HEAT FLUX EXHAUST IN TORE SUPRA IN ERGODIC DIVERTOR AND LIMITER CONFIGURATIONS

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Abstract

Tore Supra being devoted to long pulse physics and technology, this paper discusses recent advances in the installation of actively cooled plasma facing components and on physics methods to mitigate the heat flux, such as edge radiation in the ergodic divertor configuration of Tore Supra. The paper also stresses the understanding requirements in terms of heat deposition, especially for wide area limiters.

1. INTRODUCTION

Tore Supra is a tokamak dedicated to the study of steady state regimes. This implies at first a careful control of the heat exhaust in such regimes. In that respect, a continuous policy of improving the technology of heat exhaust component has been undertaken [1]. The first generation of actively cooled components showed a poor reliability, due to the difficulty of insuring the quality of the « brazed » bonding of carbon on the metallic water pipes over large areas. Recent progress has been made by use of the active metal casting technology ; however, its successful implementation stressed the necessity to better characterise and understand the heat exhaust in limiter configurations, especially when the limiter is tangent to the plasma. In addition, the incomplete covering of the vacuum vessel by an actively cooled structure will be shown to result in uncontrolled oxygen desorption for very long discharges.

The ergodic divertor of Tore Supra studied especially in view of its radiation capability, has been shown to behave better than the average performance of both limiter and X point divertor discharges. This will be shown to be related to the screening properties of the ergodic divertor. A major difficulty is however, to control this radiative edge in situations where a complete detachment may lead to a loss of ICRH wave coupling. Feedback techniques were therefore developed.

2. POWER DEPOSITION ON LARGE LIMITERS

Tore Supra was equipped from the beginning with actively cooled plasma facing components. However, their implementation did not prove to be very successful for many technical reasons., as described in [1]. The brazing techniques of CFC (carbon fibre composites) to the metallic coolant conveyor had to be improved, essentially as far as their reliability on an industrial scale was concerned. Another design constraint stems from the difficult adjustment of the material structure to the magnetic configuration of the plasma. In Tore Supra, alignment of the former to the latter is now insured in the mm range. [2,3].

One sixth of the inner first wall, which had suffered from both misalignment and braze flaws, has been replaced with new elements using more resilient CFC, instead of graphite, and new brazing techniques. They proved to work satisfactorily and contributed to the obtention of new performant long discharges, using combined heating by lower hybrid and ion cyclotron range of frequency (ICRF) waves. The total power coupled was thus extended to more than 6 MW for 25 s, corresponding to a total injected energy of 155 MJ. The surface temperature of the new inner wall elements remained below 500C (i.e. a factor 2 margin to the heat flux exhaust limit), in spite of a strong peaking of the heat flux near the equatorial plane~~.~~ , shown by both the observation of a complete poloidal section of the inner first wall by infrared thermography and calorimetric and Langmuir probe measurements [4]. Figure 1 shows the poloidal profiles of the calorimetric thermocouples and the infrared thermography for three successive shots. The strong peaking around the mid plane cannot be explained without considering very short values of the heat flux e-folding length close to 5 mm, i.e. 3 times less than the average one on the whole area.

This stresses the specific limitations encountered when using large and difficult to align structures. The CIEL project, now approved and to be implemented in Tore Supra in 2000, includes a toroidal flat bottom limiter for which the heat flux limitation should only occur at the leading edge and for which real time feedback control will be provided by means of a complete thermal imaging of the 7.5 m2 surface.

3. DENSITY CONTROL FOR LONG DISCHARGES

Another limitation occurred in the long discharge experiments as an uncontrolled density increase after some time. This phenomenon is shown on figure 2, which displays the density evolution for long shots in a low density, low power (2.5 MW) case. This delay varies with the amount of average power coupled to the plasma, ranging from 100s for low power (about 2.5 MW) to less than 20 s for high power (about 7 MW). Calculation of the temperature increase of recessed non cooled parts of the torus inside such as ports, due to the radiative power (about 20 to 40% of the total one in such shots), indicate that non chemically adsorbed water or oxygen could then be released. Most of the electron content increase is related to an oxygen increase, whereas the evolution of the isotopic ratio H/D seem to indicate that water desorption is at stake. [5]. Consequently, the CIEL project will also include a quasi complete coverage of such surfaces by a water-cooled structure.

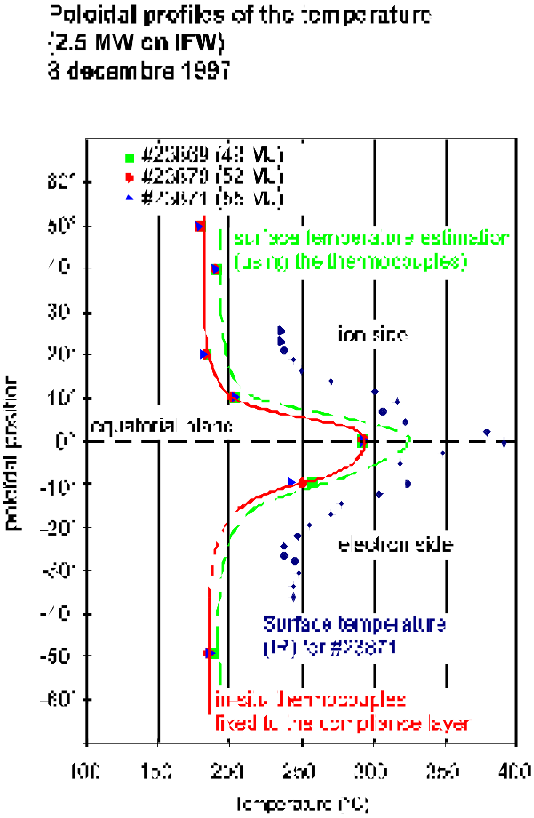

Figure 1 : Poloidal profile of power deposition on the inner first wall showing a strong local deposition around the midplane. Solid lines refer to thermocouples measurements and dots to IR thermography.

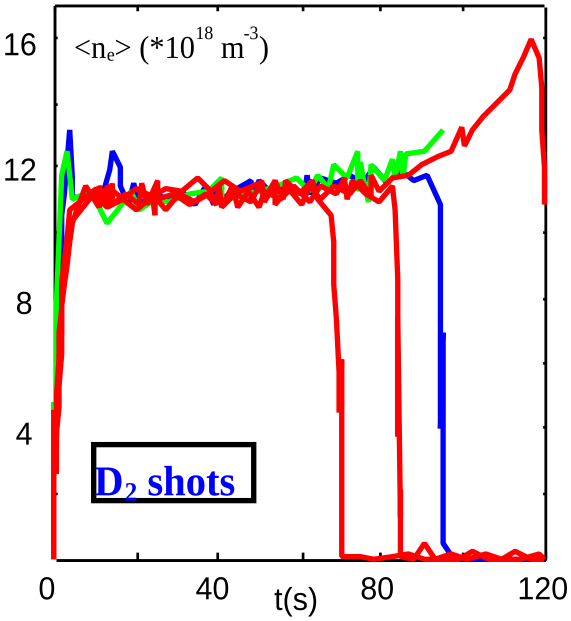

Figure 2 : Time evolution of the line average density for 3 successive discharges ranging from 70 to 120s with 2.5 MW injected power. An uncontrolled density rise is recorded after about 80s.

4. RADIATION CONTROL IN THE ERGODIC DIVERTOR CONFIGURATION

Control of heat exhaust requires the minimisation of the fraction of conducted-convected power at the benefit of radiation, which is easier to spread and allows a power exhaust without impact on first wall erosion. The Ergodic Divertor (ED) has been implemented in Tore Supra in order to improve control of the plasma edge [6]. A reinforced ergodic divertor has been installed in 1996 and operated since with two major objectives. The first one is to promote operation at a large radiative fraction while minimising the core impurity content. The second one consists of testing the specific requirements of such magnetic configuration in order to allow an extrapolation of the concept to reactor relevant conditions.

The radiative scenarios have been implemented up to 8 MW of additional power. They are favoured by the obtention of high recycling regimes at the edge, yielding local edge densities similar to the central ones (4-5 10^{19} m^{-3})[6]. In Tore Supra a limitation stems from the physics of detachment. The latter phenomenon may lead to edge conditions incompatible with a smooth coupling of the RF waves, which are the only auxiliary heating systems available in Tore Supra. Nevertheless, feedback techniques on gas injection using edge parameters relevant to detachment (ratio of outermost bolometer signals on the low-field side of the torus, total radiation power measurements) allow to remain at tolerable levels of detachment [8].

Generally,–with or without extrinsic impurities, the radiation efficiency appears to be among the best encountered in terms of bulk pollution. This is shown in figure 3, where the measured radiation is compared to ~~a~~ the multi-machine law derived by G. Matthews et al. [9]~~.~~ The observed enhancement is related to the large effective volume of diverted plasma in the ED configuration. However, the actual value of the enhancement factor is difficult to evaluate, because of the presence of a spurious signal, due to ion ripple losses, in the vertical bolometer system.

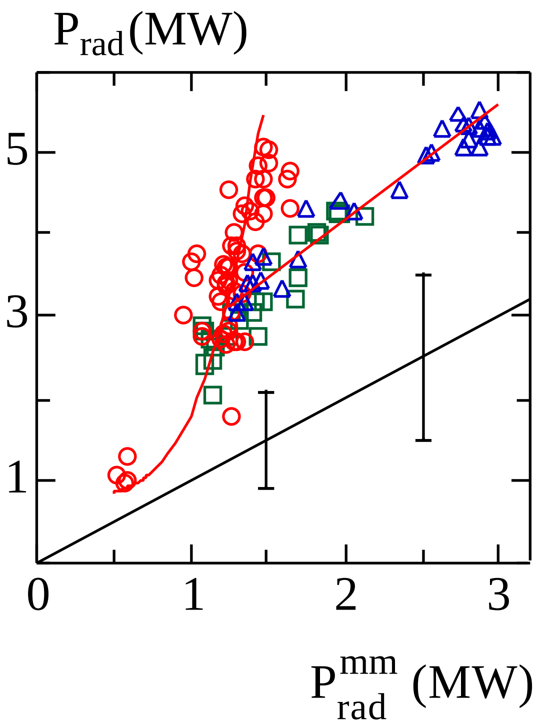

Figure 3 : Comparison of the radiated power measured to the multimachine law after Matthews et al [9] (straight line). The dots refer to D2 gas injection whereas squares and triangles refer to N2 and Ne injection

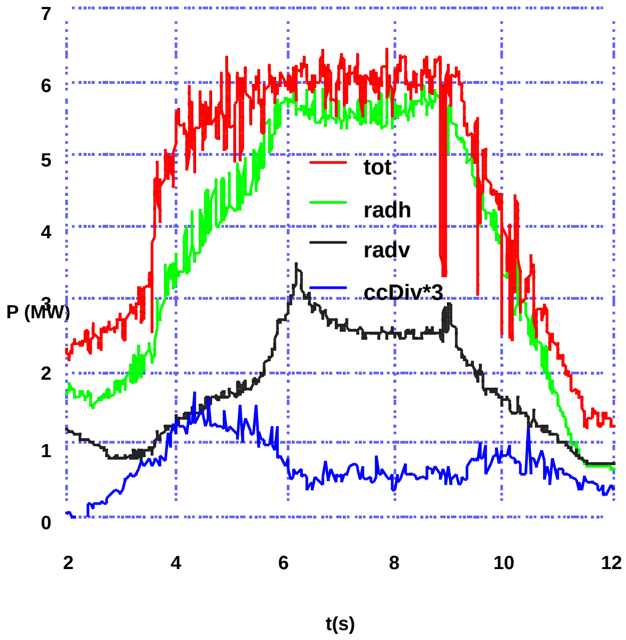

Figure 4 : In an experiment where up to 6 MW are injected, time traces of the total power measurements of radiated power from an horizontal and vertical bolometers and an evaluation of the conducted power from IR thermography measurements is displayed

To better evaluate the power balance, measurements of the power flux onto the divertor plates is measured from infrared thermography. It appears (figure 4) that the local average heat flux onto the plates reaches values as low as 0.2 $\mathrm{MW.m^{-2}}$. This agrees well with the very low values of the electron temperature at the detachment onset (about 10eV) for a density of approximately 5 10^{19} $\mathrm{m^{-3}}$. The overall conductive and convective power is assumed to be about 3 times the value deposited on the plates surface (0.6 $\mathrm{m^2}$). In this experiment, the–radiation level is enhanced by an Argon injection. It is worth noticing that the best efficiencies are obtained using deuterium injection although an easier control of the discharge is obtained using neon injection ; the latter allows to extend the range of temperature for which the plasma radiates without overlapping with zones where the deuterium recycling is strongly affected (i.e. T_e<13 eV). The experimental results are consistent with an analysis of the radiated power scaling through the following equation expressing the radiation power for a heat conduction dominated heat transport (where Z is the impurity charge , Z_{eff} the effective charge, L_z, the radiation function and f_sc the decontamination factor i.e. the ratio of edge and bulk impurity concentration)

$$P_{rad}^{TS} = \frac{4.5 \times 10^{14}}{\sqrt{Z(Z-1)}} \sqrt{(Z_{eff} - 1) f_{sc}}\, n_e^{div} T_e^{div} \sqrt{\int_{T_e^{div}}^{100} T_e^{0.5} L_Z(T_e) dT_e} \quad (1)$$

This suggests that impurity screening is the dominant mechanism controlling divertor radiation. [10]

The relevance of this concept needs, however, to be proved in a more relevant configuration, including a certain flexibility of the required magnetic configurations with those required to improve the confinement. A major difference to the X-point divertor is the necessity to install the perturbing coils no too far from the plasma. This is considered possible even when locating them behind a neutron shield. Moreover, the openness of the ED may lead to extended plasma wall interactions structures, while the neutral recirculation will be controlled by the edge plasma parameters themselves.

5.CONCLUSION

Control of the heat exhaust is one of the major topics to be studied and developed in Tore Supra with regard to its long shot capability. Thus, a development of plasma facing components involving active cooling with water pipes has been undertaken for more than 10 years now. This allowed to install in Tore Supra elements which are technically acceptable; However, the physics of heat deposition onto large surfaces tangent to the plasma leads to strong local deposition. The ergodic divertor has shown a capability to increase the radiation capability compared to a multi-machine law. This is true at low edge electron temperature even when one has as in Tore Supra to stay above the full detachment level to allow RF waves coupling for auxiliary heating.

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