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Localized heat flux due to lower hybrid wave coupling in the Ergodic Divertor configuration on Tore Supra

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Abstract

Lower hybrid (LH) current drive experiments were carried out in the ergodic divertor (ED) configuration. In this configuration, at low density ($\langle n_e \rangle = 1.7 \times 10^{19}$–$2.3 \times 10^{19}$ m^{-3}), up to 4.5 MW of LH power was coupled and 65% of the plasma current (here equal to 1.4 MA to match the resonant edge safety factor needed for divertor operation) was driven by the LH waves. With an optimized position of the grills, it was possible to obtain a reasonable steady state temperature of the neutralizers ($T_{neut} < 800$°C) and 3.9 MW were coupled for 20 s leading to a record total injected energy of 93 MJ in this configuration. The power deposition can be derived from the surface temperature of the boron carbide coating of the neutralizers by infrared thermography. A well localized heat flux is observed on the divertor neutralizers magnetically connected to the grills. Such heat flux is known, from previous work, to be due to LH power dissipation near the grills. This heat flux is here studied in detail. In the shots analyzed here, parallel heat fluxes up to 15 MW/m^2 were measured, but values exceeding 50 MW/m^2 have been recorded. The use of the field line tracing code MASTOC allows one to link the power deposition on the neutralizer plate to specific regions in front to the grills, thus underlying the importance of the electromagnetic fields there. The edge density is shown to be a key parameter. Not-well-understood local effects arise when the LH is activated, and accurate measurement and analysis of local density and electric field are needed. It has to be noted that a trade-off between the decrease of the edge density at the grill and its coupling capability which drives the electric fields quoted above has to be dealt with; the positioning of the grill has then to be optimized and eventually feedback controlled. In order to increase the operational margin, the spreading of the heat flux was efficiently obtained by a moderate modulation of the divertor current by less than 30%.

Keywords: Tore Supra; Ergodic divertor; LHCD; Power deposition; Thermography

1. Introduction

Tore Supra is a superconducting tokamak devoted to the study of steady state plasmas. An essential requirement is to sustain the plasma current by a noninductive scheme. Lower hybrid (LH) waves are effective in achieving this goal [1] but until recently most of the experiments were done in limiter configuration. The ergodic divertor (ED) configuration has demonstrated the capability to control energy and particle deposition while providing both screening of impurities and stable radiating layers [1]; recently the reinforcement of the Tore Supra ED has led to an increase of the heat exhaust capacity [2] thereby allowing the study of long diverted discharges as well [1]. Several physics questions arise in this operation scenario. Of particular importance is the capacity to couple the waves through a diverted edge plasma. Specific edge power deposition on first wall components has been reported in Tore Supra [3,4] and other tokamaks such as TdeV (Tokamak de Varennes)

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[4]. It is believed that this deposition results from acceleration of thermal edge electrons in the LH electric field in front of the grill. The power delivered to the electrons in front of the grills is only a small fraction of the total LH injected power, but the resulting power flux is very large and can lead to severe damage of objects magnetically connected to the couplers. Section 3 describes how the localized LH power flux deposition onto the neutralizers is discriminated from the heat flux due to the bulk energy outflow from the main plasma. Section 4 quantifies the values of the heat flux involved; we will present an analysis of the spatial distribution of the power flux *in front* of the LH grills through the use of detailed infrared maps of the neutralizer plate, and of the field line tracing code MASTOC [5]. It will be shown that the heat flux deposition pattern depends very sensitively upon the physical and magnetic geometry of the system, and upon the edge density. The peak power flux deposition can be reduced by modulating the divertor current.

2. Experimental tools

The tokamak Tore Supra ($R = 2.38$ m, $a = 0.79$ m, $B_t \leqslant 4.5$ T) is equipped with an ED comprising six internal modular coils that induce a resonant magnetic perturbation [5]. This perturbation, mainly radial, creates a strong local deflection of the field lines causing them to impinge on seven neutralizer plates placed inside each divertor module (Fig. 1). Each neutralizer plate is composed of four actively water-cooled copper bars covered by a plasma-sprayed 100–200 μm B_4C layer, as shown in the figure. The temperature of the coolant is maintained at 150°C. An IR thermography system with two possible spatial resolutions is available and in the following only the better spatial resolution (1.1 mm/pixel) is used. In this configuration the neutralizer plate located on divertor module PJ1, i.e. the one adjacent and magnetically connected to both LH couplers, can be nearly fully viewed: only the bottom three of the four bars are visible because of the shadowing by the structure of the module itself. The surface temperature of the ED plate is usually lower than 1000°C. The temperature drop between the surface and the coolant occurs mainly in this surface layer, because of its low thermal conductivity (1–2 W m^{-1} K^{-1}) with respect to the underlying copper (300 W m^{-1} K^{-1}), but in spite of the low conductivity, the thermal time constant of the thin B_4C layer is shorter than that of the underlying copper due to its very thin thickness (150–200 μm). Consequently the thermal images of the bars are maps of the heat flux impinging upon the plates. The relation between surface temperature T and heat flux ϕ is given by the formula $\phi = P/S = k(T - T_0)/d$, where P is the power through the layer, S the surface, k the thermal conductivity assumed constant with the temperature, T_0 is the coolant temperature, and d the measured thickness of the boron carbide layer. The camera setting was chosen, during the shots analyzed, to measure temperatures in the range 150–1150°C, corresponding to a power flux of 0–8 MW/m^2. The bars have an inclination of 8° with respect to the toroidal direction at the tangent plane. Consequently, a radial and poloidal mapping of the parallel power flux can be deduced from the temperature profiles along the bars. The incidence angle α of the flux tube varies along the neutralizer bars and can be calculated with MASTOC. In the paper, we will address the heat flux inside the flux tubes $\phi_\parallel = \phi/\sin\alpha$.

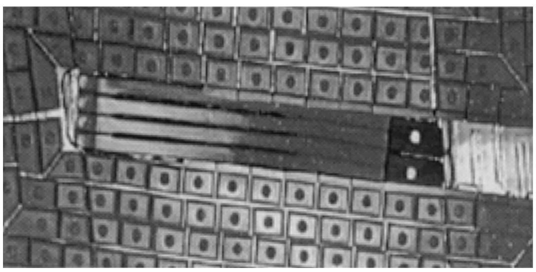

Fig. 1. Photograph of a neutralizer plate showing the boron–carbide coated copper bars.

3. Zone characterization

The two LH grills are located side by side between two ED modules (Fig. 2(a)). They are normally

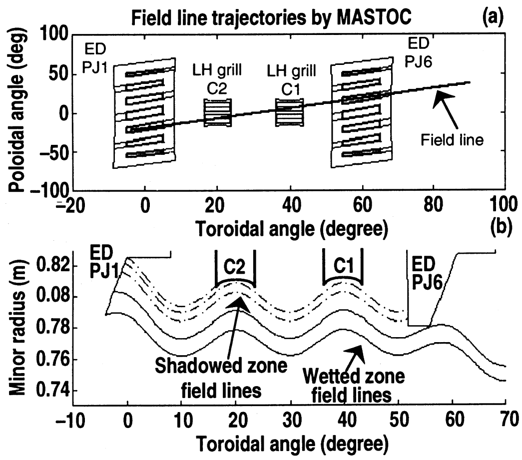

Fig. 2. (a) Frontal view of ergodic divertor and lower hybrid grills. A magnetic field line is shown intercepting one of the neutralizers of PJ1. (b) Top view of line trajectories in front of the grills. The effect of shadowing and toroidal field ripple are evident.

positioned about 2 cm behind the front face of the modules. To understand the power deposition pattern, we can imagine a magnetic flux tube in the edge plasma layer, simulated with MASTOC in Fig. 2(b), coming from the high field side (right direction), jumping radially outward each time it passes through the radial perturbation in front of a divertor module, arriving in front of the LH grills, going through the LH power injection region, and finally impinging on the neutralizer plate (on the left). The field line oscillation is due to the toroidal field ripple, an important factor on the low-field side of Tore Supra.

A power flux image, calculated from the thermal image, of one of the neutralizer plates is displayed in Fig. 3. We can distinguish the three bars and along each bar two regions of high power deposition: one at the right of the black line and a second one at the left. The MASTOC field line tracing code predicts a magnetic shadowing effect by the upstream ED module PJ6 upon the module PJ1 that is viewed by the camera. The area of the bars on the right side of the image is shadowed; the area on the left is unshadowed and wetted by the main plasma. The shadowed zone is then expected to be not magnetically connected to the main plasma and is locally heated only during LH power injection (the couplers themselves being shadowed in the same manner). In accordance with the calculated magnetic geometry, we find in the thermal image the two distinct 'hot' regions along the toroidal direction, separated by a zone with low power deposition. The temporal evolution of the power deposited on the unshadowed zone is well correlated with the total input power (LH + ohmic) as shown in Fig. 4(a), while in the shadowed zone (corresponding to larger radius) the correlation is only with the LH power injected (Fig. 4(b)). The shadowed region remains cold when the LH heating is off. The power deposition in the shadowed zone can be analyzed to get

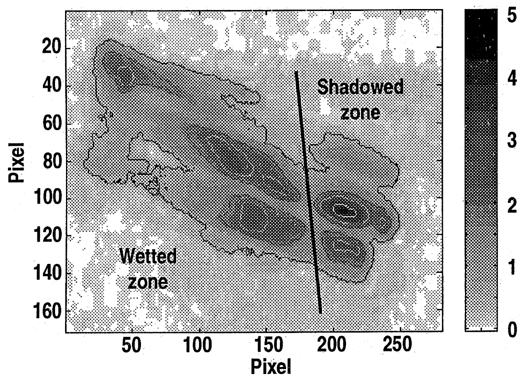

Fig. 3. Infrared image converted to a power flux map on the neutralizer plate, expressed in MW/m^2. Two power deposition zones are visible: the one on the right is due to electron acceleration by the electric field in front of the lower hybrid grills.

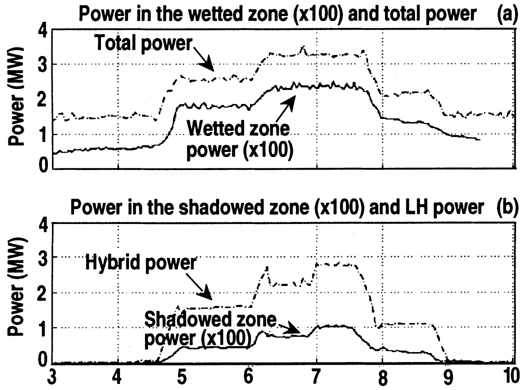

Fig. 4. (a) Total input power and power deposited on the wetted area of the neutralizer plate (left hand side of thermal image Fig. 3). (b) Injected LH power and power deposited on the shadowed area of the neutralizer plate (right-hand side of thermal image Fig. 3).

a better understanding of the plasma–wave interaction in the edge. The study of such a topic is technically necessary to permit the maximization of the LH power injection without damaging the divertor modules, and the achievement of steady state operation. The present limit of total power exhaust for all the divertor modules is 10 MW for 30 s, limited by non-actively cooled CFC protection tiles heating on the ED front face. A second limit arises by the critical flux limit which is about 10 MW/m^2 upon the neutralizer bars. For the field line pitch calculated by MASTOC, this corresponds to a parallel power flux of about 50 MW/m^2.

4. Analysis of power deposition in the shadowed zone

During the shots analyzed the sequence of the power injection by the LH grills was: C1 on, C2 on, C1 off, C2 off. We have therefore four different phases: an ohmic phase before and after the injection, a first phase with the grill C1 only, an overlapping phase with both grills, and a final phase with the grill C2 only. The temperature profile along the bar in the toroidal direction can be translated into a radial power flux profile. Using the field line tracing code MASTOC, we have mapped the deposited power flux to the thin region in front of the grills. The ratio $\Delta R/\Delta X$ relating the displacement ΔR at the radial position of concerned flux tubes, to the displacement ΔX of the heat deposition location on the bar, has been calculated by MASTOC, obtaining in the shadowed region a value of $(\Delta R/\Delta X)_{\mathrm{MASTOC}} = 0.24$. During some shots one grill was moved: in the course of the discharge the correlation between the position of the maximum flux deposition and the grill position was calculated. The experimental value obtained $\Delta R_{\mathrm{grill}}/$

$\Delta X_{maximum}$ is 0.25, very similar to the MASTOC code value. The good agreement between the measured and the calculated value indicates the coherence between the radial grill position and the power absorbing layer position, and suggests that some power is transferred to the plasma immediately in front of the grills following the field lines to nearby objects. The power deposition layer is approximately 5 mm thick radially at the grill location (Fig. 5(a)). Between the two shots shown in Fig. 5(a) the grill C1 was moved 5 mm inward and the power deposition profile shows the correspondent maximum shift, as predicted by MASTOC.

Analyzing in more detail the power flux profile due to the grill C2 only, we can observe a double peak (Fig. 5(b)), with the second peak radially shifted toward the plasma core. This feature can be understood by taking into account the detail of the field line trajectory in the vicinity of the grill. The grills have four rows of waveguides each and the electric field strength is expected to be maximum near the center of each row. The electrons moving along field lines will pass through two zones of intense electric field corresponding to the two rows of waveguides on C2, whereas in front of C1 they only pass in front of a single row (Fig. 2(a)). The radial axis of coupler C2 is slightly misaligned [6] so the intersection between the field lines and the maxima of the electric field are at different radial locations. The distance between the two peaks is in rough agreement with the measured misalignment of the grill. Yet, the shape of the second peak seems to be influenced by the position of the neighboring, inactive grill C1, and in some cases (Fig. 5(b)) it actually vanishes when the two couplers fire together. These effects are not well understood and a more accurate analysis is needed. Furthermore, it is interesting to note that the total power flowing along a given field line during the overlapping phase when both C1 and C2 fire together is often substantially less than the sum of the total powers generated by the grills individually (Fig. 5(b)). This could be due to the fact that the edge density is modified by the total launched power and therefore the LH coupling may change. Moreover, simulations of the stochastic electron heating in front of the grills indicate that the average energy gained by the electrons saturates after the electrons traverse a certain number of waveguides [3]. In this case the electrons could have reached the maximum energy in front of the first grill and they are not accelerated further in front of the second one. The deposition profile is very complicated and seems to depend sensitively on local conditions and geometry.

An analysis of the total power deposited in the shadowed zone has been done, on a shot-by-shot analysis. Fig. 6(a) shows the total power deposited in the shadowed zone as a function of the hybrid power injected for shots at the same average density ($\langle n_e \rangle = 2.1 \times 10^{19}$ m^{-3}). The power deposited is proportional to the power injected, as already found in similar analysis [7]. The power deposited on the viewed plate is normally less then 1% of the LH power injected. It is expected that only 3–5 plates are directly linked to the grills. Normalizing the power deposited for the only studied plate to the hybrid power injected, we can show

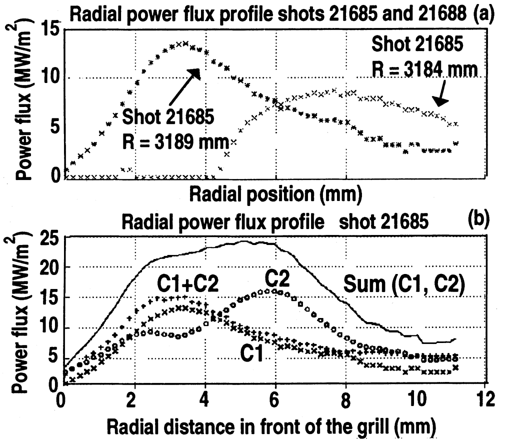

Fig. 5. (a) Radial profile of the parallel power flux generated by coupler C1. This is a magnetic mapping of the measured power flux from the bar to the front of the grill. The shift of the power maximum is in agreement with the displacement of the grill. (b) Radial mapping of the parallel flux from one shot. Shown are the power flux profiles during the three phases of LH power injection (x: C1 only, +: C1 and C2, o: C2 only). The sum of the power fluxes generated by the grills separately is greater than the power generated when the grills fire simultaneously.

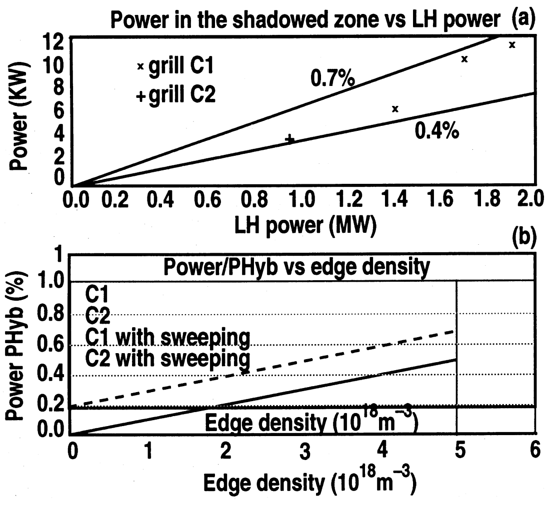

Fig. 6. (a) The total power deposited on the neutralizer in the shadowed zone as a function of LH power. The power is between 0.4 and 0.7 of the total LH power injected. (b) Power deposited normalized by the LH power as a function of edge density measured by a Langmuir probe.

the dependence on the edge density (Fig. 6(b)). The dependence is linear for edge densities up to 5×10^{18} m^{-3}. Above this density the edge region is in the high recycling regime [8]. Yet, the density was measured by a Langmuir probe in a nearby neutralizer plate and is representative of the edge density in that region of the torus, but may not be sensitive to local effects observed in the flux tubes connecting the ED plate to the grills.

By sweeping the divertor current it has been possible to spread the power flux impinging on the neutralizer over a wider surface, lowering the peak temperature and enhancing the power exhaust capability. Two factors have to be considered: first we need a sufficient sweeping velocity to move the maximum faster than the thermal equilibrium time, spreading uniformly the power on the wetted area; second the area needs to be wide enough to bring the average power flux under the maximum exhaustion capability of the neutralizer. As a rough estimation, if $D = 5$ mm is the power peak dimension and $\Delta = 25$ mm is the shift along the neutralizer induced by a 30% change in the ED current, we can utilize the following formula to estimate the necessary sweeping frequency:

$$v = 1/(2T) \geqslant 1/2\, D/\Delta t \cong 20 \text{ Hz},$$

where T is half-period, and t the thermal time constant of the boron carbide layer (~5 ms). With such a modulation it is possible to enhance the power exhaust capability in the shadowed zone of a factor given by the ratio of the areas $\Delta/D \sim 5$.

5. Conclusion

On the neutralizer bars magnetically connected to the LH grills there is a shadowed region not connected to the plasma core. In this region the LH power is deposited in a flux tube directly in front of the grills in a radial layer approximately 5 mm thick. The position of the power peak is directly connected to the grill position and the geometry is well simulated by the MASTOC field line tracing code. The deposited power depends on the field line trajectory, on the electric field generated by the grill, and on the edge density. A modulation of the divertor current induces sweeping of the peak power strike point and this spreads the thermal load over a wider surface enhancing the power exhaust capability of the ergodic divertor.

References

[1] Ph. Ghendrih, Plasma Phys. Control. Fusion 39 (1997) B297–B222.
[2] L. Doceul et al., Proc. 19th SOFT, Lisbon, 1996.
[3] M. Goniche et al., Report EUR-CEA-FC-1598, 1997.
[4] J. Mailloux et al., J. Nucl. Mater. 241–243 (1997) 745.
[5] Ph. Ghendrih, A. Grosman, J. Nucl. Mater. 241–243 (1997) 517.
[6] J.J. Cordier, Bilan des mesures dimensionnelles effectuees lors de l'arret d'hiver 97-98, private communication.
[7] M. Goniche et al., Proc. 24th EPS Conf. on Contr. Fusion and Plasma Phys., Berchtesgaden, vol. I, 1997, pp. 217–220.
[8] T. Loarer et al., these Proceedings.