*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.063 (2007)*

Divertor characterisation and data consistency in ASDEX Upgrade

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Introduction

Despite the ELMy H-mode is the standard scenario foreseen for ITER, thorough divertor characterisation and -modelling over a complete ELM cycle are hardly found in the literature. One reason is the considerable experimental effort, requiring strike point sweeps and discharge repeats. Regarding data evaluation, different key diagnostics have been put into question. Examples are surface effects on thermography evaluation or the validity of Langmuir probe theory used to derive electron temperature, densities and even the ion flux from triple probe measurements. On the modelling side, deviations from the fluid ansatz caused by collisionless electrons or ions have been named as the possible cause for the failure to obtain a good match between code calculations and experimental data for low collisionality conditions [1]. This paper presents spatially and ELM time-resolved divertor data obtained in dedicated discharges in the ASDEX Upgrade tokamak (W walls and strike points on C). Special emphasis is placed on data consistency checks with regard to the power flux obtained from Langmuir probes (LP) and IR thermography (IR) and the ELM power asymmetry leading to higher loads in the inner divertor.

Inter-ELM measurements

Figure 1 shows time traces and profiles of divertor data for a dedicated discharge with strike point sweeps to obtain LP profiles. After the ELM, a phase with cold divertor conditions develops which lasts a few ms [2]. Despite the quite large variation in T_e, quite similar power fluxes are obtained from LP and IR during the different inter ELM divertor states. The power flux from the probes is calculated using the standard formula $P = (8kT_e + E_{rec})\,j_{sat}$. The inner divertor is completely detached between ELMs, resulting in very low power flux from probes. Comparing the outer target electron pressure from LP with the midplane electron pressure, a pressure drop by about a factor of 5 is found at the target. This factor stays about constant in the SOL region (ds= 0.1 m along the target or dR=1.3 cm in the outer midplane) and is significantly larger than the factor 2 expected for the typical Mach=1 flow. There is currently no explanation for the high pressure drop between midplane and outer target for these medium density conditions. T_e is too high to expect recombination to become important. On the other hand, H_α emission measured by radial divertor chords gives $\approx$ factor 3 higher line integrated photon fluxes than expected from j_{sat} and simple S/XB evaluation. Bolometry suggests that the difference between LP and IR in the outer divertor SOL can be caused by the radiative power flux. The electron pressure at the inner target is an order of magnitude lower compared to the outer. The large H_α photon emission here is attributed to recombination, in line with T_e of 1-3 eV measured by the probes.

Measurements during ELMs

Figure 2 shows divertor profiles along outer and inner target during the coherent averaged ELM. Most striking is the large discrepancy between the inner power load obtained from IR versus LP. Moreover, the ELM deposition zone is much broader in the inner divertor, even if the larger flux expansion is taken into account. Also shown is an extrapolation of the ELM

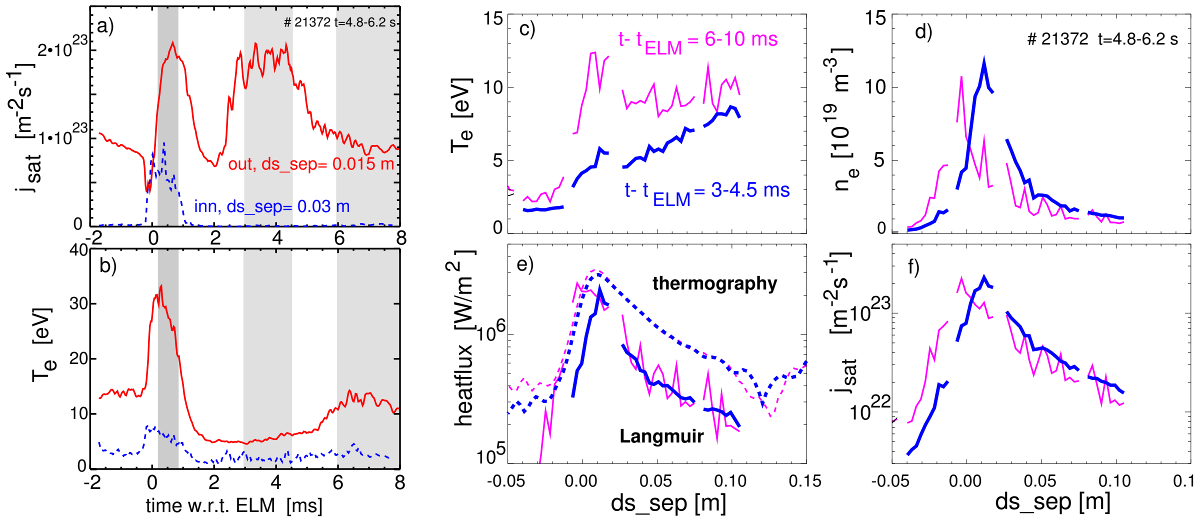

Figure 1: *Time traces of a) ion saturation current and b) electron temperature during the ELM cycle of a medium density H-mode discharge. c)-f) spatial profiles along the outer target during the hot and cold phases after the ELM heat pulse. Data are coherent time averages w.r.t. to start times of 166 ELMs.* P_{heat} *= 10 MW, Prad= 4 MW,* f_{Green} *= 0.7,* q_{95} *= 3.3,* I_p *= 1 MA. The shaded time intervals in a+b) are used for the profile characterisation.*

radiated (H+C) power from spectroscopic measurements [3] (bolometry is not fast enough to resolve ELMs). The total line emission of the most important transitions has been related to the measured line by a collisional radiative model, using T_e and $2\times n_e$ as measured by the LP. The factor 2 takes into account the acceleration to Mach=1 in the pre-sheath. For the almost perpendicular geometry of viewing lines, about 50 % of the line integrated radiated power density is deposited at the target provided the emitting layer is close to the surface. Although the extrapolated radiation may be uncertain by a factor 3, radiative power load can be excluded to explain the large difference between IR and LP power during the ELM around the inner strike point. In the far inner SOL region, the inferred radiation may be the dominant contribution to the power load.

Possible origin of the ELM power in-out asymmetry

The standard power calculation from Langmuir probes does not take into account net electric currents flowing in and out of the targets, causing an imbalance of electron and ion fluxes. Allowing for non-ambipolar fluxes, which are obvious from the electric current measurements [4], neglecting secondary electron emission the power derived from the LP can be written as

$$P = \Gamma_i \cdot (2kT_i/e + V_{sh} + E_{rec}) + \Gamma_e \cdot 2kT_e/e \quad (1)$$

The standard value of the sheath potential V_{sh} is $+3kT_e/e$. Figure 3 shows coherent ELM averaged electric currents integrated over the lower divertor, floating potentials at selected positions close to the separatrix, as well as j_{sat} signals for a typical ELM. The electric current flowing during the ELM is significant and can approach the ion saturation current. As is seen from V_{fl}, the origin of the ELM current is of strongly fluctuating nature. During the ELM, negative values of the ion saturation current appear. j_{sat} is measured between two probe tips separated by about

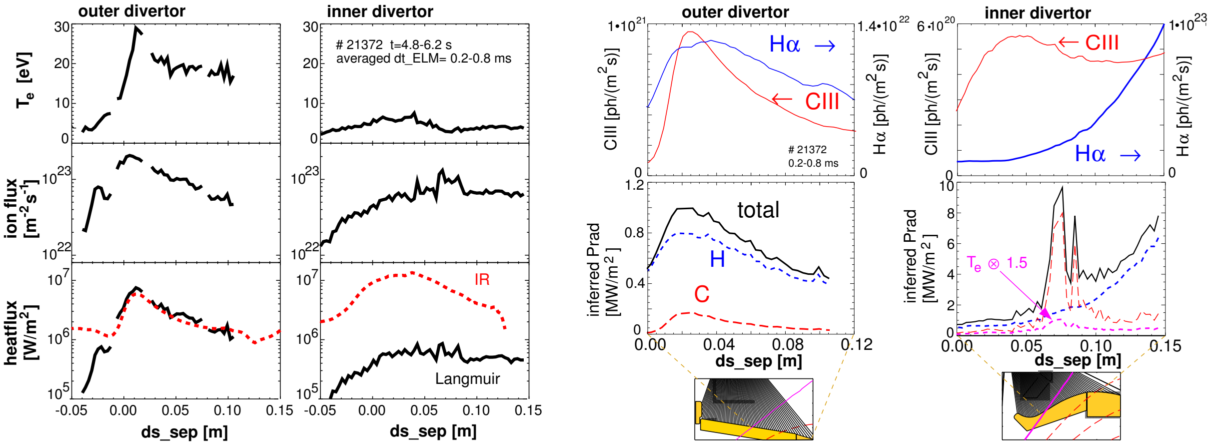

Figure 2: Divertor parameters during the ELM for the discharge of figure 1. left: T_e, ion flux density and heatflux in outer and inner divertor. upper right: H_α and CIII radiation along outer and inner divertor chord. Spatial coordinate is the distance of the viewing line hit points from the separatrix. lower right: radiated power extrapolated from the line radiation using the inverse S/XB method [4]. The carbon radiation from CIII is overestimated due to too low T_e for application of the influx method.

0.1 m in toroidal direction with a bias voltage of 72 V. The negative values of j_{sat} suggest a dynamic plasma potential variation in excess of this voltage over a corresponding distance.

There are 3 different explanations/contributions to the net ELM electric current and the power in-out asymmetry. A thermoelectric current is driven by the temperature difference in both divertors, but this cannot explain the power asymmetry. Second, a loop voltage is expected to show up along the field lines close to the separatrix during the ELM. This voltage is caused by flux conservation as a reaction on the flattening of the ETB profiles which is according to Lenz' rule the reaction to the reduction of the electro-motoric force which drives the bootstrap current. The divertor ends of the field line act like a double Langmuir probe, and the voltage drop mainly occurs at the ion end, which is the inner divertor for standard field direction. This voltage then drives the electric current and accelerates the ions towards the inner target, resulting in an increased ion power load. V_{sh} can become much larger than $3kT_e/e$ at the ion end (inner div.) if the electric current approaches the ion flux, but not much lower than $3kT_e/e$ at the electron end due to the high electron mobility. The voltage associated with the ETB profile flattening has the right sign to explain the ELM power asymmetry for the various combinations of field directions. The third mechanism which might explain electric current and power load asymmetry during an ELM is the preferential loss of fast ions to the inner divertor. Hahn et al. [5] have shown that in the presence of a large negative E_r in the plasma edge, ion orbits with their kinetic energy less than the potential energy shift their wall intersection location to the inner divertor.

To learn more about the relative contribution of the mechanisms described above on the ELM power in-out asymmetry, a quantitative evaluation is required. For this purpose, various quantities of the coherent averaged ELM of figure 2 have been integrated/averaged from 0.2-0.8 ms wrt the ELM start time. Table 1 shows the deposited particle numbers and energy according to equation 1, where the ion temperature T_i and the additional sheath potential are unknown quantities. The last two columns show the required additional sheath potential drop $V_I = V_{sh} - 3kT_e/e$ assuming $T_i = T_e$ and the ion temperature T_i assuming $V_I = 0$ to satisfy equation 1. The additional sheath potential drop V_I in the inner divertor required to explain the power asymmetry is

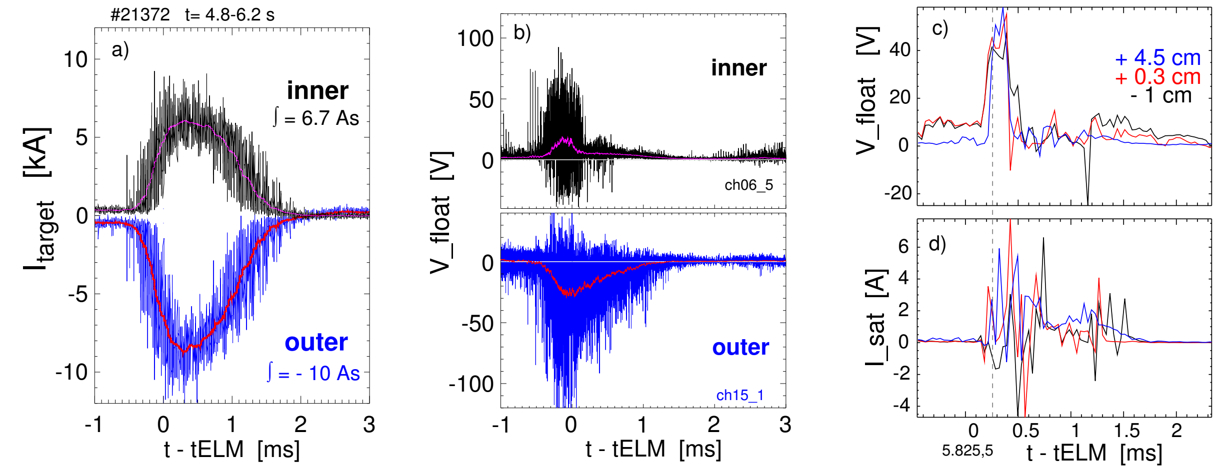

Figure 3: coherent ELM averaged a) electric current into inner and outer divertor from tile shunt measurements and b) floating potential measured at in the divertor SOL closely outside sep. c) and d) show floating potential and ion saturation current for a typical ELM at 3 positions in the inner divertor.

shot	divertor	E_{ELM}	$E_{rad}(est.)$	N_{jsat}	$N_{current}$	T_e	V_I (T_i=T_e)	T_i (V_I=0)
		[kJ]	[kJ]	[As]	[As]	[eV]	[V]	[eV]
21372	inn	7.0	1.1	9	3.4	6	604	308
	out	3.3	0.2	15	-4.7	25	2	26
21301	inn	4.0	0.9	6.7	1.85	5	416	213

Table 1: ELM divertor parameters (dt= 0.2-0.8 ms) for medium density discharge 21372, t=4.8-6.2 s and high density discharge, 21301, t= 5.2-6.4 s. $\int\Gamma_i = N_{jsat}$, $\int\Gamma_e = N_{jsat} - N_{current}$.

considerably larger than the measured V_{fl}, which approximately measures the deviation of V_{sh} from $3kT_e/e$. The pedestal ion temperature has the right magnitude, making the preferential ion loss the dominating candidate.

Conclusions

In between ELMs, reasonable data consistency is obtained in the outer divertor for intermediate densities, using a sheath heat transmission factor of $\gamma = 8$ and taking into account divertor radiation adding up to the thermographic power flux. The power decay length in the outer divertor obtained from LP is shorter in comparison to IR, suggesting an effect of ions with $T_i > T_e$. The inner divertor strike zone is completely detached between ELMs, making data consistency checks difficult. During ELMs, the applicability of the probe theory used to evaluate the triple Langmuir probes is questionable. The ion saturation currrent exhibits a strongly fluctuation nature and adapts negative values transiently. This can be explained by transient floating potential differences between the two probe tips used for the j_{sat} measurement which exceed the biasing voltage. If these transient time phases are omitted from the data evaluation, (coherent) averaged LP data (T_e, n_e, j_{sat}) can be derived during ELMs, albeit with reduced accuracy. The quantitative analysis of the ELM power load using various diagnostics suggests the directed loss of pedestal ions to the inner divertor as the most important contribution to the power in-out asymmetry.

References [1] A.V. Chankin et al., Plasma Phys. Controlled Fusion **48**, 839 (2006). [2] M. Wischmeier et al., J. Nucl. Mat. **363-365**, 448 (2007). [3] A. Kallenbach et al., Nucl. Fusion **39** (1999) 901. [4] T. Eich et al., J. Nucl. Mat. **363-365**, 989 (2007). [5] S.H. Hahn et al., Phys. of Plasmas **12** (2005) 102501.