DETACHMENT CONTROL BY HEAT FLUX ANALYSIS ON TORE SUPRA

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1. Introduction

Power flux flowing onto the divertor plates is expected to be more than 20 MW/m² for the next generation of fusion reactors such as the International Tokamak Experimental Reactor (ITER). The reduction of the thermal deposition on the plasma facing components is thus one of the most specific problems to surmount. By creating a dense and cold plasma in the neighbourhood of the divertor plates, it is possible to reach the "detached" regime, characterized by low electron temperature (T_e), strong reduction of particle flux (I_{Sat}) and power flux on the plates, pressure drop along the field lines and significant fraction of radiated power (P_{Rad}) in the SOL [Kra 95]. Two methods defining this detachment exist on Tore Supra : one based on local measurements obtained with Langmuir probes and one obtained by integrated measurements of bolometry [Mes 99, Gri 99]. Infrared thermography measurements, on the other hand can be either local or integrated depending on the plasma configuration. The Degree of Detachment (DoD) deduced from the Langmuir probes is defined as the ratio between a theoretical ion current density extrapolated to high density from the high recycling regime and the measured ion current density. The DoD is unity in the high recycling regime and increases as the detachment occurs [Loa 98]. However, the complex power deposition patterns in the various configurations of divertor involve difficulties to determine the DoD in particular with the fixed probes. We have developed a new way to measure detachment onset based on the parallel heat flux ($Q_{//}$) variation on the plates derived from the infrared signals.

2. Heat flux behaviour during detachment

The analysis of experimental data during ergodic divertor (ED) operation on Tore Supra showed that the detachment occurs when the heat flux reaches a threshold value $Q_{//Threshold}$ which depends on the main plasma parameters (injected power, P_{Rad}, gas, $\langle n_e \rangle$...).

Figure 1 illustrates this threshold value. For this shot which detaches, one has represented the evolutions of the particle flux I_{Sat}, T_e and $Q_{//}$ on the neutralizer. Three characteristic phases are successively observed for I_{Sat} : a sheath-limited stage up to 4.25 s, a high recycling regime up to 5.25 s and then detachment. For $Q_{//}$, a regular decrease is followed by a clear drop at the detachment. A similar behaviour between $Q_{//}$ and T_e in terms of critical control parameter is highlighted. Figure 2 shows the evolution of $Q_{//}$ versus T_e, emphasizing the thermal flux sensitivity in the detachment phase. The thermal time constant of the B_4C target surface layer is about 20 ms, the infrared image being thus a direct image of the heat flux impinging onto it. As soon as the plasma detaches, a sudden decrease of $Q_{//}$ is observed from 1.75 to 0.5 MW/m^2 respectively for $T_e \sim 12$ eV and 10 eV.

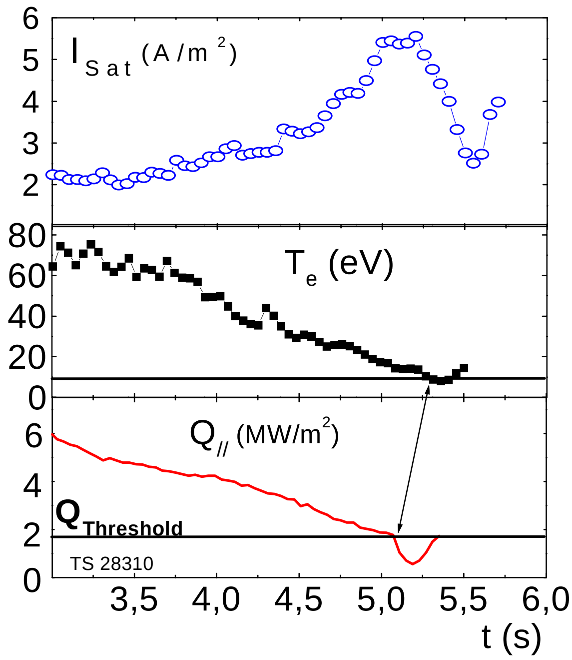

Figure 1 : Temporal evolutions of particle flux, edge temperature and parallel heat flux for a shot which shows a transition from a high recycling regime to a detached regime.

The notion of "infrared" DoD, based on the same concept as for the "probe" DoD, can be introduced. It is defined as the ratio of the extrapolated heat flux in the high recycling regime ($Q^{scaling}$) to the measured heat flux ($Q^{measured}$) as follows :

$$"IR"\,DoD = \frac{Q_{//}^{scaling}}{Q_{//}^{measured}}\,.$$

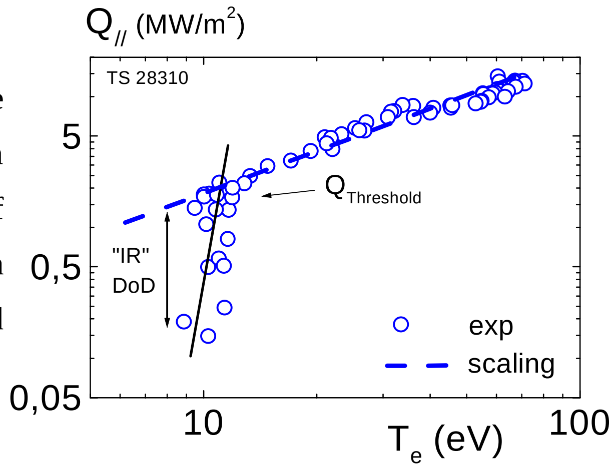

Figure 2 : Evolution of $Q_{//}$ as a function of edge temperature.

This extrapolation is plotted on figure 2.

The theory can lead to a calculated $Q^{scaling}$ but the classical two point model doesn't fit very well with the ergodic or axisymetric divertors cases. It is more effective to define an experimental value.

3. "Infrared" degree of detachment

The infrared camera provides a full 2D view of the target plate, and thus offers the possibility to follow any movement of the strike point. This is a distinct advantage over the fixed target probes that give local measurements. These remarks have led to the development of a new detachment criterion.

The concept of definition of "IR" DoD can be schematized according to the following stages : a) the experimental data related to the detachment has allowed to establish a database of threshold values; b) these values depend on the main plasma parameters; c) "IR" DoD is directly proportional to the difference of the temporal heat flux evolution and the threshold value for the considered shot (including a standardization factor); d) one can then carry out a real time control during the shot.

Figure 3 exhibits the evolutions of the three detachment criteria : bolometry, probe and infrared. A very good agreement is observed between the criteria. For this shot, the infrared DoD increases with a very slight advance compared to the other concepts (also seen on figure 1). This advance is due to the choice of the exposed zone with the infrared diagnostic. The application of this method is direct on Tore Supra. It can be applied without difficulty to JET, CIEL (new toroidal limiter on Tore Supra) and even to ITER. The effect of the edge localized modes (ELMs) phenomena is likely attenuated in comparison with others diagnosis. Moreover, in a reactor environment, it may be unacceptable to install target plate Langmuir probes. Infrared imaging obviously has an important potential role to play in divertor diagnosis and feedback control.

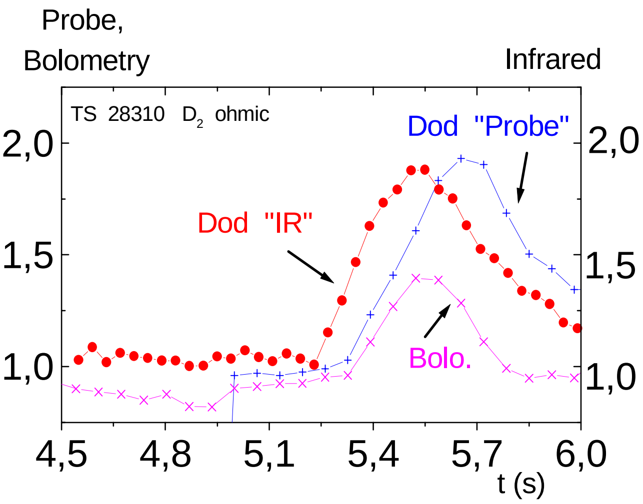

Figure 3 : Temporal evolutions of the "Probe" DoD, the "Infrared" DoD and the bolometry detachment criterion.

4. Dependence of $Q_{//Threshold}$ on various plasma discharge parameters

The values of $Q_{//Threshold}$ depend on the main plasma parameters (conducted power, edge density). Figure 4 indicates the evolution of $Q_{//Threshold}$ versus the conducted power (total input power – P_{Rad}). The characteristic values obtained vary from $Q_{//Threshold}$ ~ 1.5 MW/m^2 (ohmic discharge with P_{ohm} ~ 1.3 MW) to 5 MW/m^2 (discharge with additional heating P_{ICRH} = 4 MW and conducted power P_{cond} = 2.75 MW). In the concerned power range, a factor 2 produced a doubling of $Q_{//Threshold}$. It should be specified that T_e stays in the range 10-15 eV for these shots. The increase of $Q_{//Threshold}$ is also observed as a function of the edge density from ~ 1,5 MW/m² at n_{e_edge} = 0,3.10^{19}m^{-3} to 5 MW/m^2 at 1,6.10^{19}m^{-3}.

These dependences allow an extrapolation of acceptable heat flux value to control the detachment phase. One can thus predict the detachment threshold and determine $Q_{//Threshold}$ for a given discharge. This analysis has permitted the establishment of a $Q_{//}$ database for the high recycling and detached regimes.

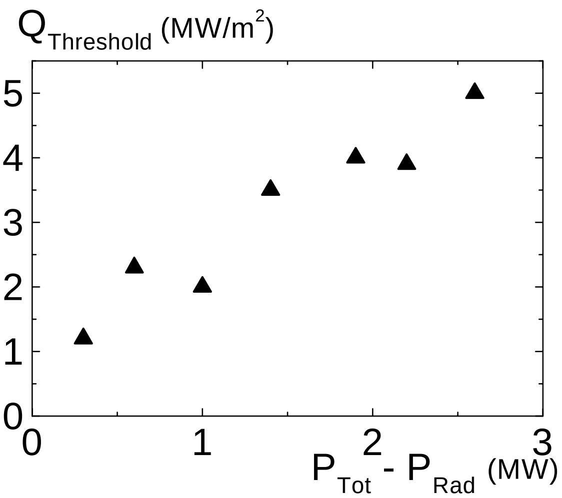

Figure 4 : Evolution of $Q_{//Threshold}$ as a function of conducted power.

5. Discussion and summary

Detached regime is an acceptable solution for extending the lifetime of the divertor components. The control of detached divertor plasmas is a key factor to develop a robust divertor concept for future reactors. This point is also crucial in order to maintain the ICRH coupling capability [Ngu 00]. The heat flux analysis on the neutralizer plates shows a clear behaviour as the plasma detaches. Threshold detachment values depend on conducted power and edge density for a constant T_e (10-15 eV). An infrared DoD can be defined in the same way as for the probe DoD and a good agreement with others detachment criterion is observed. This new tool is very promising since it takes into account the surface distribution. With its great flexibility, "IR" DoD emphasizes the double role of the thermal imaging diagnostic : measurements of the absolute surface temperature on the plasma facing components preventing a risk of overheating and now detachment characterization.

References

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