Experimental study of the spreading of the deposited heat flux on the toroidal pumped limiter of Tore Supra

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1. Introduction.

Understanding heat flux deposition processes is essential for the design of the plasma facing components allowing reliable high power steady state plasma operations. Due to the magnetic configuration of Tore Supra, the heat flux pattern deposited on the Toroidal Pumped Limiter (TPL) exhibits, every 20° (from one toroidal coil to the following), two heat flux peaks separated by the plasma contact point where magnetic field lines graze the surface (incident angle typically ≤1°). The heat flux deposition pattern depends of several plasma parameters (assuming the TPL castellated tiles are perfectly plane, no tile misalignments): the geometry of the magnetic field lines (characterized by safety factor q), the heat flux decay length (λ_q) and also the ion Larmor radius (r_L) which increases the spreading of the heat flux on the TPL due to gyro-radius effects. Recent Tore Supra experiments have been carried out with λ_q varying between 1.5 and 3cm and with r_L varying between 0.5 and 0.85mm.

2. Description of the TS experiment

Diagnostic set-up: The surface temperature on a 20° toroidal section of the TPL ($T^{IR}_{\lim iter}$, °C) is obtained with a thermography system that provides IR images with a spatial resolution of about 4 mm at 50Hz. Heat load ($Q^{IR}_{\lim iter}$, MW/m²) is estimated from the 1D linear deconvolution of the temperatures maps ($T^{IR}_{\lim iter}$, °C), using the analytical thermal quadrupole method to model the impulse thermal response of the limiter, as described in [1] and [2]. The scrape-off layer is characterized by reciprocating Langmuir probe measurements [3] (localized in the top of the torus), providing electron temperature (T_e, used here to evaluate the averaged ion Larmor radius $< r_L^{LP} >= \frac{m_i \cdot C_s^{LP}}{e \cdot B}$), density ($n_e$) and parallel heat flux ($Q_{//}^{LP}$, MW/m²) radial profiles. The experimental parallel heat flux $Q_{//}^{LP}$ is used between 1 and 5cm outside the LCFS to evaluate the heat flux decay length (λ_q^{LP}, cm).

Description of the experiment: The target plasma is long duration plasma discharges (>20s) in order to reach the thermal steady state in the TPL. Central density is fixed to $<n_e>\sim 3.10^{19} m^{-3}$ and 2MW of additional heating power (provided by LHCD launchers) is used to heat the TPL to significant values (>200°C for reliable IR surface temperature measurements). 2 series of discharges have been designed in order to study the spreading due to magnetic reconnection (edge safety factor varying in the range 8-4) with and without gyro-radius variation. In the first series, the magnetic field is fixed to 3.8T and plasma current I_p varies in the range [0.6–1.2MA]. In this series λ_q^{LP} varies from 3cm down to 1.8cm. In the second series the plasma current is fixed to 0.6MA in order to vary the magnetic field in the range [3.8–2.3T]. In this series r_L^{LP} varies from 0.5mm up to 0.85mm (values that have been evaluated assuming $T_i = 2 \times T_e$ as shown in [4]). Analysed discharges and main plasma parameters are summarized in the following table:

pulse number	B (T)	I_p (MA)	q	I_p (MA)	P^{LHCD} (MW)	$T_e^{LCFS}(eV)$	$\lambda_q^{LP}(cm)$	$< r_L^{LP} > (mm)$
46655	3.8	0.6MA	8	0.6MA	1.8	30	~3	0.5
46654	3.8	1.2MA	4.2	1.2MA	1.8	40	~1.8	0.5
46671	2.3	0.6MA	4.7	0.6MA	1.8	30	~3	0.85

3. Numerical evaluation of the gyro-radius effect:

One interesting effect difficult to observe experimentally is the gyro-radius effect. This effect has been extensively studied numerically in [5] showing that heat packet of the size of the order of r_L is enough to simulate wide plasma. Simplified evaluation of the spreading due to gyro-radius effect has been recently performed assuming transport along magnetic field lines with finite orbit size (r_L). Figure 1 shows the distance between the position of the centre guide trajectory which impacts the TPL and the position of the centre guide trajectory when $z = r_L$ (i.e. when the particle can theoretically impacts the TPL due to gyro-radius). Figures (a) and (b) shows the result with r_L=0.5 and 1mm respectively (and magnetic configuration compatible with the experiments #46655 and #46671). The gyro-radius effect is stronger at low incidence angle (near the separatrix, when α<1°). The spreading numerically evaluated goes up to 10cm maximum (therefore 5cm in average if one takes into account the distribution function of the particle in space) near the separatrix down to 6cm maximum (3cm in average, about one TPL tile) in the far SOL. A macroscopic effect is therefore expected near the separatrix.

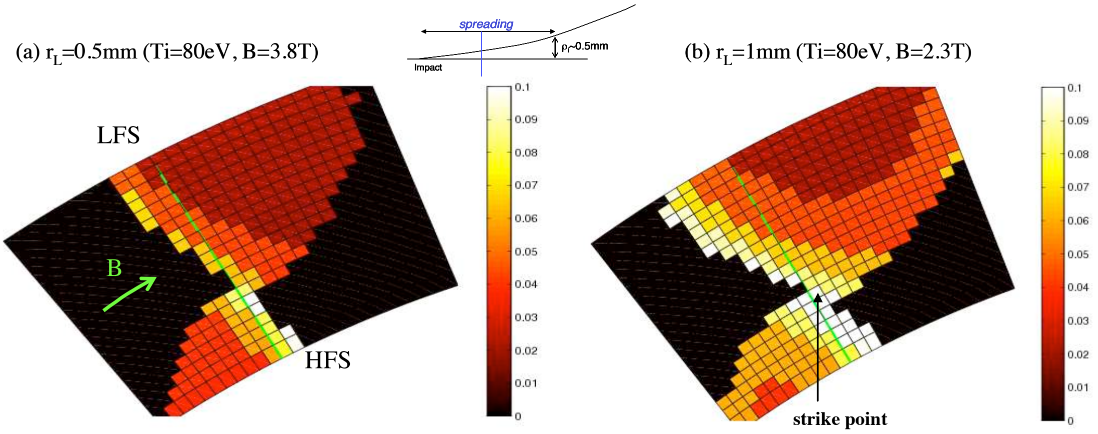

Figure 1: Numerical evaluation of the maximum distance between particle impact and magnetic field line impact with the TPL: (a) with r_L=0.5mm and q=8 (#46655). (b) with r_L=1mm and q=4 (#46671).

3. Experimental results

Qualitative effects at play are visualized by subtraction of IR images (ΔT°) when the thermal steady state is reached. Figure 2-a shows 2D map of ΔT without gyro-radius variation. The spreading of the heat flux (when ΔT>0) is clearly visible in the far SOL region as expected by the magnetic reconnection when q factor varies from 8 to 4. No particular effect is observed in the region near the separatrix where α<1° (none on the shadowed, neither in the wetted areas). In the same time, the heat flux decay length decreases from 3cm down to 1.8cm, leading to possible peaking of the deposited heat flux near the separatrix (this effect appears to be negligible compared to modification attributed to the magnetic reconnection). Figure 2-b shows 2D map of ΔT with gyro-radius variation. The spreading of the heat flux (again when ΔT>0) is similar than previous figure in the far SOL region as expected by the magnetic reconnection. In this case, an additional effect is observed in the region near the separatrix where α<1°, as expected when the gyro-radius increases (see figure 1-b). The effect is clearly visible in the shadowed area near the separatrix (prone to C-deposit).

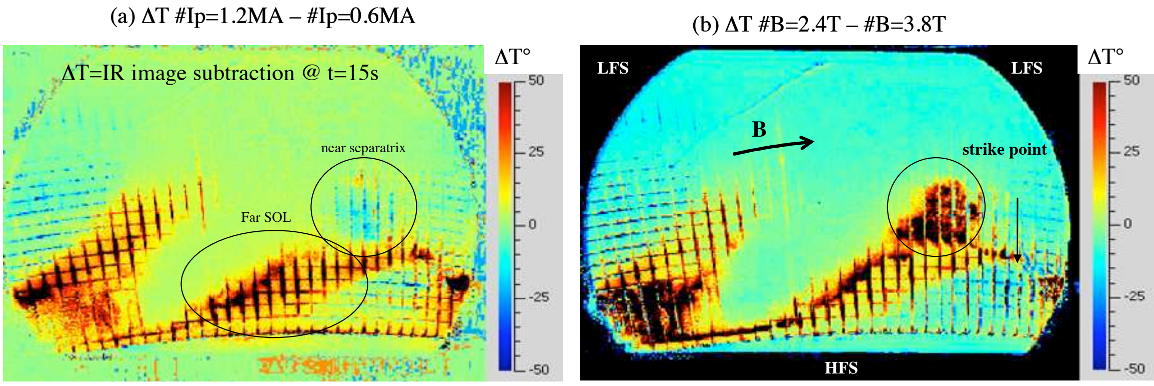

Figure 2: Difference of surface temperature between two plasma discharges when steady state is reached (@ t=15s). (a) when B is fixed, between #46654 (I_p=0.6MA) and #46655 (I_p=1.2MA). (b) when I_p is fixed, between #46671 (B=3.8T) and #46655 (B=2.3T).

Heat flux calculations have been performed (as described in [2]) to quantify these effects in term of heat loads. The average heat flux is plotted along the TPL, in the wetted area, in figure 3-a (heat flux is averaged over tile row N°4, 5 and 6 starting from the HFS side of the TPL, bottom of the picture). A significant effect is observed in the far SOL region as depicted above. Figure 3-b plots the % of heat loads variation attributed to magnetic connection when q is varying from 8 to 4 (*with* and *without* additional gyro-radius effect in green and blue respectively). In both cases, the region where the variation of heat flux is >50% is about 20cm wide and localized in the far SOL region (prone to C-deposit), a distance which is equivalent to the wetted width when q=8 (the wetted area is two times higher when q=4).

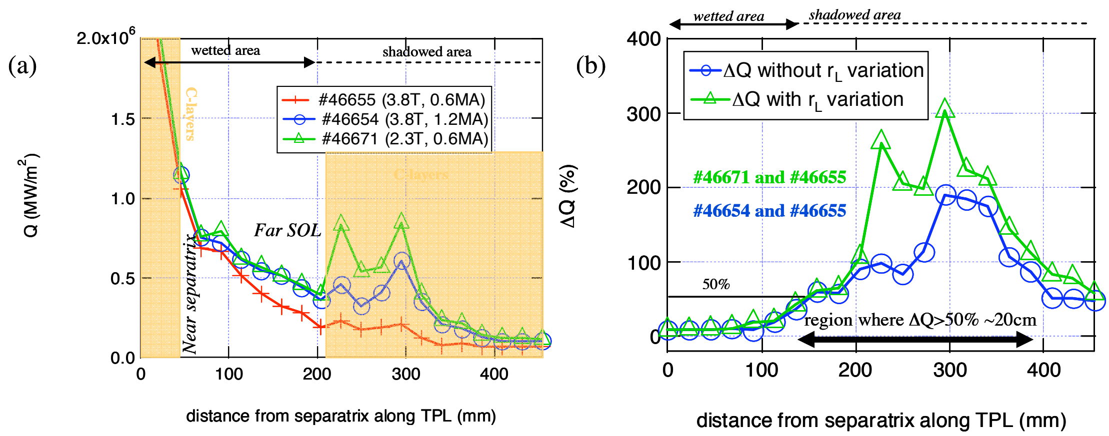

Figure 3: Heat flux spreading due to magnetic reconnection with and without gyro-radius effects. (a) Averaged heat flux on row N°4,5 and 6 for #46655 (q=8, rL=0.5mm), #46654 (q=4 rL=0.5mm) and #46671 (q=4, rL=0.85mm). (b) Variation of heat flux in % with and without r_L variation: $\Delta Q = \frac{Q_{pulse2} - Q_{pulse1}}{Q_{pulse1}}$

4. Conclusion

The deposited heat load can vary by a factor of two in the far SOL region (thus changing the erosion/deposition ratio and particle recycling on C-deposits) by changing the q safety factor from 8 down to 4. A significant effect is observed near the separatrix when r_L varies from 0.5 up to 1mm, confirming the numerical prediction (note that gyro-radius effect could be enhanced by a factor of 2 when P>10MW with higher T_e and T_i). In upcoming experiments, the experimental evaluation of these effects (magnetic reconnection, λ_q and gyro-radius) will be used to address the physics of plasma deposition in castellated tile gaps (critical issue for ITER especially with gaps misalignments and tungsten environment).

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