

## **Investigation of Power Deposition on Large Surfaces, Experiments and Simulations of the Tore Supra Inner First Wall**

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### **I. INTRODUCTION**

The design of actively cooled Plasma Facing Components for steady state operation faces a technological limitation in terms of extracted power per unit surface. In standard analysis of Scrape Off Layer (SOL) transport, the power flux to the wall results from a balance between parallel and transverse transport. In this approach, the energy deposition is governed by parallel transport while cross field transport determines the SOL radial depth,  $l_q$ . As a consequence, large surface elements with shallow impinging angles have been designed to handle large powers at reasonable power flux. The actively cooled Inner First Wall (IFW) of Tore Supra follows this prescription. It is a continuous 10 m<sup>2</sup> toroidal limiter with curvature  $R_{\text{IFW}} = 2.36$  m,  $a_{\text{IFW}} = 0.80$  m located on the high field side [1]. The elementary unit of component is a flat area (so called "sites") of 130×80 mm comprising six tiles. The assembly of these sites forms a polygonal surface which matches closely the magnetic surfaces. The rows of tiles are separated by toroidal gaps measuring between 8 and 40 mm. For standard plasma operation,  $a = 0.75$  m, 10 % of the SOL length can stand at less than 1 mm from the IFW surface. Infrared imaging (poloidal and toroidal coverage), Langmuir probes and thermocouples in a given poloidal plane are used in the experimental investigation of this specific geometry.

### **II. EXPERIMENTAL OBSERVATIONS**

Unfolding the data for the shot #23871 [2,3] shows that the power flux pattern on the IFW is characterised by a large continuous background,  $\sim 0.3$  MWm<sup>-2</sup>, with  $\sim 1.2$  MWm<sup>-2</sup> peaks in the equatorial plane. These peaks are located toroidally between the toroidal coils. For plasmas leaning on the IFW with additional heating, this pattern is constant. Only the heat flux levels depend on the injected power. The continuous background accounts for 50 % of the deposited power, the peaks for the other 50 %. The power repartition between the two contributions is not known with accuracy, because the temperature rise of the background is small (20-40°C) in the operational range of the infrared camera (typically 150°C-650°C with the wide optic) and the measure has a large error bar. The peaks are not only confirmed by

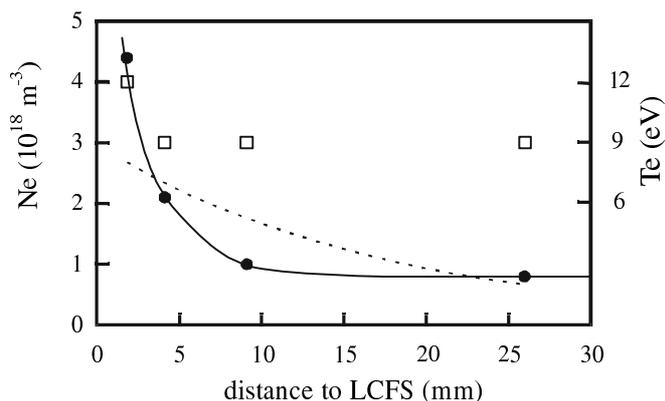


Figure 1 : density (●) and temperature (□) profiles obtained from langmuir probes on the IFW and comparison to the density with global e-folding (dotted line) and e-folding with continuous background (continuous line)

thermocouples [2], but also by the Langmuir probes fixed on the IFW (figure 1). The equatorial probe (not in function until 1998) shows a strong peaking of the electronic density close to the last closed flux surface (LCFS). The following interpretation and modelling will focus on the peaks which are the most striking pattern. Conventional e-folding (continuous curve for the least square best fit) does not apply when all points are considered. The contributions of the peak and the background have to be separated before evaluating the characteristic lengths. Considering solely the peak gives a  $l_N$  of 5 mm. The electronic temperature being almost constant at 10 eV on the IFW, this  $l_N$  is equivalent to  $l_Q$ . This is coherent with the observation that the power of the peaks is deposited in the first millimetres of the SOL. Their periodicity being 18 (the number of toroidal coils in Tore Supra), they are associated with the ripple of the toroidal magnetic field. The maximum is found where the LCFS is in contact with the IFW, at vanishing impinging angles. This is in contradiction with the usual cosine model for which a twin peak pattern would be expected. The peaks were therefore associated with some kind of "anomalous perpendicular heat flux" [2]. In that description, the effect of incidence angle disappears and the heat flux is mainly a function of the distance to the LCFS. Consequently, the belly of the ripple in the equatorial plane leads to the one-peak pattern. However, this idea is not supported by a close observation of the IFW which was carried out in 1998 with an infrared camera equipped with a zoom  $\times 3$  (figure 2). On the infrared picture, only one site is integrally observed. The spatial resolution is sufficient to show that the ridges of the tiles are much hotter than the front faces. This is an evidence of parallel heat flux, because the perpendicular deposition would heat the tiles uniformly.

### III. MODELLING

For the peaks, the modelling of the conventional cosine law has then to be reconsidered in view of these results. As it appears that a decisive part of their physics happens in the first few millimetres of the SOL, the model should at least consider all phenomena with that scale. The ripple with a characteristic length of 2 mm is already accounted for. But previous heat flux

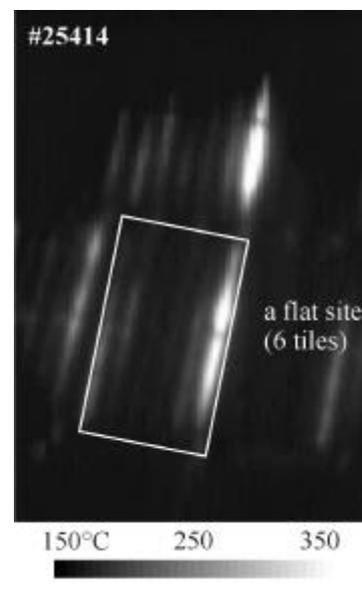


Figure 2 : close infrared view of one site (130×80 mm) location  $\varphi = -1.6^\circ$ ,  $\theta = 210^\circ$

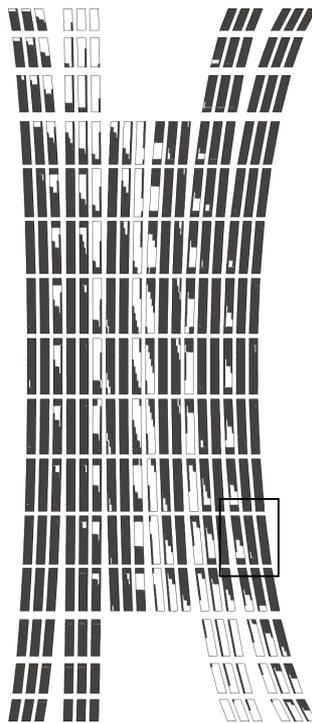


Figure 3 : Pattern of the shadow on 20° of the IFW (observed site is framed)

models supposed an idealised IFW with a perfect toroidal shape. The characteristic length of the perturbation caused by polygonality to the ideal toroidal surface is 0.5 mm and it has also to be considered. This requires however to consider the shadowing effects. Two of them occur : the shadowing of a tile by itself and its immediate neighbours, and the shadowing caused by the ripple which takes place over longer distances. This latter effect is described in [4]. The numerical code TOKAFU was upgraded in 1998 to integrate the shadowing effects, allowing such a calculation. Another difficulty comes from the gaps situated between the tiles, into which a significant fraction of the power flows. Considering individual tiles requires also to consider the gaps. The penetration of the field lines here is a few tenths of millimetres. The mesh close to the surface has therefore to be finer than this value to avoid averaging errors. The first result obtained with the code is the shadowing pattern shown figure 3. The sketch displays a 20° toroidal sector limited by toroidal coils, and the cuts correspond to observation ports. The white areas are wetted whereas the black ones are shadowed. The area wetted by the parallel convective heat flux is only 18 % of the overall carbon surface. The equatorial sites with the largest wetted surface are located in the same poloidal section as the ports. This is coherent with the position of the peaks observed on the infrared images. Local heat fluxes in the peaks are calculated by the classical cosine

law  $\Phi = \Phi_0 \cdot e^{-\frac{\delta}{\lambda_q}} \mathbf{b} \cdot \mathbf{n}$  where  $\Phi$  is the heat flux,  $\Phi_0$  the heat flux on the LCFS,  $\delta$  the depth in the SOL,  $\lambda_q$  the heat e-folding length,  $\mathbf{b}$  the unit vector along the magnetic field and  $\mathbf{n}$  the unit vector out of the surface.  $\Phi_0$  is deduced from a normalisation to the overall power extracted by the IFW (2.2 MW measured by calorimetry) assuming a continuous background of 0.3 MWm<sup>-2</sup>. Maximum heat deposition is found at the same location as the infrared images (figure 4), thus showing that parallel heat flux can explain the peculiar heat flux peaks observed on the IFW. A least square method on the averaged power per elementary units gives a  $\lambda_q$  evaluation of 2.5 mm for the peaks, comparable to the one found with the Langmuir probes. The calculation shows that 37 % of the parallel power goes into the gaps and only 63 % on the front faces. A zoom on the result of the simulation for the site observed by the infrared camera shows that the heat fluxes are very disparate (figure 5). On shadowed

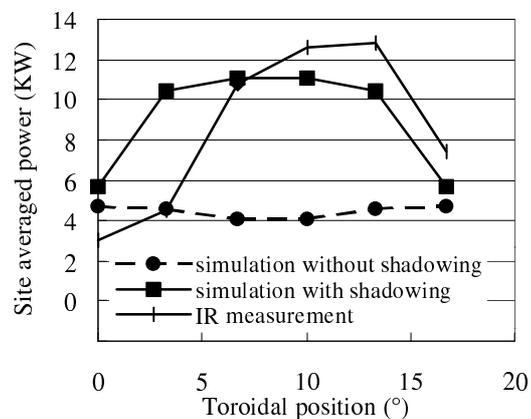


Figure 4 : toroidal profile on 20° of the equatorial plane

simulation with shadowing and IR measurement show a peak around 10-15 degrees, while the simulation without shadowing is much lower and flatter.

areas, the heat flux amounts to  $0.3 \text{ MWm}^{-2}$  due to the continuous background. On wetted area, the flux increases to  $0.5 \text{ MWm}^{-2}$  on the front faces and up to  $3 \text{ MWm}^{-2}$  on the ridges. This pattern is coherent with the IR image shown figure 2, although the pattern observed is dominated by a misaligned row of elements. The most exposed sites of the equatorial plane receive  $3 \text{ MWm}^{-2}$  on the front face and up to  $20 \text{ MWm}^{-2}$  on the ridges. Due to the angle variation caused by the ripple, the penetration of the field lines into the gaps can reach  $0.8 \text{ mm}$ .

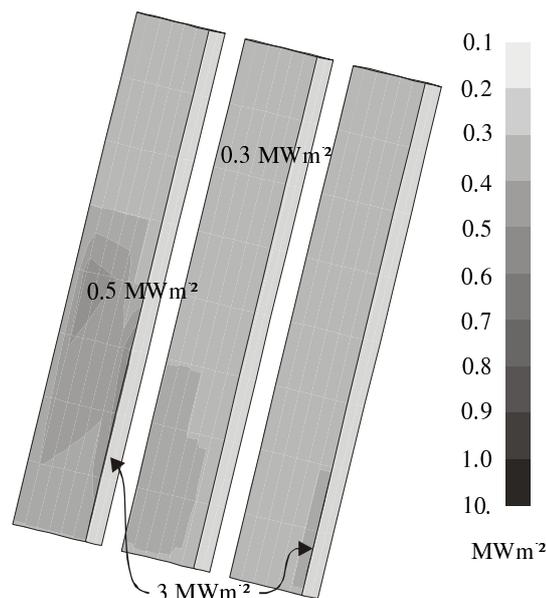


Figure 5 : Calculated heat flux on the observed site

#### IV. CONCLUSION

The heat flux deposition on the IFW is marked by hot peaks located on the equatorial plane between the toroidal coils. The pattern suggests at first a perpendicular heat flux with a very short decay length. It can however be explained by parallel heat flux alone. The peculiar shape of the peaks obtained on this very tangent limiter is caused by a combination of effects of the toroidal field ripple, the surface polygonality and the shadowing effects. The decay length in the peak is  $2.5 \text{ mm}$ , showing an increased heat flux in the first few millimetres of the SOL. This results is similar to the one observed on TEXTOR'S ALT-II [5]. The good agreement between the simulation and the observed heat flux pattern is a validation of the heat flux deposition code TOKAFU. It gives confidence in the engineering work that was done to prepare the Tore Supra's Toroidal Pumped Limiter. More work has to be done to investigate the causes for those very short decay lengths which can not be linked today to a unique phenomenon.

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