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Langmuir probe measurements in the lower x-point vicinity of the ASDEX Upgrade divertor

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Abstract

Measurements made with a reciprocating Langmuir probe which crosses both divertor legs of the ASDEX Upgrade tokamak just below the lower x-point are presented. The electron temperature, density and pressure profiles obtained in ohmic discharges are similar to previous measurements but the detailed structure, especially near the nominal separatrix, is rather complex and differs from earlier divertor configurations. Observations made in H-mode discharges near the L–H power threshold indicate that the probe tip influences the ELM signature when crossing the vicinity of the inner and outer leg separatrices, causing a temporary reduction of the ELM signature amplitude accompanied by an increase in the frequency. We briefly discuss possible mechanisms responsible for this effect.

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1. Introduction

Of significant concern in ITER is the divertor plate heat load, particularly during type I ELM's, as recent estimates suggest that they could cause fast divertor plate erosion and enhancement of tritium co-deposition in carbon [1]. The study of plasma parameters in divertors of existing tokamaks is therefore essential, as better understanding of the physical processes occurring can aid in the optimisation of particle and energy exhaust. Langmuir probes are commonly used to study divertor properties and, despite uncertainties in their data interpretation, have been employed extensively in most tokamaks (see e.g. [2–5]). To study the Div IIb divertor of ASDEX Upgrade [6], a reciprocating Langmuir Probe system [7] was used to measure electron temperature, density, ion saturation current and floating potential in the vicinity of the lower x-point for several discharge configurations.

To reduce the power load during type I ELM's, several ELM mitigation techniques have been proposed, including pedestal density increase by gas puffing, radiation cooling by nitrogen puffing in the divertor [8] and manipulation of the target plate currents [9]. ELM control by pellet injection [10], by supersonic gas puffing

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and by vertical plasma wobble [11] has also been tried. However, despite the relative success of these experiments, there are still open questions concerning the mechanisms of ELM mitigation and control. Here we describe an observation made in H-mode discharges near the L–H power threshold, namely an influence of the probe tip on the ELM signature, an effect whose study could contribute to further understanding the mechanisms of ELM mitigation and control.

In Section 2 we first give a brief description of the reciprocating Langmuir probe system. In Section 3 we present measurements performed in ohmic discharges. Finally in Section 4 we describe and discuss the observed probe influence on the ELM signature.

2. The reciprocating Langmuir probe system

The divertor reciprocating Langmuir probe system at ASDEX Upgrade was originally designed for the Div I divertor and subsequently modified for the Div IIa (Lyra) divertor [7]. It was refurbished during 2003 for the divertor Div IIb and used in the 2004 campaign.

The position of the reciprocating arm at full extension is shown in Fig. 1(a). For several plasma shapes, the probe track can approach or, if the power load is tolerable, cross both divertor legs just below the x-point, which lies on the 'first' separatrix for bottom single null and double null equilibria, but on the 'second' one for upper single null equilibria. The full movement takes approximately 300 ms, the fast data acquisition system (~100 kHz) permitting the detection of events occurring on timescales of the order of 10^{-4} s. The probe head consists of three graphite tips, two of which are in Mach probe arrangement. The probe can be used in single, double, mach and floating configurations. The probe shaft is floating.

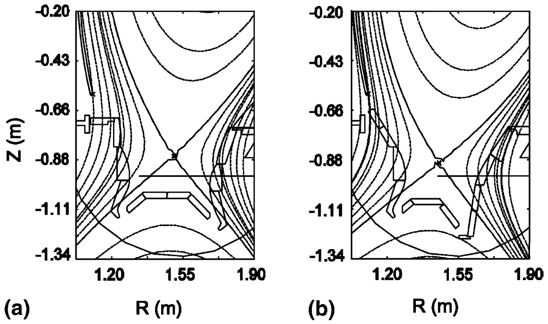

Fig. 1. Position of the reciprocating arm at full extension and magnetic flux surfaces in discharges (a) #11817 and (b) #18789.

3. Results from the standard ohmic discharge

3.1. Setup

Ohmic discharges at ASDEX Upgrade with $I_P \sim 800$ kA, $B_T \sim -2$ T (ion grad**B** drift towards the x-point), and $q_{95} \sim 4$, at low triangularity were used, with probe insertions during two density plateaus, at $\langle n_e \rangle \sim 2.5 \times 10^{19}\,m^{-3}$ (~0.265 of n_{GW}) and at $\langle n_e \rangle \sim 3.5 \times 10^{19}\,m^{-3}$ (~0.36 of n_{GW}). One tip operated in sweeping mode (sweeping frequency ~650 Hz) measuring characteristics, one was biased at −150 V to measure the ion saturation current (I_{sat}) and the third one measured floating potential (V_{fl}).

3.2. Profile measurements

The ion saturation current (I_{sat}) and the floating potential (V_{fl}) measured during a full probe sweep in the lowest density case are shown in Fig. 2, together with the separatrix positions, determined from equilibrium reconstruction of magnetic probe measurements [12]. Experience from past Langmuir probe measurements (see e.g. [5]) suggests that the actual separatrix positions are very near the observed minima of I_{sat}, which also approximately correspond to sudden drops in the floating potential. A 1–2 cm downward shift of the true plasma position compared the equilibrium reconstruction could explain this discrepancy, shifting the separatrix positions given in Fig. 2 by 1–2 cm towards the centre of the graph. The structure of both signals suggests complex processes are involved, but are difficult to interpret

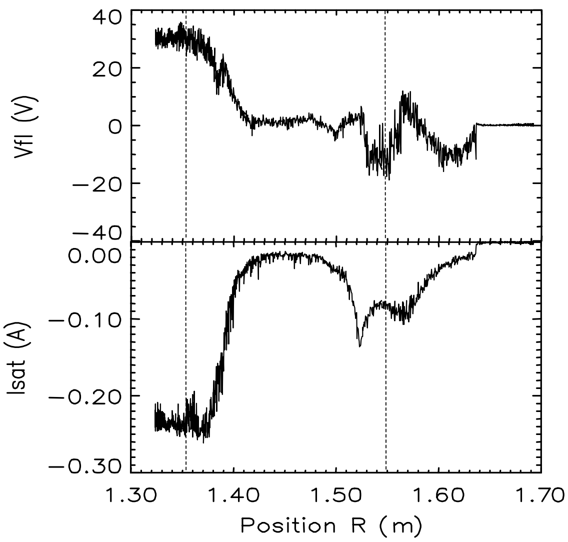

Fig. 2. Ion saturation current (I_{sat}) and floating potential (V_{fl}) profiles in the lower density plateau of the ASDEX Upgrade standard ohmic discharge.

due to the possible separatrix positioning error. The two legs are found to have a voltage difference of approximately 40 V.

Fig. 3 shows the electron temperature, density and pressure across the probe trajectory for the two cases as measured by the sweeping probe. The separatrix crossings are again obtained from equilibrium reconstruction of magnetic probe measurements. Strong asymmetries are observed between the two legs, the inner one being cooler and denser with an almost flat temperature profile in the higher density plateau of about 10–12 eV. The temperature reaches its maximum value in the vicinity of the outer leg separatrix (at ∼30 and 20 eV respectively), and subsequently drops steeply into the private flux region.

The density maxima in the outer leg are shifted by about 1–2 cm to the left of the nominal separatrix, inside the private flux region. Again however the error in the nominal separatrix position must be taken into account. It is also observed that in the outer scrape-off layer (SOL) the density gradient is not constant. This effect is more pronounced in the lower density case, where there seems to be a smaller maximum approximately 2 cm before the nominal separatrix. A similar change of gradient in the outer SOL was observed in the original Div I divertor of ASDEX Upgrade, but not as clearly in the Div IIa configuration [7]. In the inner leg, in the lower density case there is only a change of gradient on the separatrix, the density then decreasing very slowly in the inner SOL. In contrast, in the higher density case the density profile seems to peak on (or very near) the separatrix.

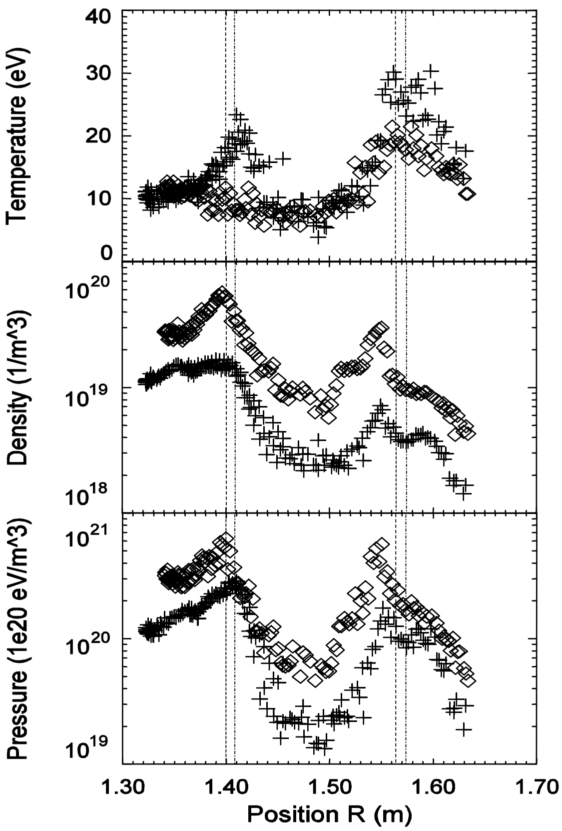

Fig. 3. Profiles in the lower (+) and higher (◊) density plateaus ofthe ASDEX Upgrade standard ohmic discharge. The lines correspond to separatrix positions, obtained from equilibrium reconstruction (-.- lower density, -- higher density).

The pressure profiles peak approximately on the nominal separatrices in the inner leg but slightly inboard of the separatrix in the outer leg. Again, it is not immediately clear if this apparent shift is due to an error in the separatrix position. A small electron pressure imbalance is observed between the two divertor legs in both cases, with the outer leg being at slightly lower pressure. This is in contrast to what was found in [7] for Div IIa, where at similar densities the outer leg was observed to be at a slightly higher pressure. We also find that, as the density increases, the pressure peaks more steeply around the separatrices. The inner leg profile flattening observed in [7] at densities above $3.0 \times 10^{19}\,m^{-3}$ is not observed here.

4. Influence of the probe on ELM characteristics

4.1. Discharge setup

We focus primarily on three ASDEX Upgrade H-mode discharges, where this effect was observed. The first two discharges, #11817 and #11820, where very similar, with low triangularity, $I_P \sim 1$ MA, $B_T = -2.57$ T (ion grad**B** drift towards the x-point) and $q_{95} \sim 4$. Both discharges occurred during the time ASDEX Upgrade operated with the Div IIa (Lyra) divertor. In the time window where the probe was used, discharge #11817 had a main chamber average density $\langle n_e \rangle \sim 5.64 \times 10^{19}\,m^{-3}$. The second discharge (#11820) had a slightly lower density ($\langle n_e \rangle \sim 4.6 \times 10^{19}\,m^{-3}$). The total injected neutral beam power was the same for the two shots, starting from 2.5 MW at $t \sim 1.195$ s. The probe reciprocation started at $t \sim 1.5$ s and lasted approximately 320 ms. During this time the plasma was in H-mode although, significantly, both discharges were close to the L–H power threshold, with the total power loss from the main plasma near the L–H transition power threshold value (as calculated from the $2.15 n_e B_T$ scaling observed in ASDEX Upgrade with the Div IIa divertor [13]). The position of the probe at maximum extension and the topology of the magnetic flux surfaces (which are similar for both discharges) are shown in Fig. 1(a). The probe tip entered the divertor plasma at $t \sim 1.51$ s, crossed the separatrix at the outer leg at $t \sim 1.565$ s, passed approximately 91 mm under the lower x-point, crossed the inner leg separatrix at 1.61 s and again coming back at $t \sim 1.745$ s and finally crossed again the inner leg separatrix at $t \sim 1.79$ s. The two tips from the mach probe were operated as sweeping probes. The third tip measured the floating potential.

The third discharge where this effect was observed (#18789) is somewhat different in that it was performed in hydrogen plasma in the new Div IIb divertor, with parameters $I_P \sim 0.8$ MA, $B_T \sim -2.39$ T, $q_{95} \sim 4.45$, line-integrated central density $\sim 4.3 \times 10^{19}\,m^{-3}$ (about 0.42 of the Greenwald limit), 2 MW of NBI, but also modulated ECRH averaging at approximately $\sim$0.7 MW. Again the discharge was very near the L–H power threshold, which is higher for hydrogen plasmas. The probe entered the plasma at approximately $\sim$3.5 s and, because of the larger value of auxiliary heating power, performed only half a sweep, crossing the outer leg separatrix at $t \sim 3.55$ s, reaching the centre of the private flux region approximately 52 mm under the x-point and, going back, crossing once more the separatrix at $\sim$3.66 s. The probe position at maximum extension and the magnetic flux surfaces are shown in Fig. 1(b). Only two tips were used this time, the main one as a swept probe (to measure characteristics) and one of the tips from the mach probe measuring floating potential.

4.2. Observed effect of the probe on the ELM signature

The effect of the probe on the ELM signature in discharge #11817 is shown in Fig. 4. The probe position is plotted alongside the floating potential of one of the tips, the H_α signal from the outer divertor leg, the main chamber line-averaged density, the divertor neutral pressure measured under the divertor dome and the carbon monitor signal, measured along a vertical line of sight from the top of the vessel. The separatrix crossings are deduced here from the floating potential and correspond approximately to sharp drops of the signal. Discharge #11820 had very similar characteristics.

It is observed that the probe has no significant impact on the ELM signature until it reaches the outer leg separatrix. Then, as soon as it has crossed it, the ELM amplitude is reduced and the frequency increased. The effect resembles a type I to type III transition, although it is difficult to say whether the smaller ELM's are actual type III or if they are only phenomenologically similar. This lasts until the probe tip is approximately 8 cm inside the private flux region and is accompanied by a small reduction of the main plasma density. The effect on the confinement time, τ, is not clear, as the change in density occurs in $\sim$50 ms, which is smaller than τ ($\sim$100 ms). When the probe reaches the middle of the private flux region the ELM's seem to return to approximately the original frequency. Then, the probe tip

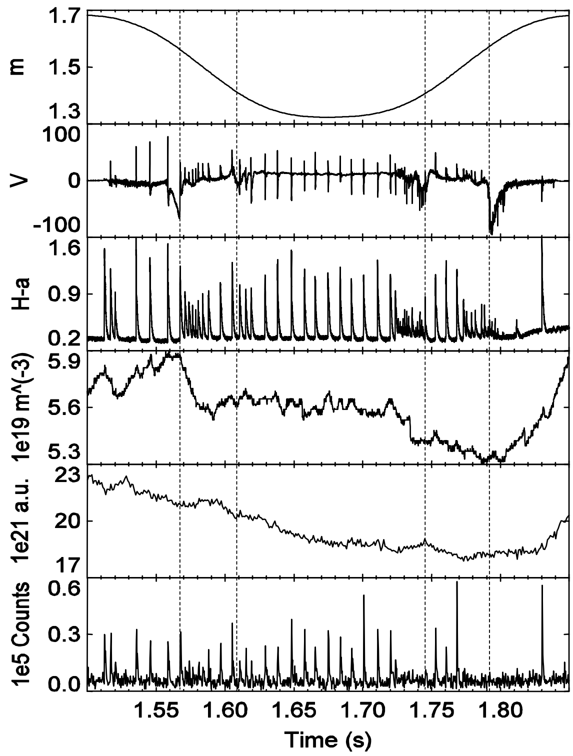

Fig. 4. From top to bottom: (a) Probe position (R), (b) floating potential (V), (c) H_α, (d) line averaged density $\langle n_e \rangle$, (e) divertor neutral pressure (P_n/div) and (f) carbon monitor signal, during the probe reciprocation in discharge #11817 (note suppressed zero for a few signals).

crosses the inner leg separatrix, again influencing the ELM's for about 4 cm inside the inner SOL. This time the influence is smaller and no decrease in the density is observed. When the probe reaches maximum extension, the ELM's completely return to their original size and frequency, despite the fact that the probe body now crosses both separatrices. Interestingly, exactly the same behavior is observed during the probes' return trajectory. Approximately 4 cm before the tip crosses again the inner leg separatrix, the same mitigation is observed, again accompanied by a small central density decrease. While the probe tip is in the private flux region the ELM's return once more to their original characteristics, before being reduced yet again when the tip reaches the outer private flux region, approximately 8 cm before the separatrix.

The probe influence on the ELM signature for the third case (discharge #18789) is shown in Fig. 5, where very similar effects to the previous example are observed. In both examples, significant ELM mitigation (in the sense of reduced ELM amplitude) occurs only when the probe tip is near either of the two separatrices. The influence seems to be the strongest when the tip is in

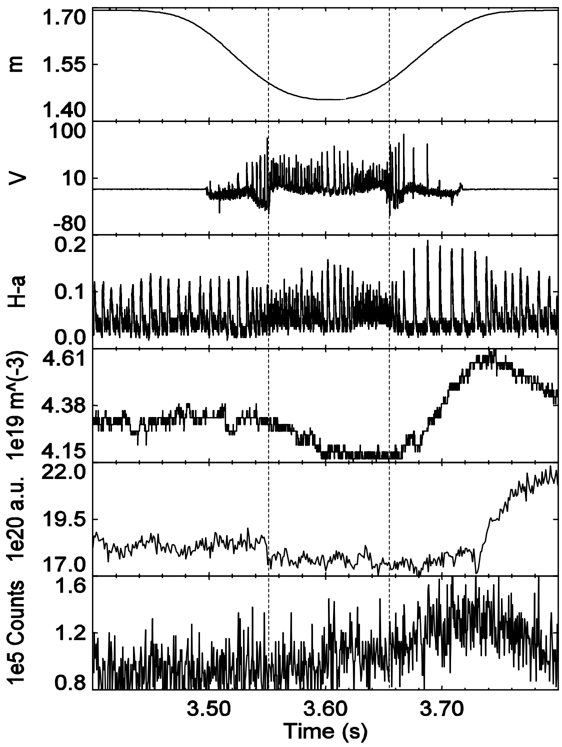

Fig. 5. Same as Fig. 4 for discharge #18789.

the private flux region near the outer separatrix and when it is in the inner SOL near the inner separatrix. This could be linked to the fact that the plasma density (and therefore the current drawn) is higher in these regions. Significantly, no immediate increase in the impurity level is observed, that could associate the mitigation effect to a radiation increase (in discharge #18789 the slight increase in impurity level occurs after the mitigation is observed and is probably due to the fact that the probe started emitting during the return trajectory). Variations in the density are most probably related to changes in the ELM frequency, with faster ELM's reducing the particle confinement time.

Concerning the mechanisms causing this mitigation, a possible explanation is that the probe as a whole might cause a severe plasma perturbation, creating impurities etc., helping cool down the plasma edge. However, if this were the case, the mitigation should have been observed throughout the whole of the probe trajectory and not only during the separatrix crossings. A more plausible explanation, which would also explain why the mitigation is observed only when the tip (and not the body) of the probe crosses the separatrix is that the current drawn by the probe (typically of the order of 2–4 A) locally interferes with the edge current on a narrow flux bundle, altering the local edge stability, which then acts as a trigger for a more global perturbation. Considering the small size of the probe current (compared to the total edge current) and the distance of the probe from the main plasma, such a result would be remarkable.

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