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Power deposition behaviour on the neutralizer plates during detachment with the ergodic divertor on Tore Supra

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Abstract

The behaviour of the particle and of the power deposition on the neutralizer plates of the ergodic divertor (ED) of Tore Supra is reported for density ramp up experiments in deuterium. Both the particle flux and the power deposition are shown to be non-uniform when the plasma is attached while a uniform deposition is obtained when it is detached. A degree of detachment (DoD) is proposed, based on IR measurements using the ratio of the heat flux deposition from a 'hot' and a 'cold' area. This infrared degree of detachment (IR_DoD) is larger than 1 in the attached phase and decreases towards 1 when the plasma approaches detachment. A comparison between the classical DoD deduced from Langmuir probes and the IR_DoD deduced for IR data is given, showing a similar sensitivity when the density increases. Finally, since the IR_DoD does not require any modification of the IR system, it is an opportunity to optimize the ratio by a careful selection of the viewed area, free from major drifts and calibrations of the measurement system.

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Keywords: Ergodic divertor; Particle flux; Power flux; Degree of detachment; Tore Supra

1. Introduction

In diverted tokamak, a considerable part of the outgoing power is channelled onto the target plates via the parallel heat flux ($Q_{\parallel}$). The control of power deposition on the target plates of limiters and divertors is not a major constraint in today's tokamaks, but it will likely be for future fusion devices like ITER [1]. Reliable methods of measurement and control of $Q_{\parallel}$ are therefore needed in order to maximize the lifetime of plasma facing components. Among the different plasma scenario used, high recycling and detached plasma in the divertor region are candidates to limit the power deposition on the divertor target plates. Over the past years, the Ergodic Divertor (ED) of Tore Supra has demonstrated capabilities to control particle and heat fluxes in the plasma edge [2].

In this paper, the behaviour of the power deposition on the neutralizer plates (NPs) of the ED of Tore Supra is reported for density ramp up experiments with deuterium. Both parallel heat flux, $Q_{\parallel}$, and particle flux, $\Gamma_{\parallel}$, have been monitored, respectively by infrared thermography (IR) and Langmuir probes.

The first part of this paper presents density ramp up experiments in D_2, with gas puffing. An evolution of power deposition non-uniformities in the three classical regimes (linear, high recycling and detachment) is observed except for the detached plasma. In the second section, a degree of detachment deduced from IR measurements (infrared degree of detachment, IR_DoD) is proposed. It is defined by the ratio of two measurements of $Q_{\parallel}$ from a 'hot' and a 'cold' area and it characterizes the modification of the power deposition from attached (non-uniform) to detached (~uniform) plasma. A comparison with the 'classical' degree of detachment (DoD) deduced from the Langmuir probes [3] is given. Finally,

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the least part deals with the methods used to define a DoD with the associated advantages of performing a ratio of two measurements.

2. Power deposition: experiments in D_2

Experiments have been performed in D_2 with the ED to study the power deposition and the particle flux during the detachment phase from the NPs. They are equipped with a set of 14 Langmuir probes and infrared cameras allowing a simultaneous monitoring of the NP surface for both particles and power.

Fig. 1(a) shows the time evolution of the average plasma density (density ramp up by gas puffing) and of the resulting saturation currents, I_{sat}, of three Langmuir probes. At low density the linear dependence of I_{sat} with the density is observed, followed by the high recycling regime ($I_{sat} \propto \langle n_e \rangle^2$) for larger density. The first 'sign' of detachment is observed at $t \sim 5.2$ s on the 'b' probe only, characterized by a drop of I_{sat} while the two others ('a' and 'd') still exhibit a strong increase characterizing a local high recycling regime. The drop of I_{sat} for these two probes occurs about 100 ms later, for a density about 0.2×10^{19} m^{-3} higher. This delay shows that the detachment process from the NP is not uniform. A feedback control on I_{sat} allows [4] to cut off the gas injection and due to the pumping, the plasma remains detached.

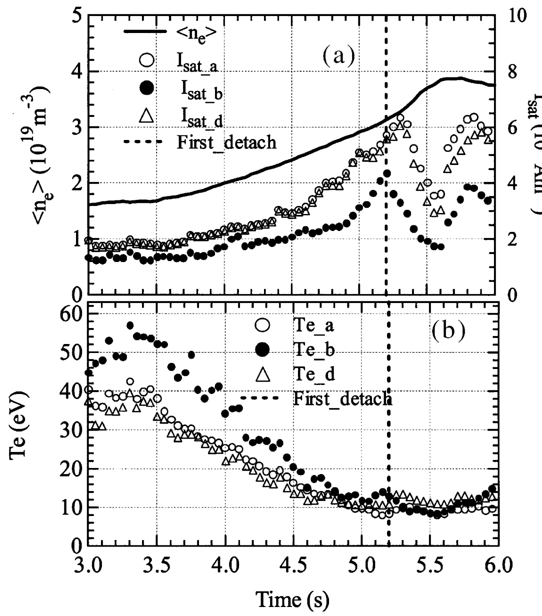

Fig. 1. (a) Time evolution of the volume averaged plasma density and saturation current for the three Langmuir probes located on the same NP. The detachment is clearly observed on the three probes by an abrupt decrease of I_{sat} but not at the same time. (b) The corresponding electron temperature T_e is around 10 eV for $t > 5$ s independently of the behaviours of the I_{sat} and for all the probes close to detachment.

The corresponding T_e, measured on the three probes, all show (Fig. 1(b)) a constant value of ~10 eV about 200 ms before the first I_{sat} drop on probe 'b'. No particular behaviour on T_e can be noticed when I_{sat} decreases except that a uniform T_e is seen on all the probes.

The IR system of the ED consists of a periscope allowing to view either a complete ED module [5] or a single NP (0.3 m of length and 0.12 m large) over the wavelength range from 3 to 5 μm with a temporal resolution of 20 ms. From the IR measurement, the heat flux is deduced from

$$Q_{\parallel} = \Delta T \frac{\lambda_{B_4C}}{e_{B_4C}} \frac{1}{\sin \alpha}, \tag{1}$$

where ΔT is the surface temperature variation of the plate, λ_{B_4C} the thermal conductivity (1.5 W m^{-1} K^{-1}) of the boron carbide (B_4C) coating, e_{B_4C} its thickness (200 μm) and α the incidence angle between the field line and the NP.

The thermal time constant of the B_4C layer is 5 ms; the temperature gradient occurs mainly across this layer and the thermal image of the plate is consequently a direct image of the thermal flux impinging onto it. The IR picture of a NP is shown on Fig. 2 taken at $t = 4.5$ s. On this picture a Langmuir probe (which is not actively cooled) can be distinguished and, as for the particle flux, it is obvious that the power deposition is not uniform either. Fig. 3 displays the $Q_{\parallel}$ as a function of time for the six points located on the NP and shown on Fig. 2. All the six $Q_{\parallel}$ increase for $t > 3.0$ s, corresponding to the resonance of $q_{edge} \sim 3$, and a regular decrease is then observed as $\langle n_e \rangle$ is rise. The drop in $Q_{\parallel}$ is nearly linear with the density when the plasma is attached and independently of the location on the NP. An abrupt drop from ~10 to 7.5 MW m^{-2} is observed between 4.9 and 5.0 s, on both the 'green' and the 'yellow' points while there is no modification observed on the red, black and magenta points. This drop corresponds to the same time when all the three T_e (Fig. 1(b)) converge towards a constant and uniform value of 10 eV. Finally, as the plasma detaches, all the $Q_{\parallel}$ measured at six different locations are very close one to each other, showing a uniform power deposition. From the strong differences of $Q_{\parallel}$ variations as a function of $\langle n_e \rangle$, it is proposed to define an IR_DoD.

3. Degree of detachment

The classical DoD is defined using the measured I_{sat} to a high recycling scaling normalised to the experiment, Fit_I_{sat} : DoD $\propto$ (Fit_I_{sat}/I_{sat}) [3]. The use of the IR data to calculate a DoD is more recent [5,6] mainly based on

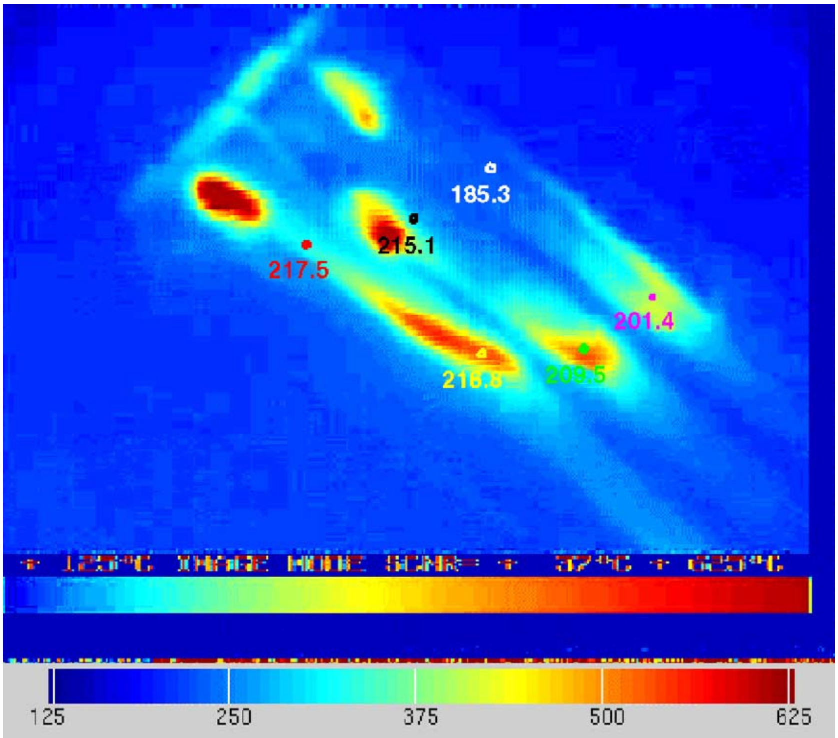

Fig. 2. Infrared picture of the NP at $t = 4.5$ s. The surface temperature shows very strong non-uniformity. The six points noted on the figure are the location of the $Q_{\parallel}$ measurement deduced from the surface temperature variation.

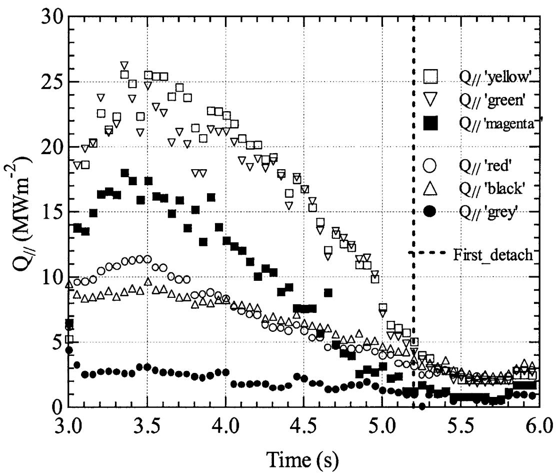

Fig. 3. Time evolution of $Q_{\parallel}$ for the six points noted on the picture. The non-uniform power deposition is observed on the $Q_{\parallel}$ intensity (ratio of 8 between the 'green' and the 'grey' point) and also on the time behaviour.

the spatial resolution capability of the IR system, but also based on adjustment of data since only one signal was used. In axisymmetric divertor, strong asymmetries in the power deposition between the inner and the outer legs have been already reported [7,9] during density scans and for different gases [10]. In all the cases, the inner leg detaches first and for higher density, the outer leg also detaches with similar power reaching the target plates. From the present proposal, the difference of power deposition between attached plasma and detached (respectively non-uniform and uniform) is used to perform the ratio of a $Q_{\parallel}$ corresponding to a 'hot flux tube' divided by a $Q_{\parallel}$ from a 'cold tube flux':

$$\text{IR\_DoD} = \frac{Q_{\parallel}\text{'hot'}}{Q_{\parallel}\text{'cold'}}. \qquad (2)$$

With this definition, an attached plasma leads to a IR_DoD larger than 1 while as the detachment is approached, this ratio becomes close to 1.

The IR_DoD and the DoD deduced from I_{sat} are plotted as a function of the plasma density on Fig. 4. It can be seen that the dynamics of the two DoDs are comparable and that both of them can be used to characterize a detached or attached plasma. It can also be seen that the IR_DoD decreases as soon as T_e becomes constant close to 10 eV ($\langle n_e \rangle \sim 2.9 \times 10^{19}$ m^{-3}) as shown on Fig. 1(b) while the transition from the attached to detached regime characterized by the DoD is more abrupt.

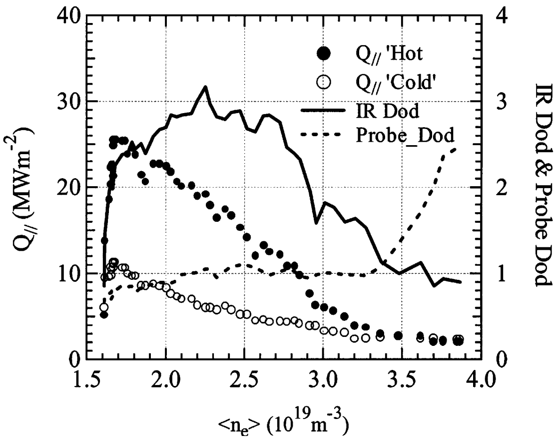

Fig. 4. DoD deduced from the Langmuir probes and from the IR data as a function of the plasma density. The IR_DoD shows a smooth decrease as soon as T_e is close to 10 eV, while the DoD from the probes shows an abrupt increase which is directly linked to the reduction of I_{sat} as the detachment occurs.

4. Discussion

Since only one signal was used, the previous DoD calculated with I_{sat} or $Q_{\parallel}$ both require a density scan in order to build a reference; the gap between the measurement and the reference giving a DoD. The idea of the proposed IR_DoD is to use the ratio of two signals in order to avoid complication of any fit. Moreover, since the IR camera collects a flux, the ratio of the received fluxes allows to prevent the IR_DoD from calibration and/or drift in the optical transmission. In these conditions, the error on the flux measurement does not exceed 10% [11]. In the case of the ED, the magnetic configuration is known and the power deposition (hot and cold area) on the NP can be predicted [12]. However, from experimental observations, it is known that with the ED, the power deposition is very sensible particularly to the edge safety factor. Nevertheless, the global behaviour of the power deposition profiles on the NP is always the same. For all the ED shots, and also as observed in axisymmetric tokamaks [7–9], a very peaked profile is observed for attached plasma and a more uniform one is obtained for detached plasma. For all these shots, the difference of intensity between the $Q_{\parallel}$ corresponding to a hot and a cold tube flux vanishes as detachment approaches. Since the location of the power deposition can change, the IR system allows to adjust the viewed area to optimize the ratio. Using the cold area as a reference, the ratio of $Q_{\parallel}$ hot flux tube and the reference is significantly larger than 1 and as the detachment is approached, this ratio becomes close to 1 (Fig. 4). Actually, the idea of the IR_DoD is only adopted and applied to the ED, but this idea could also be used in axisymmetric divertor by making the ratio of the power deposition on outer and inner leg which is larger than 1 for attached plasma (even when the inner leg is detached) and very close to 1 when the two legs detach [7]. It has to be noted that this definition is not only dedicated to IR data and that it can also be applied to H_α signal [13] as well as to the I_{sat} measured on Langmuir probe. As an example, from Fig. 1(a), performing the ratio of I_{sat} 'a' and I_{sat} 'b' would lead to a constant as far as the plasma is attached for the 'b' probe. The IR_DoD deduced from a ratio of IR data shows a nice dynamic with the plasma density and is in good agreement with the classical DoD deduced from probes.

On Tore Supra, the power deposition on the toroïdal pump limiter is non-uniform [10] due to the self-shadowing and an IR_DoD is foreseen to characterize the detachment. Taking advantage of the flexibility of the infrared diagnostic, the power deposition can be taken as a profile along a target plate (0 to ~25 cm) or even over an area (from few mm^2 to 20 cm^2) in order to adjust the sensitivity of the measurement. Finally, for long pulse operations, IR systems will be implemented in devices and such an IR_DoD will not require any particular constraint while the measurements with probes will become more difficult if not actively cooled.

5. Conclusion

The density scans performed with the ED in D_2 have shown that the particle flux dependence with the density exhibits the three classical regimes (linear, high recycling and detachment) but with a non-uniform particle deposition on the NP except for the detached regime. The evolution of the power deposition on the NP has been analyzed as a function of the density and a non-uniform distribution is also observed with cold and hot tube fluxes independently of the working gas while a uniform deposition takes place for detached plasma. The IR_DoD based on the ratio of a hot and a cold heat flux tube shows a similar trend as the DoD deduced from the Langmuir probes to characterize the detachment. The main advantages of the IR_DoD come from the fact that it does not require any adjustment or scaling of data and that the ratio is performed with two signals extracted simultaneously from the same diagnostic. Moreover, for a known magnetic configuration, independently of the considered device, a DoD, based on the ratio of two signals (IR, $H_\alpha \ldots$), can be predicted by calculating the particle and/or the power deposition pattern on the viewed targets allowing to set free from the major consequences of likely drift due to signal transmission. Finally, since the IR diagnostic will be intensively used for long pulse operations, the proposed IR_DoD does not require any modification and allows to optimize the ratio by a careful selection of the viewed area.

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References

[1] G. Federici, C.H. Skinner, J. Brooks, et al., Nucl. Fusion 41 (12R) (2001).
[2] Ph. Ghendrih, A. Grosman, H. Capes, Plasma Phys. Control. Fusion 38 (1996) 1653.
[3] A. Loarte, R. Monk, J.R. Martin-Solis, et al., Nucl. Fusion 38 (1998) 331.
[4] J. Gunn et al., Plasma Phys. Control. Fusion 42 (2000) 557.
[5] L. Costanzo, J. Gunn, T. Loarer, et al., J. Nucl. Mater. 290–293 (2001) 840.
[6] L. Costanzo, T. Loarer, B. Pégourié, et al., in: 28th EPS Conference on Controlled Fusion and Plasma Physics, ECA, vol. 25A, 2001, p. 197.
[7] C.S. Pitcher, P.C. Stangeby, Plasma Phys. Control. Fusion 39 (1997) 779.
[8] A. Hermann, Plasma Phys. Control. Fusion 44 (2002) 893.
[9] W. Zhang, T. Fall, B. Terreault, et al., J. Nucl. Mater. 244 (1997) 44.
[10] R.A. Pitts, P. Andrew, Y. Andrew, et al., these Proceedings.
[11] R. Mitteau, J.C. Vallet, A. Moal, et al., these Proceedings.
[12] Ph. Ghendrih, A. Grosman, J. Nucl. Mater. 241–243 (1997) 517.
[13] T. Loarer, L.D. Horton, H. Kubo, et al., private communication, 1999, JET-R(99)05.