*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-5.113 (2007)*

High RF power operation issues on Tore Supra

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Introduction

The superconducting tokamak Tore Supra ($R = 2.4$ m, $a = 0.72$ m) has been designed to address the physics and technology of long duration plasma discharges. The additional heating power is provided by RF systems, namely ICRF (up to 9 MW with 3 antennas), LHCD (up to 4 MW with 2 antennas) and to a lesser extent ECRH (up to 0.6 MW). 1 GJ discharges were obtained in 2003 using 3 MW of LHCD only [1].

The 2006 experimental campaign was mainly dedicated to the simultaneous operation of the RF heating systems at their maximum power level over long duration (typically 30 seconds limited by the ICRF system). Injected power values in the range of 10 MW, which is representative of ITER operation in terms of average power density (0.4 $MW.m^{-3}$) and heat exhaust capability, have been achieved in several discharges and a total of 65 GJ of RF power was coupled to the plasma during this year. However, approaching 10 MW was found to be difficult and to require a lot of experimental times. The main limitations encountered during this high power campaign are discussed in this paper.

Experimental scenario

The experimental scenario was designed in the perspective of the CIMES project upgrade [2], which mainly consists in increasing the LHCD power towards 6 MW. With 6 MW of LHCD, fully non inductive operation should be feasible up to 0.9 MA of plasma current, electronic ripple losses limiting the access to higher currents. 0.9 MA of plasma current was chosen, optimising confinement in particular with respect to the fast ions generated by the IC waves. ICRH system was used in the hydrogen minority heating scheme at 57 MHz (deuterium plasma) with 3.77 T of toroidal magnetic field (resonance layer located at $R_{1H} \sim 2.4$ m). A rather high density was chosen n_e~4 10^{19} m-3 ($n_e/n_{Gr} \sim 0.8$) to allow for good coupling of ICRH power and to limit the fast ion ripple losses. The main parameters of one of the best discharges obtained during the campaign are displayed in Figure 1. All the plasma parameters, in particular the impurity level, were kept constant during the 26 s high power flat-top phase. The radiated power fraction was around 20%. The wave coupling was simultaneously optimised for both ICRH and LHCD systems [3], by varying the relative radial positions and power level of the different antennas, in order to minimize the hot spot formations due to RF sheath effects and to fast particles generated by RF systems (fast protons with large orbits created by the IC waves and fast electrons accelerated at the plasma periphery in the near field of LH launcher). Safe and reliable operation was obtained through the use of a set real time control tools. In particular, each antenna front face temperature is monitored by IR endoscope. Images are analysed in real-time and when a hot spot is detected, a specific strategy (reduction of the power of one or of several antennas for instance) can be applied according to hot spots location, each location being related to a particular phenomenon (fast electrons, fast ions, arcing, etc.). Cu and Fe brightness levels are also monitored to detect wave absorption problems, arcing or damaging of inner components (not covered by the IR system). Thus, good RF coupling without excessive heat load on the 5 antennas and their guard limiters have been achieved up to 10 MW of coupled power [3].

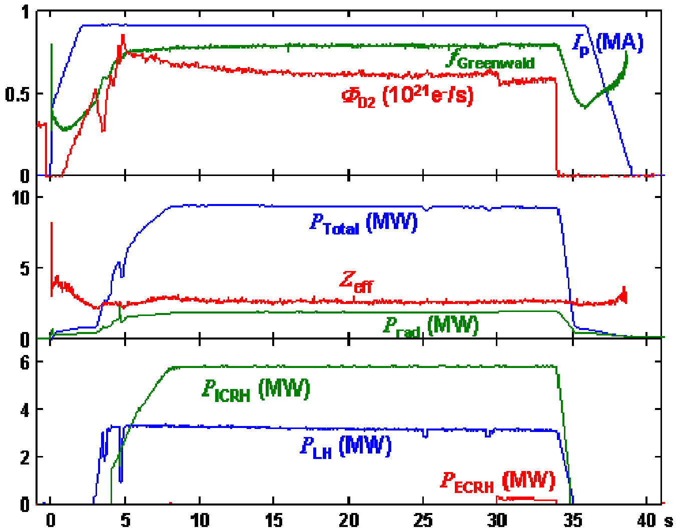

Fig. 1: time evolution of the main parameters of a 9.5 MW, 26 s discharge (TS-37685).

Main limitation

Above 8 MW of RF power, sometimes even at lower power, a slight increase of the injected power (typically 200 kW) often resulted in a disruption. After a quiet phase which is generally longer than the time constant of the actively cooled plasma facing components, a MARFE is triggered and a disruption eventually occurs. The scenario is far below any known MHD stability limits ($\beta_N \sim 1$), and no MHD activity is detected before the MARFE formation. The radiated power remains low during all the discharges indicating a good overall vessel conditioning (boronisations were regularly performed). Several tokamak experiments have reported the appearance of MARFEs at densities well below Greenwald density limit, in the range 0.4-0.5 n_e/n_{GW} [4]. In HT-7 similar difficulty are observed in LHCD discharges at low density at typically 33% of the n_{GW} density ($Z_{eff}^{1/2} f_{GW}$ in the range of 0.6-0.9) [5], while in these Tore Supra discharges, $Z_{eff}^{1/2} f_{GW}$ is higher, in the range of 1.2-1.4. Figure 2 shows a typical disruption in a high RF power discharge. The non-homogeneity and the roll-over of the radiated power towards the inner side of the vessel are observed via a set of bolometers.

Investigations to determine the origin of the MARFE were carried out and 84 disruptions were analysed. In each case, an electron density increase is observed before the plasma detachment. Spectroscopic measurements from independent diagnostics gave complex patterns of impurity influxes in which either carbon or iron or sometimes copper or oxygen dominates. The IR movies analysis gave useful information: normal behaviour of surface temperature for ICRH antennas prior to the disruptions while arcing were observed in front of LH launchers in 36% of the disruptions which does not allow concluding. Arcing can be the cause of the density increase but also the consequence. Finally, the IR observation of the Toroidal Pumped Limiter (TPL) revealed the sudden apparition of unexpected hot spots, before the eventual appearance of an arc in front of the LH launchers, in 18% of the disruptions (60° i.e. 1/6 of the total surface of the TPL is observed). These hot spots appeared in regions of co-deposition of the TPL as showed in Figure 3. Higher temperature regions (> 800°C) correspond to co-deposition regions [6]. The temperature excursion (ΔT) of the hot spot is

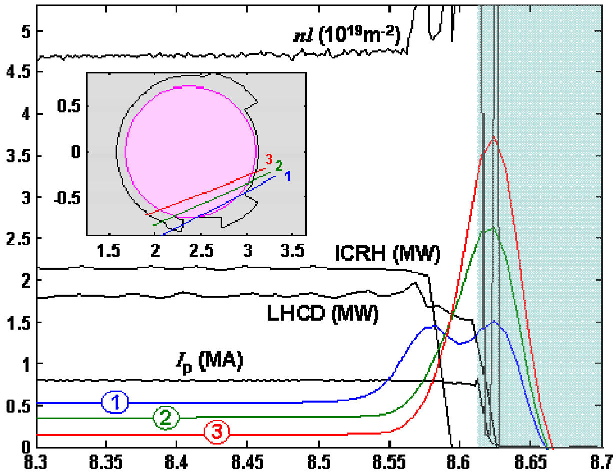

Fig. 2: Time evolution of main plasma parameters and three bolometer signals (u.a.) aiming at the Toroidal Pumped Limiter (TPL) region, before a disruption (TS-36687).

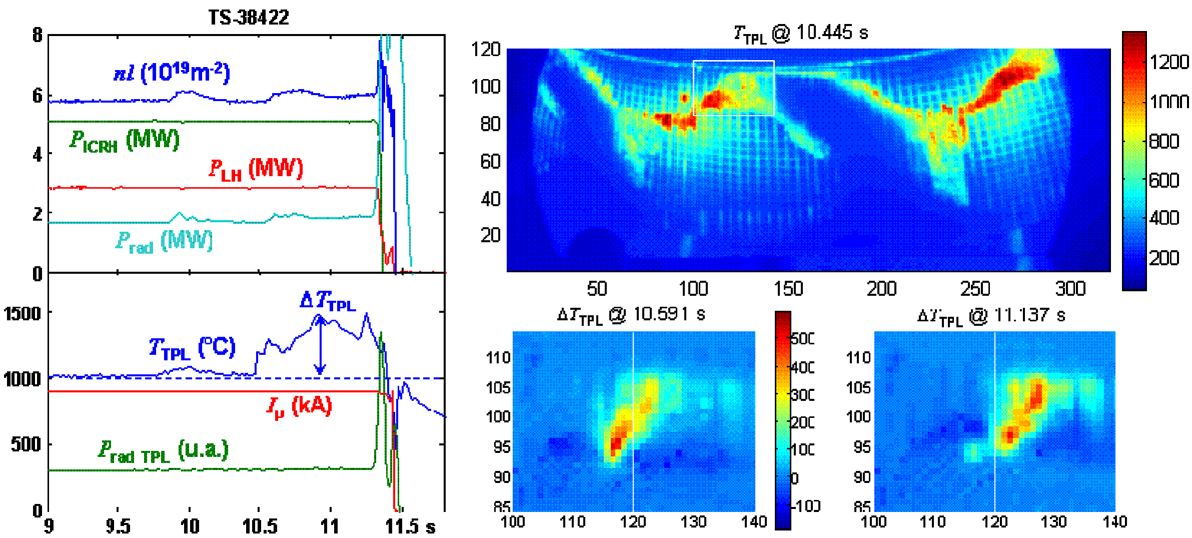

Fig. 3: left: time evolution of main discharge parameters with TPL surface temperature (from the box in the IR image on the right); right: IR image of a 30° sector of the TPL (axis in pixels) and $\Delta T_{TPL} = T_{box}(t)$-$T_{box}(10.445$ s) at 10.591 s and 11.137 s. Disruption occurs at 11.432 s. (TS-38422)

typically in the 500°C range while its area covers several pixels (1 pixel ~ 0.3x0.3 cm). A displacement of the hot spot is also generally observed. The present interpretation of these observations is the flaking of the carbon deposits (carbon deposits of >100µm were already found on the TPL surface, figure 4) under inner thermal stresses due to the heat load from convected and radiated powers. Above a certain threshold of injected power, the deposits partially detach from the surface. Thus, the thermal resistance between the deposit and the actively cooled component suddenly increases, resulting in a rapid increase of its temperature. The flaking process induces a movement of the deposit towards the plasma (limiter geometry) that may result in a large influx of impurities entering the plasma edge. Depending on the size of the flake, and possibly on its chemical composition (iron is sometimes observed), this movement can lead to a MARFE (Figure 4).

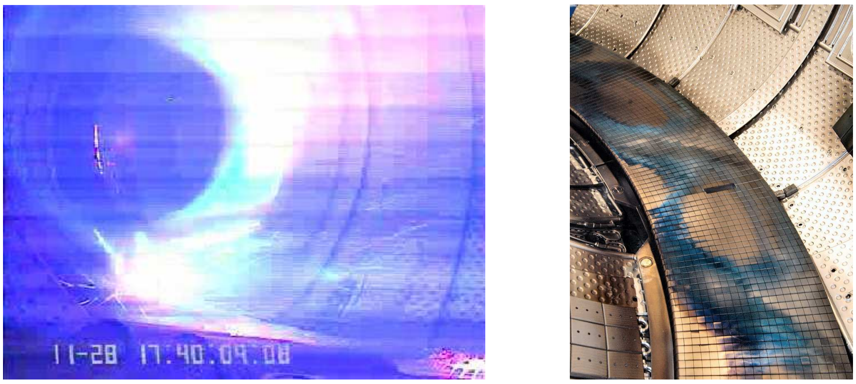

Fig. 4: on the left, CCD image of a MARFE (TS-38702); on the right, photographic picture of the TPL showing erosion and co-deposition complex patterns.

Conclusion

High RF power operation over long durations on Tore Supra (at ITER relevant power density and heat exhaust) raised the issue of the flaking of deposits on components in the vicinity of the last closed flux surface. Indeed, carbon deposits generated by hours of plasma operation seem to reduce the operating window. Above a threshold power, probably depending on the thickness and the distance of the deposits to the plasma, the deposits flake inducing an overheating that can generate a MARFE that eventually lead to a disruption. An intervention aiming at removing all the carbon deposits from the surface of the TPL accumulated since its installation (6 years of operations corresponding to 36 hours of plasma) is foreseen thus restoring the initial conditions. This action could confirm the impact of the carbon deposits on the power limitation faced during the 2006 Tore Supra experimental campaign.

Reference

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