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Power and particle flux to the neutraliser plates of the Tore Supra ergodic divertor modules

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Abstract

In order to investigate steady-state regimes, the ergodic divertor of Tore Supra must control the power flux to the neutraliser plates while ensuring a sufficient pumping capability. New actively cooled neutraliser plates have been developed to allow spreading of the heat flux on a wider zone. One prototype of such plates has been installed inside Tore Supra. The infrared imaging of an actively cooled plate with a low thermal time constant (~ 5 ms) yields a precise map of the 2D patterns of the power flux which is shown to display large modulations related to the connection properties of the field lines to the plate. The sensitivity to changes in the magnetic equilibrium and/or the level of the magnetic perturbation is analysed. The particle flux does not give evidence for such large modulations, suggesting that the patterns are essentially governed by the temperature field.

Keywords: Tore Supra; Ergodic divertor; Energy deposition

1. Introduction

The ergodic divertor (ED) has provided an efficient way to implement conventional divertor effects in the circular tokamak Tore Supra without using a magnetic configuration with an X-point [1–3]. Its general and macroscopic properties such as the change of energy transport at the edge [4], the impact on the edge MHD [5] or the impurity screening effect [6] are now well documented but should be complemented by studies in which the detailed physics of the edge region is addressed. The heat and particle flux onto the divertor neutraliser plates are of particular importance since they will determine the heat and particle exhaust capabilities of the device. The complexity of these problems has already been reported in other devices such as TEXT [7] or CSTN [8] and a preliminary analysis has been carried out for Tore Supra [9,10]. The plasma edge exhibits a complex structure when stochastic regions are in contact with the wall: the stellerator possess intrinsically these features [11]. The contents of this paper are essentially based on the measurements of power deposition on a new prototype neutraliser plate of the Tore Supra ergodic divertor. The experimental environment will be described in the first part. In the second part, various experiments will be described, in which the magnetic configuration was varied by modifying both the plasma edge safety factor and the amplitude of the magnetic perturbation. The effects of a modification of the total conductive power efflux by inducing more radiation will then be addressed. These results will finally be discussed in the framework of the connection properties in each magnetic configuration.

2. Experimental procedures

Tore supra is a circular tokamak ($R = 2.38$ m, $a = 0.8$ m, $B_t \le 4.5$ T), which is equipped with 6 internal modular coils to induce a resonant magnetic perturbation. The spectrum of this perturbation is characterised by high toroidal ($n \approx 6$) and poloidal ($m \approx 18$) mode numbers. The total current flowing into the bars may be increased up to 45 kA. It should be stressed that the local perturbation in between the bars is much higher and $\delta B_r/B_t$ may reach, for the maximum toroidal field, a value of about 1.5×10^{-2}, which induces a relatively large deflection of the

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field lines between the bars. This effect is supplemented by the radial component of the ripple of the toroidal field. The magnitude of the latter is comparable to that of the radial component of the field induced by the ED. However, its direction reverses along the bar. Indeed, each ED module is located between two toroidal field coils.

The experiments have taken advantage of the installation of a prototype of the new neutraliser plates to be installed in between the bars. During the 1996 Tore Supra shutdown, the first generation of neutraliser plates will be replaced. The latter were too small to allow a power exhaust exceeding 0.6 MW. Moreover, their plasma-facing side could not be looked at; thus, a test plate had been installed for preliminary studies of the heat deposition with the ED [9]. The new target plates should be implemented for all the divertor modules by the end of 1996. As displayed in Fig. 1, they consist of four actively water-cooled copper tubes covered with a 100 μm plasma-sprayed B_4C layer. Vents have been accommodated to allow for particle pumping [12]. The target plates are inclined at 14° across the toroidal direction and this allows a wide spreading of the heat flux along the 0.3 m length of the active part of the neutraliser plate. The incidence angle will be reduced in the final design to insure a maximum spreading even at maximum toroidal field.

The technical solution used here is characterised by a limited lifetime due to sputtering which exceeds one year of Tore Supra operation. The thermal time constant of the B_4C layer is very short (about 5 ms) in spite of the low thermal conductivity of this material (1 W/m/K): consequently the temperature drop occurs mainly across this layer and the thermal image of the plate is thus a direct image of the thermal flux impinging onto it. An infrared image of the plate is recorded during the whole shot every 40 ms. The actual space resolution is estimated to be about 5 pixels, about 0.01 m. An example of the thermal image of the neutraliser plate is given in Fig. 2. The viewing angle of the IR imaging is such that only 3 of the 4 tubes building the neutraliser plates can be seen. The analysis is restricted to profiles along the axis of each of the three tubes.

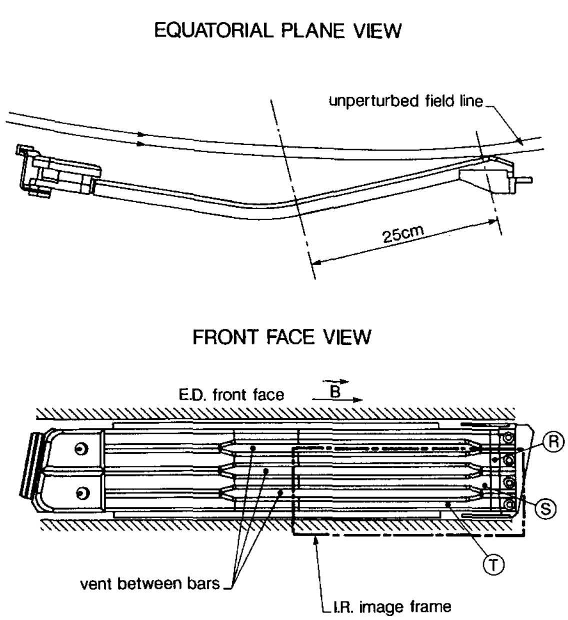

Fig. 1. Schematic view of the prototype of the neutraliser plate.

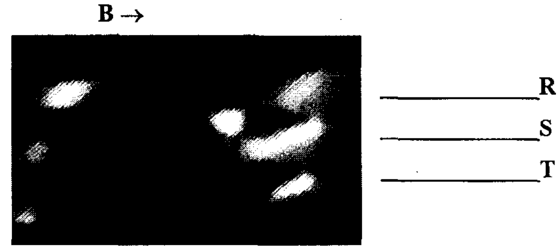

Fig. 2. Thermal image of the neutraliser plate in shot 17375. Note that only 3 out of 4 elements are visible. Two 'structures' can be noticed along the plate.

This neutraliser plate was equipped with one Langmuir probe embedded in between the neutraliser tubes. Its electrical insulator, made of boron nitride allows some thermal cooling, so that the surface temperature of the tip never exceeded 1000°C. This probe yields the particle flux to the neutraliser plates while the IR imaging allows one to compute the parallel heat flux provided that one unfolds the deposited flux from the impinging angle.

3. Characterisation of the heat flux on the neutraliser plate

Regarding heat flux exhaust in steady state conditions, it is an essential issue to estimate the mean heat flux value together with the peaking factor, namely the ratio of the peak heat flux to the mean heat flux. The smaller the peaking factor the smoother is the energy extraction. It is therefore of importance to evaluate the performance in terms of heat exhaust of the various magnetic equilibria within the resonance region of the ED (typically $2.5 < q_{edge} < 3.5$).

3.1. Experimental studies of the thermal flux map as a function of the edge safety factor

The edge safety factor q_{edge} is assumed to play a major role in determining the heat flux deposition on the plates for many reasons. First, the current bars are oriented along a direction which is generally not equal to the local helicity of the field lines, hence a shadowing effect, preventing the whole plate to be wetted. Another important factor is the variation of the connection lengths induced by such changes and possibly providing large changes in power deposition related to the phasing of the field line poloidal position after one poloidal turn, as described in Ref. [13].

Experiments were carried out in which a plasma current ramp-up was made for two values of the toroidal magnetic field, i.e. 3.04 T in shot 17375 and 2.09 T in shot 17380. The total current in the divertor bars was 43 kA in the former case and 36 kA in the latter, a 36% larger relative perturbation. The ramp-up spanned from 1.33 MA to 1.63 MA (q_{edge} from 3.3 to 2.65) in the first case and from 0.9 MA to 1.09 MA (q_{edge} from 3.45 to 2.85) in the second. During the current ramp-up, heat flux structures such as displayed in Fig. 2 are found to be shifted along the toroidal direction. A poloidal reshaping is also noticed as expected from the specific magnetic field map in between the bars. It is found that the typical structure explores the whole accessible extension of the bar for a q span of about 0.18. This corresponds to a poloidal relative deflection of the flux tube after one poloidal turn of about $\Delta q/q = 0.18/3 \approx 1/17$: one finds as expected the inverse of the poloidal main mode number of the magnetic perturbation [13]. On Fig. 3 the average heat fluxes for two values of toroidal field during the slow current ramp experiments are displayed. The mean heat flux ranges from 1.5 to 3 MW m^{-2} in this experiment with Ohmic heating and low radiation. The very mild change in mean heat flux with the plasma current stems from the small variation in Ohmic power due to the confinement time scaling on the plasma current ($\tau_E \propto I_p^{1.7}$), which governs significant modifications of the plasma resistivity.

The observation that the peaking factor is high relates to the fact that the transport is mainly parallel, preventing a

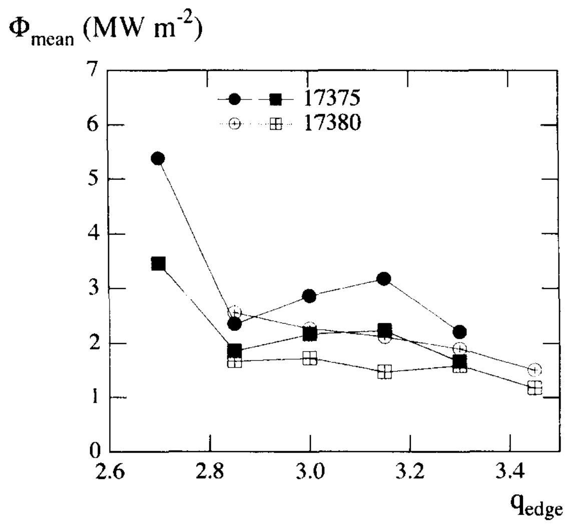

Fig. 3. Average heat flux on the plate for the two shots with different values of the toroidal magnetic field B_t (17375: $B_t = 3.04$ T and 17380: $B_t = 2.09$ T) to yield various values of the edge safety factor for the two central tubes R (squares) and S (circles).

significant radial diffusion to fill the gap. Consequently, the zones, corresponding to short connection lengths receive a very small fraction of the flux, below 2 MW m^{-2}. This results in peaking factor exceeding the design value in this case. The heat flux being conducted to the plates depends little on the q value in the range studied. The main effect governing the deposition is the shadowing effect of the bars themselves, which was difficult to study by thermography as they are themselves optically shadowed, the strong excursion of the heat flux for the shot 17375 at $q = 2.7$ possibly relates to the specific conditions encountered for such high I_p values: in fact for power flux in the flux tubes around 2 to 4 MW m^{-2}, the parallel thermal transport length ($T_e/\nabla_{\parallel} T_e$) depends strongly on this value for a given edge density.

3.2. Experimental studies of the thermal flux map as a function of the ergodic divertor magnetic perturbation

The major interest of studies in which the magnetic perturbation is varied stems from the possibility to assess the actual spreading of the heat flux onto the neutraliser plate. Experiments were done at toroidal field $B_t = 2.1$ T in order to reach very high values of the relative magnetic perturbation $\delta B_r/B_t$. The total divertor current was varied during the shot from 20 to 44 kA. Fig. 4 displays the average (open symbols) and maximum (filled symbols) heat flux onto the neutraliser plate. As already noticed [14], the power flux onto the plates increases about linearly with the perturbation above a certain threshold. The latter cannot be determined accurately from the experiment but it was extrapolated to be about 10 kA. In Ref. [13], it is shown that the expected neutraliser wetted area should behave as $(\delta B_r/B_t)^{0.5}$. There is no discrepancy between these two scalings if one considers that more field lines impinges on the plates and less on other plasma facing components when the perturbation strength is increased. Another interesting feature is that this increase appears to occur in steps. This might be due to quantization of the field line incremental step, given the discrete effect of the plasma facing components on the variation of the field line correlation length.

Comparing low and high magnetic perturbation indicates that there is a significant decrease with the perturbation. Furthermore, there is a shift of the pattern deeper between the current bars. This trend is somewhat reversed at very high value of the magnetic perturbation. In those cases and as shown in Fig. 5, very peaked heat flux distributions are recorded. As they reach values above 10 MW m^{-2}, one could relate this peaking to an increased conduction along field lines for such high heat exhaust; this may stem from the balance between parallel and perpendicular energy conduction which becomes very favourable to the parallel one as the electronic temperature increases.

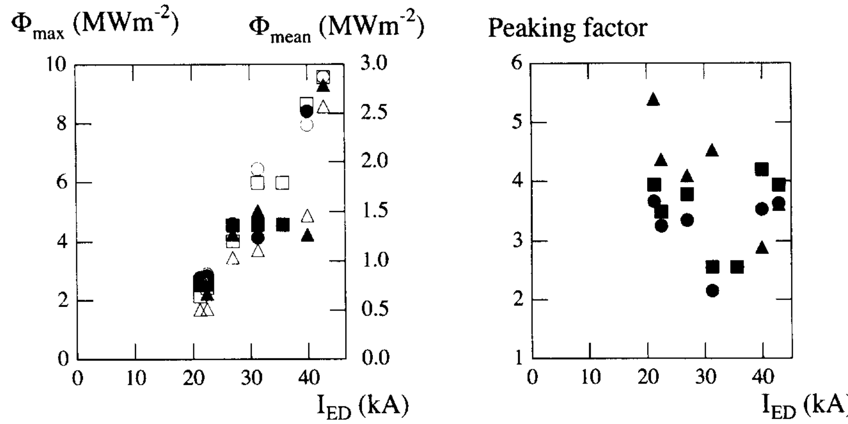

Fig. 4. Average (open symbols) and peak (filled symbols) heat fluxes onto the neutraliser plates and corresponding peaking factors for different values of the relative magnetic perturbation (here the total current in the divertor module I_{ED}). This is displayed for 3 tubes: R (squares), S (circles) and T (triangles).

3.3. Particle flux structure on the neutraliser plate

For the experiments in which the plasma current is ramped up, the saturation current of the embedded Langmuir probe has been recorded. Fig. 6 displays its evolution which gives evidence of little modulation; this has been compared to the evolution of the heat flux impinging onto the two neighbouring elements of the neutraliser plate at the same toroidal position. It is obvious that the heat flux is much more modulated than the particle flux; this trend is general and could be attributed to the fact that particle sources are located very close to the plate. This case is very different from that of the heat flux, the source being located in the plasma core. Furthermore, the smaller ratio of effective transport through the stochastic boundary to anomalous diffusion for particle transport versus energy transport will lead to less pronounced modulations of the density field versus the temperature one.

3.4. Highly radiative experiments

Experiments in which the density was raised by gas puffing usually lead to an increase of the radiative losses. The total radiated power is measured by a bolometer system, assuming toroidal homogeneity. It is clear that the conducted heat flux is reduced to values which are very close to 0 (i.e. less than 0.3 MW m^{-2}) for cases in which the bolometric measurements only account for 80% of the total Ohmic input power. It must be added that, although

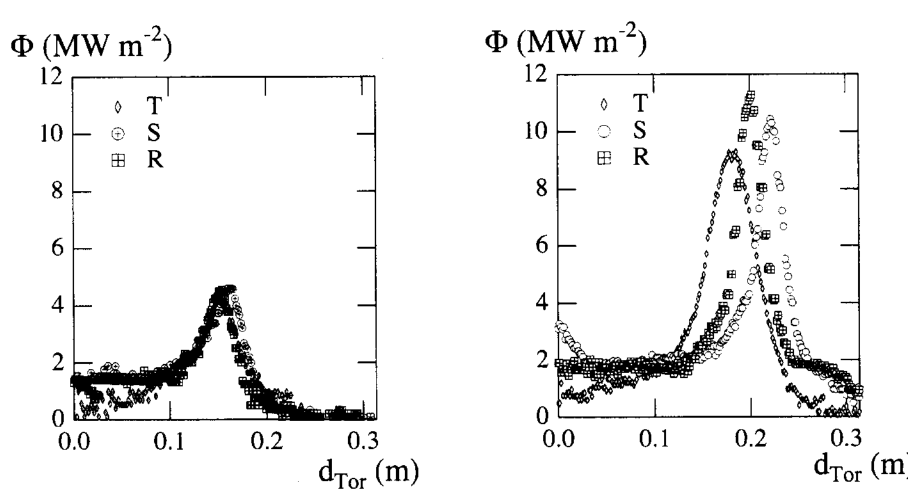

Fig. 5. Profile of the heat flux along the 3 visible elements (R, S, T as depicted in Fig. 1) of the neutraliser plate. d_{tor} is the toroidal coordinate along the plate for I_{ED} = 22 kA (left) and 42 kA (right).

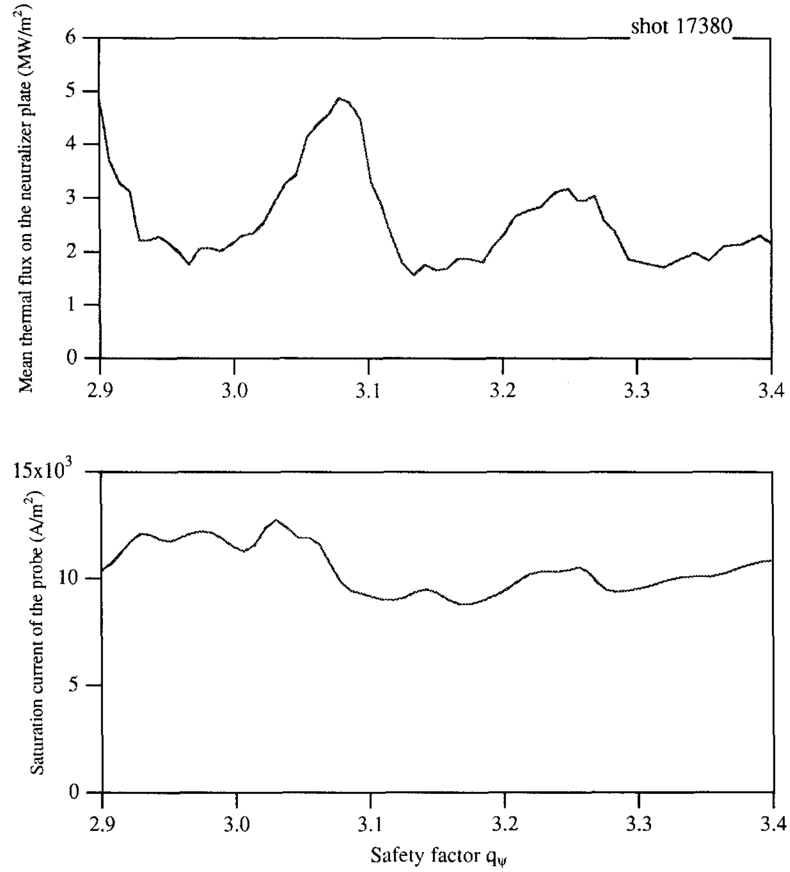

Fig. 6. Average heat flux and saturation current of the embedded Langmuir probe in shot 17380 when varying the edge safety factor.

the conducted heat flux decreases when the density is raised, the Langmuir probe ion saturation current is observed to decrease only when the heat flux is reduced to practically zero. This behaviour is very similar to detachment obtained in conventional X-point divertor tokamaks [15].

4. Discussion and conclusions

The experimental study of the heat flux deposition onto a neutraliser plate was assisted by the use of a new neutraliser plate for which the thermal image from IR thermography can be translated directly into heat fluxes. This clearly shows a noticeable spatial modulation of the plasma parameters in the perturbed edge region.

The main trends are in agreement with the simple idea that the heat flux is mainly transported along the perturbed magnetic flux tubes for about one poloidal turn. A comparison with outputs of the MASTOC code [16] shows an excellent qualitative and quantitative agreement with the experimental data [13]. Nevertheless, it appears that the physical picture might be somewhat different in cases for which the heat flux which is transported to the plates is generally lowered. Then, the thermal scale length $(T_e/\nabla_\| T_e)$ might be lower than the field line correlation length of the order of one poloidal turn. For densities around 3×10^{18} m^{-3}, this corresponds to parallel heat fluxes of about 4 MW m^{-2}.

The sensitivity of the modulations to variation in both the edge safety factor and the amplitude of the magnetic perturbation will easily allow the achievement of power flux spreading onto the whole active area of the neutraliser plate by a small time variation of the plasma current for example, in spite of a relatively large static peaking factor. By raising the density and increasing the radiative power losses, the power heat flux may be reduced to very low values, below the experimental detection threshold. The particle flux onto the neutraliser plate does not display such modulations, which may be linked to strong ionisation sources, located very close to the plate. The experimental results achieved with this prototype give confidence for the operation of the upgraded ergodic divertor in Tore Supra after completion of the installation of such plates on every modules.

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