H.W. Müller, ECA 29C (EPS 2005) P1.009.
[13] I.H. Hutchinson, Phys. Rev. A 37 (1988) 4358.