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Self-shadowing, gaps and leading edges on Tore Supra's inner first wall

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Abstract

Operation with the actively cooled inner first wall of Tore Supra shows that even such a large area limiter is subjected to anomalous heat deposition where the plasma contacts the limiter. This can be modelled by a parallel convective heat flux with a e-folding length of the order of a millimetre. In some extreme cases, associated with lower hybrid heating in a low density plasma, the situation could degenerate into a runaway situation associated with large carbon influx into the discharge and ending with the rupture of elements. The analysis of the heat flux deposition on this limiter is complicated by the need to take shadowing effects into account, which are becoming significant because of the small scale phenomenon involved. It is shown that only a small fraction of the front faces is wetted by the parallel heat flux and that very disparate heat fluxes co-exists on each element. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: e-folding length; Geometry effect; Tore Supra; Heat flux

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1. Introduction

The inner first wall (IFW) of the Tore Supra tokamak is a large area limiter located on the high field side of the vacuum vessel. Its design dates back to 1980s, with small incidence angles on the equatorial plane where the plasma contacts the limiter. The Tore Supra design, since its beginning, is aimed toward stationary discharges, and the IFW is actively cooled by pressurised water. Armouring is fulfilled by graphite and carbon fibre composite tiles, which are brazed to a metallic heat sink. The design, fabrication and upgrade of the IFW have been largely described previously [1,2] and are not recalled here. The focus is rather set on the gaps and the leading edges of the IFW, which appeared in the last years to play an important role in the temperature distribution on the surface of this component. The technological constraints caused by the use of stainless steel tubes imposed gaps in the plasma facing surface. Reliable brazing favours flat bonds and it was decided to avoid overhanging tiles to reduce difficulties at the carbon/metal interface. The resulting mount is composed of individual units comprising six tiles, all braze bonds lying in the same geometrical plane. One unit and its six tiles forms a flat 'site' of 80 × 130 mm^2. To accommodate the poloidal shape of the vessel, the sites are arranged in poloidal rows, curved with the minor radius of the vessel. A poloidal row has the shape of a truncated cylinder, the gaps between two tiles having a constant value of 10 mm. When assembled along the toroidal curvature, the rows form the toroidal shape of the vessel. The gap between two rows starts from an initial value of 8 mm in the equatorial plane rising to 45 mm at a poloidal angle of 75° (Fig. 1, gives an overall view while Fig. 2 gives a better understanding). There are larger gaps to leave room for the vertical observation ports, but they are farther from the plasma. This results in the faceted structure of the IFW. The maximum deviation from perfect toroidal symmetry is 1 mm. As small this may be, each angle between two sites creates de facto two leading edges separated by the gap. The separation

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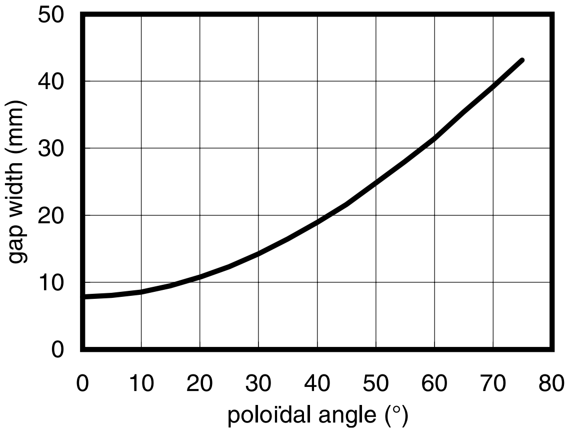

Fig. 1. Gap width function of the poloidal angle.

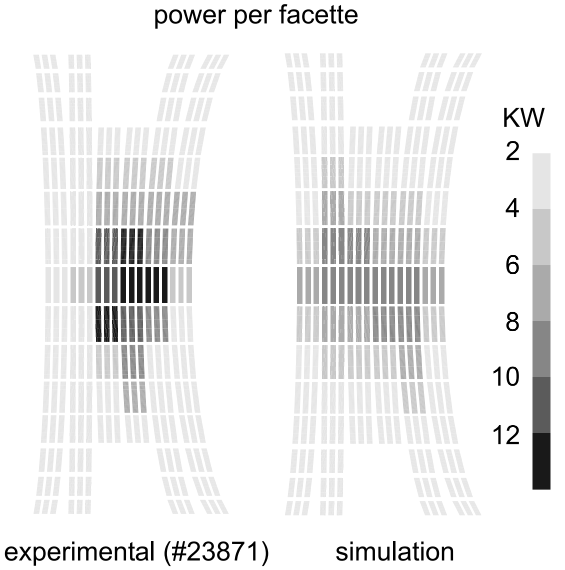

Fig. 2. Fit of the localised heat flux deposition with $\lambda q = 2.5$ mm.

is small when compared to the usual order of magnitude of the parameters governing the heat flux deposition (1 cm), but the most recent experimental campaigns as well as past experiences [3] proved that these leading edges have yet to be properly considered.

2. Heat flux deposition on the IFW

The heat flux deposition on the IFW has been characterised by numerous diagnostics: infrared cameras, thermocouples, langmuir probes, calorimetry. The thermal pattern is composed of a seemingly uniform background and of localised peaks in the equatorial plane between the toroidal field coils. These hot areas appear during shots with additional power and particularly with lower hybrid heating. Their location is a consequence of the magnetic field ripple, although the IFW is on the high field side and the magnitude of the field line deviation due to ripple here amounts only to 2 mm [4,5]. The parameters of the heat flux (power density, e-folding length) are evaluated with the code TOKAFLU. This code takes into account the classical cosine law for parallel (or perpendicular) heat fluxes, including the perturbing effects of the ripple and of the Shafranov shift [6]. A recently added feature of the code is that it allows to calculate the shadow of one component on others or on itself (self-shadowing). On the IFW, two self-shadowing effects have to be considered. One is caused by the local leading edges, it concentrates the heat flux on them and reduces the heat flux on the centres of the faces. The second is caused by the ripple, reduces the heat flux beneath the toroidal coils and concentrates it between them. Calculations are rendered quite difficult because of the many geometrical orders of magnitude necessary to make a correct simulation. On the one hand, the penetration of field lines in the gaps is of the order of a few tenths of a millimetre (thus requiring a mesh size of the order of 0.1 mm if the calculation of the fluxes on the side of the tiles is to be correct). On the other hand, a whole characteristic pattern of the IFW has to be modelled (2 m long and 20° toroidal, approximately 1.5 m^2) to be able to calculate the heat flux at the last closed flux surface from the given data of convected power. The IFW is here the main limiter, and a local calculation produces only the relative profile of the heat flux distribution. Only a normalisation to the total incoming convective power on the limiter provides absolute values for the heat flux. This requires calculation of the individual power extracted by each tile with sufficient precision. The mesh thus requires 100 000 nodes and the duration of the run is counted in weeks.

First, shadowing results show that only 15% of the front faces are wetted by the heat flux. The rest is shadowed and subjected only to radiative and perpendicular heat fluxes. Second, the measured heat flux pattern cannot be reproduced by a single exponential profile in the scrape-off layer, and at least two separate contributions have to be included to obtain a correct simulation. In the case of the shot #23871, the e-folding length in the peaks is calculated to 2.5 mm (Fig. 2). This small characteristic length is a general feature, which departs a common observation of a 1 cm scrape-off layer width. This component of the heat flux deposition is ‘abnormal’ and its physical causes are still under discussion (ion finite larmor radius, magnetic pre-sheaths effects, heat transmission factor, funnelling effect [7]). Other descriptions can be found in the literature, such as an amplification for tangential surfaces, or a minimal angle of incidence. This abnormal component leads to increased peaking of the heat flux on the surface of the main plasma facing component.

Other results of the TOKAFLU simulation are that more than one-third (37%) of the convective power arrives in fact in the gaps, where it is actually retrieved by the leading edges. By considering also the fraction of the convective power that arrives on the front faces in the vicinity of the leading edges, that figure can even rise to 50% which is an unexpected effect of that geometry. The penetration of the field lines into the gaps can reach 1 mm and several mm in the observation ports. This makes the heat flux pattern on each site very complicated. Three orders of magnitude of heat flux are calculated on each site: radiated heat flux in shadowed areas (0.1 MW/m^2), convection on the front faces (about 1 MW/m^2) and the heat flux along the field lines on the lateral faces amounting to more than 10 MW/m^2. This is shown in Fig. 3 for one of the most exposed sites in the conditions of the shot #23871.

As a failure of the IFW ended the experimental campaign of 1999, this unexpected heat flux peaking was emphasised recently. An excess heat flux on the most advanced tile led to a crack in the stainless steel heat sink [8]. The other tiles recessed by only 0.2 mm are also damaged, but the peaking of the heat flux on this peculiar tile is another sign of the small scale of the phenomenon involved. The damage is attributed to fast electrons created by lower hybrid heating at low density [9]. The critical outcome of the situation may have been accelerated by some kind of runaway situation similar to the one observed previously on modular limiters [10]. This is sustained by the measurement of a large carbon influx in the discharge, however the lack of thermal measurement of the surface temperature of the tile forbid to conclude on this conjecture.

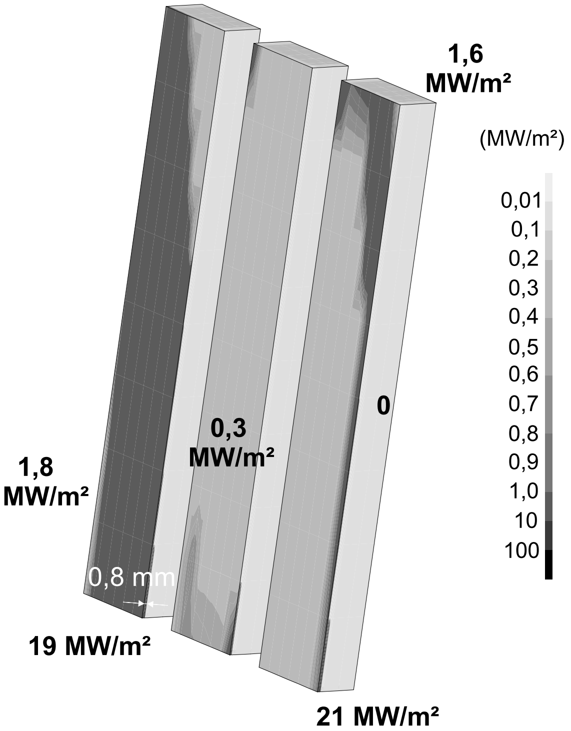

Fig. 3. Simulation of the heat flux on the most exposed site (#23871, 6 MW injected, 2.5 MW on IFW).

Fig. 4 shows the progression of discharges during the last day of operation before the terminating event. The incident heat flux on the inner wall, as determined by embedded langmuir probes, did not show significant relative variation related to the event. The total impurity content showed that a point was reached approximately 10 shots after the beginning of low density operation at which a rise could be observed. Thus, the large scale C erosion has apparently begun with the shot #28335 and was repeated on the application of heating thereafter.

To estimate the relation between the two space-scale heat deposition described earlier and the observed C content, we have modelled the C content with the MIST (1-D radial impurity transport) and BBQ (3-D scrape-off layer impurity transport) codes. The boundary conditions for the MIST calculation are taken from the 3-D BBQ code, which accounts for the fact that many impurities enter in the form of ionised particles, not just neutrals, as is conventionally assumed. This improvement is relevant here because it reduces the C influx needed to match the measured C core content by factor 2–3. Fig. 4(a) shows the fit between the observed C content, here represented by the radiated power, and the BBQ/MIST modelling. The calculation also matches the emissivity of the CVI Ly a line, which is shown in Fig. 4(b). The BBQ heat deposition model includes the ~1 mm decay length component of heat flux and the generation processes of physical and chemical sputtering and radiation enhanced sublimation (RES). Peak C influxes of 3×10^{21} particles s^{-1} are thus obtained from the fitting the radiated power as shown in Fig. 4(a). Esti-

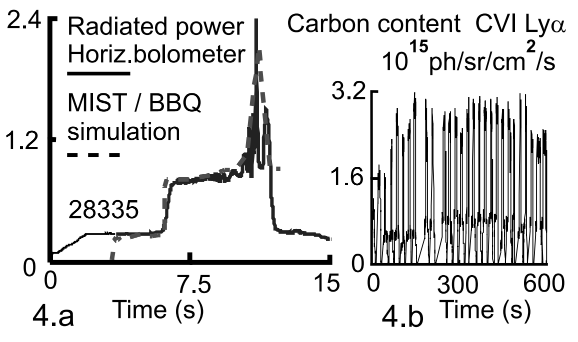

Fig. 4. Radiated power and carbon content for IFW failure.

mates of the C production expected by RES under these conditions suggest that peak rates of 3500 equiv. amp m^{-2} can be produced. Other mechanisms (physical and chemical sputtering) produce much lower peak rates. The RES value is roughly consistent with the influx rate which is needed to produce the observed C content from the small affected area. Further details of the simulation are to be reported in [11].

3. Discussion

Operation and simulation of the IFW shows that for the parallel power arriving with a small e-folding length, this limiter behaves like a series of leading edges. The individual hot spots seen on the infrared images are associated with leading edges instead of sites as was previously admitted. This is not a hindrance at Tore Supra because of the active cooling limits the temperature excursion on the leading edge and allows long pulse operation [12]. The IFW extracts up to 2.5 MW in steady state, still a factor 2 below its operational limit [4]. A total deposition of 2.5 MW corresponds to an overall average heat flux of 0.1 MW/m^2 if it is spread over the whole 25 m^2 limiter, but it leads to an tile-averaged heat flux of 1 MW/m^2 on the most exposed tile and even up to 20 MW/m^2 on its leading edge.

The experience with the IFW shows that dealing with leading edges is still very difficult. Infrared thermography measurements are imprecise because the trade-off between observing a large area with a low resolution and observing a small area with a high resolution is often settled toward the former. Temperature varies over 1000 K over a few millimetres and a high spatial resolution is mandatory. On the modelling side, the picture is not much brighter because it is complicated by sheath effects, sputtering and evaporation. There is either a redistribution or some amplification of the heat flux, all parameters being intrinsically linked. As a result, the heat flux may change dramatically over a short distance. The calculation of the temperature of the leading edge is subjected to large error bars.

From a design point of view, one tends to forbid leading edges too close to the last closed flux surface. That was the guideline for the design of the toroidal pumped limiter CIEL, the Tore Supra main plasma facing component for the future. Gaps are however, unavoidable for diagnostic openings or fabrication constraints. They are then treated by chamfering, which should be carefully done because it reduces the wetted area when done too abruptly. Even with those precautions, the prediction of the behaviour of the leading edges remains uncertain. That is why when leading edges are unavoidable, they should be carefully diagnosed to avoid accidents and too much narrowing of the operating window of the component.

4. Conclusion

Self-shadowing is a major feature of the heat flux deposition scheme on the IFW. It is caused by faceting as well as by the ripple of the toroidal field, although the IFW is located on the high field side where the ripple is low. The combination of observation and simulation allowed to demonstrate the presence of anomalous heat flux at the tangency point between the limiter and the plasma, an effect which was also observed on other tokamaks operated with limiters [7,13]. Despite their presence, leading edges were not a limitation for the operation of Tore Supra. Due to the active cooling, their temperatures remain stable at a reasonable value, even during long pulses. The limitations encountered come rather from the technological limits of the component (multi material junction and excessive heat flux). In accidental situations, leading edges may have an aggravating effect, that is why they should still be avoided, and when absolutely inevitable, the chamfers have to be carefully designed.

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