Operational Limits during High Power Long Pulses in Tore Supra

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Abstract. Issues related to limitations and optimisation of long pulse operation at high radiofrequency (RF) power levels in the Tore Supra tokamak are presented. An increasing operational limitation has emerged during the recent campaigns, affecting the high power and long pulse performance. MARFEs were triggered, followed by a disruption. The analyses undertaken reveal that this limitation could be linked to over-heating and flaking of the carbon re-deposition layers on the main plasma facing component. The carbon deposits on all plasma facing components were therefore completely removed during the winter shutdown 2007-2008. Following this, a remarkable improvement in the injected power capability was observed, resulting in almost 12MW of injected power during 10s, without any MARFE or disruption. These results indicate that carbon deposits, accumulated over a long time, may lead to operational limitations, at least in RF heated limiter plasmas. Furthermore, when operating RF antennas over long durations at several MW, localised heat loads on antennas due to RF sheath effects and interaction by fast particles need to be controlled. Experimental results on this subject are presented.

1. Introduction

The Tore Supra tokamak has a unique long pulse capability in an actively cooled machine, with injected power provided exclusively by radiofrequency (RF) waves. Due to its good diagnostic coverage, in particular the infrared (IR) imaging system, Tore Supra is a highly relevant device for studying issues related to power handling of RF antennas and plasma-wall interaction in true steady state conditions. The experimental campaigns in 2006 and 2007 have been particularly intense in terms of injected power, energy and accumulated plasma time (10 hours in both 2006 and 2007, with 65GJ injected RF energy in 2006 and 40GJ in 2007). Large experience has been gained in the understanding of localised heat loads due to RF sheath effects and interaction by fast particles [1, 2]. However, an increasing operational difficulty has emerged, limiting the high power and long pulse performance. This limitation is related to the formation of a MARFE, usually leading to disruption. Although these radiative disruptions were first observed during high power experiments (typically above 8MW) in 2006 [3], they became an increasing concern during the deuterium wall loading campaign (performed at 2MW) in 2007 [4, 5]. It has to be noted that similar scenarios could be obtained reliably over longer durations 3-4 years earlier (i.e. the GJ-discharges) [6].

The analyses undertaken [7] reveal that the MARFE and disruption in several cases was preceded by a localised hot spot in a region of thick carbon re-deposition on the main plasma facing component, the Toroidal Pumped Limiter (TPL). These deposits have grown over several experimental campaigns since the installation of the TPL in 2000. A thickness of ~100-200μm has been estimated [8]. The present understanding of the observed limitation is that over-heating and flaking of these deposits produce a localised perturbation at the plasma edge, which triggers the MARFE and ultimately the disruption. The plasma facing components (PFCs) were therefore completely cleaned during the winter shutdown 2007-2008. The effect on plasma operation before and after cleaning the PFCs is presented.

Another subject relevant to long pulse RF operation (although not related to the issue of carbon deposits), are localised heat loads on antennas due to RF sheath effects and interaction by fast particles. Some experimental results are presented in this paper. Closely correlated to the antenna heat loads is the coupling of RF waves, which is dealt with in another paper [2].

2. Experimental observations

The two scenarios analysed for this work are the following: The first one, aiming at high power long duration discharges, consisted of a combination of Lower Hybrid Current Drive (LHCD) and Ion Cyclotron Resonance Heating (ICRH), at high plasma current and density (I_P = 0.8-1.0MA and n_e/n_G ~ 0.8). This has resulted in 9.5MW coupled for ~30s in repetitive discharges [1, 3]. The second scenario, aiming at loading the vessel walls with deuterium in a campaign dedicated to fuel retention studies [4, 5], used pure LHCD discharges at 2MW for up to 120s at I_P = 0.6MA and n_e/n_G ~ 0.5. The particularity of this campaign was that no conditioning was carried out during the ten days experiment. This corresponded to five hours of plasma, which roughly equals one normal year of plasma operation in Tore Supra.

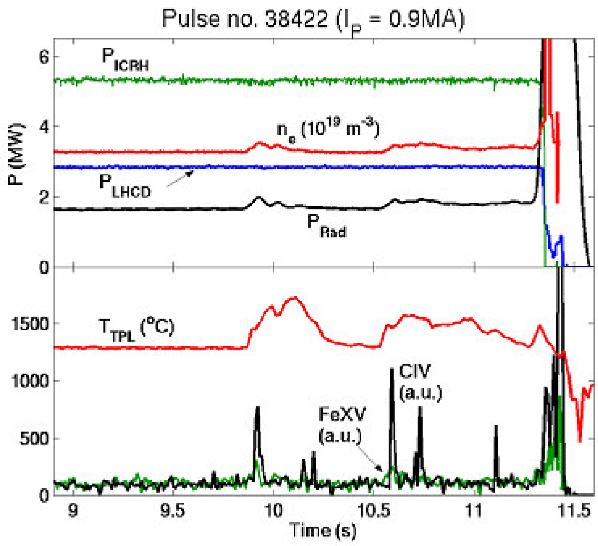

FIG. 1. Evolution of main plasma parameters in #38422, showing a hot spot on the TPL and terminating in disruption. Bursts of carbon are seen when the hot spot appears.

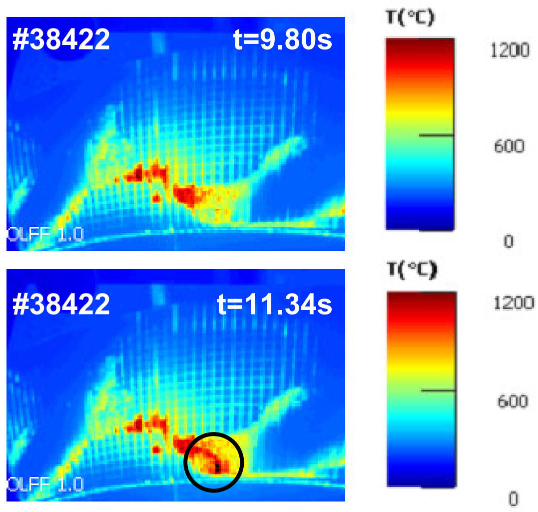

FIG. 2. IR images of one TPL segment, taken at 9.8s (before the hot spot first appears) and 11.34s (100ms before the disruption). The hot spot is localised on the high field side.

In the steady-state phase of the discharges, the radiation pattern (mainly due to carbon) is poloidally asymmetric, with its maximum localised near the surface of the TPL, at the bottom of the torus. In both scenarios a sudden, strong increase in radiation and the formation of a MARFE could be observed, as indicated by a rapid shift of the radiation maximum from the TPL towards the high field side [3]. A detailed analysis of the thermal behaviour of the carbon deposits on the TPL has been carried out, using infrared (IR) imaging as the main tool [7]. The IR cameras view almost four out of the 18 toroidal TPL segments. The five RF antennas (two LHCD and three ICRH) are also monitored by IR cameras, which allow distinguishing specific phenomena, such as arcs on front of the waveguides. To complement the IR analysis, ultraviolet (UV) spectroscopy measurements (of CIV, OIV and FeXV) are made along an equatorial line of sight [9].

More than 140 disruptions have been analysed using IR imaging. A common feature observed prior to the disruptions is the appearance of a small (~cm^2) hot spot, clearly localised in a zone of thick carbon re-deposition on the TPL. Fig. 1 shows the time evolution of the main plasma parameters during a discharge with 8MW of additional heating power. All parameters remain constant from 7s up to 9.9s, with a radiated power fraction of P_{Rad}/P_{Tot} ~ 22%. At 9.9s, a hot spot appears in the carbon re-deposition zone on the high field side (HFS) of the TPL, as revealed by an IR camera (Fig. 2). Fig. 2a shows the IR image at 9.9s, before the hot spot appears. The highest temperatures are obtained for the carbon re-deposition zones close to the heat flux zones. Fig. 2b, taken at 11.34s, reveals that a hot spot has appeared close to the high field side of the TPL. The plasma disrupts at 11.5s. The bursts of CIV, observed through an equatorial line of sight, are correlated with the shift of the radiation from the TPL towards the mid-plane. The CIV emission, usually located close to the TPL and far from the line of sight of the spectrometer, then suddenly enters into the line of sight.

The appearance and evolution of a hot spot on the TPL for another high power discharge (#37613) is demonstrated in Fig. 3. The images are obtained by subtracting the IR image frame taken during the quiet phase from the later frames with hot spots. The hot spot suddenly appears at 14.59s. During the following ~100ms, the hot spot grows and shifts towards the HFS edge of the TPL. This is accompanied by a small increase in electron density and radiated power. At 14.7s, a MARFE is triggered and the radiation shifts from the TPL towards the mid-plane. The IR image in Fig. 3, taken at 14.71s, shows a largely extended hot spot as well as ejection of flakes from the over-heated zone. The modification of the radiation pattern is also observed through the sudden increase in line brightness of FeXV, CIV and OIV, measured along the mid-plane. During the MARFE, the coupling characteristics for the RF antennas change and the heating power is reduced by the antenna protection systems. A disruption often occurs, as the radiated power exceeds the input power.

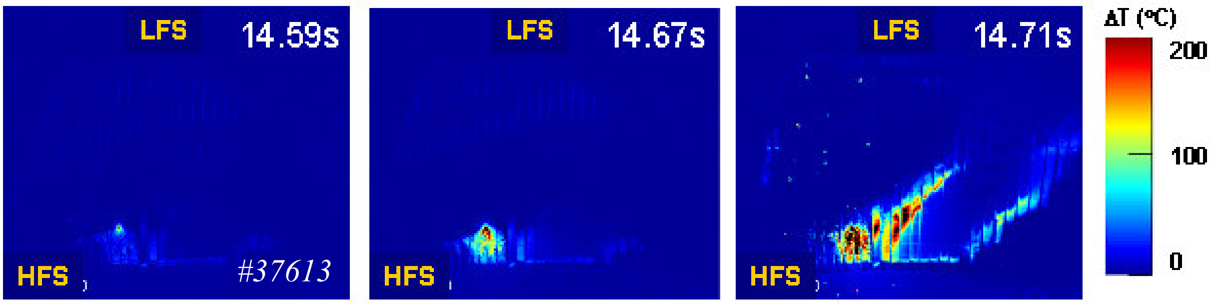

FIG. 3. Temperature difference of the hot spot, with respect to the temperature at 14.5s, at three different times before the disruption in #37613.

3. Evolution during the deuterium wall loading campaign

During the experiment dedicated to fuel retention studies (the DITS campaign), identical discharges were carried out during ten days without any conditioning between. A carbonisation and boronisation were carried out only before the start of the experiment. During the first ~3000s of plasma, the concentration of oxygen and iron increased continuously to return to the pre-boronisation level, while the carbon concentration and the radiated power remained constant [4, 9]. As described in [4, 5], the main operational limit encountered during this campaign was the increasing frequency of radiation events, defined as $\Delta P_{Rad} > 20\%$, as well as an increasing frequency of disruptions.

Several cases of localised hot spots on the TPL were observed before the disruptions, similarly as in the high power experiments carried out the year before. In addition, an extensive analysis of the CCD camera images confirms that most of the flaking events originated from the TPL [10]. Eventually, it proved necessary to reduce the LHCD power from 2MW to <1.8MW, in order to be able to run through the discharges without disruption. Consequently, the frequency of radiation events as well as the disruption frequency decreased.

4. Localisation of hot spots

For each disruption exhibiting a hot spot, the toroidal and poloidal location of the TPL tile where the hot spot was first detected was identified. The hot spot locations were then all brought into the same figure, showing one TPL segment, in order to get an overview for the two experimental scenarios. The result is shown in Fig. 4. In the first scenario, characterised by high power RF heating at high plasmas current, the distribution of the hot spots is quite equal between the outer and inner zones of thick carbon re-deposition (Fig. 4a). A hot spot was found in 20 out of the 84 disruptions analysed (i.e. ~24%). This is consistent with the fact that only four out of the 18 TPL segments (i.e. ~22%) are viewed by IR cameras.

In the scenario used during the deuterium wall loading campaign (DITS), with pure LHCD at lower plasma current, the hot spots clearly occurred on the inner carbon deposit zone, close to the HFS of the TPL (Fig. 4b). A total of 59 disruptions were analysed. Localised hot spots were observed in 12 disruptions (i.e. ~20%). From the 59 disruptions one could remove ten, which were rather due to the formation of an arc in front of the grill mouth on the LHCD launchers following the detachment of a carbon flake from the launcher side protections. The percentage of disruptions with a hot spot then becomes ~24%, which is again consistent with the IR camera coverage. In this second scenario, it could be well identified that the hot spot originated at the border between the heat flux zone and the private zone. In some cases the hot spot originated from a region close to the plasma contact point.

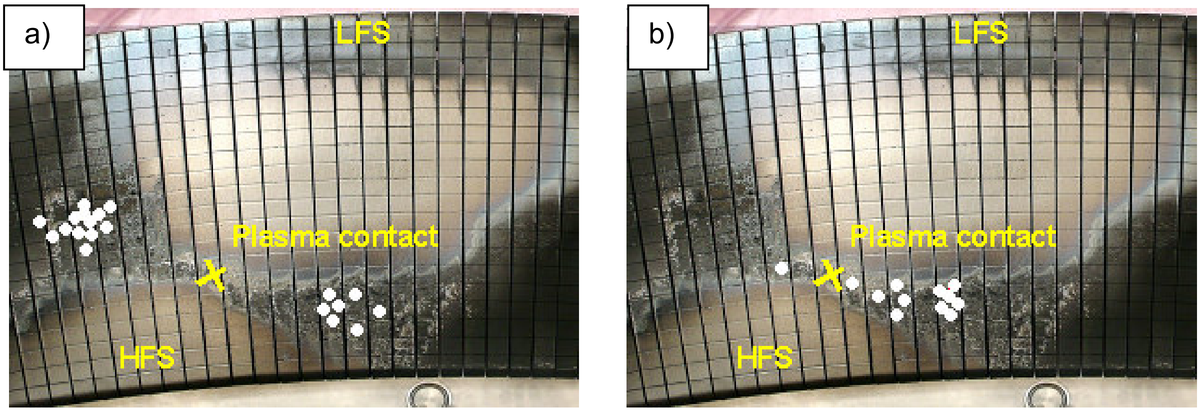

FIG. 4. Distribution of hot spots, preceding the disruptions. (a) High power RF heating at I_P = 0.8-1.0MA. (b) Pure LHCD discharges at I_P = 0.6MA.

5. Plasma operation with clean PFCs

In order to investigate the role of the carbon deposits on the operational limitations, the deposits on the TPL and on all other main plasma facing components were completely removed during the winter shutdown 2007-2008. This included the TPL surface and the gaps between the tiles, all protection limiters on the RF antennas, and the bumpers on the inner wall. A total of ~800g of carbon dust was thus removed from the chamber. The cleaning was performed by hand by four teams of two people, equipped with a gas mask for protection against carbon dust inhalation, and using tungsten carbide scrapers and vacuum cleaners.

This thorough cleaning procedure had a dramatic impact on the operation of the tokamak. The plasma restart phase, which was carried out in a similar scenario as in the earlier years and characterized by similar impurity content, was much faster. After the ohmic restart, the RF heating systems were brought onto plasma for conditioning on plasma discharges. Following a boronisation, high power operation with combined LHCD and ICRH was performed. In contrast to the preceding campaigns, less than ten discharges were sufficient to attain an injected power level of >10MW, without a single disruption. In a subsequent day, the same power level could be attained after three discharges. No signs of the previously observed phenomenology (hot spot, flaking, MARFE, disruption) have been observed during all the restart and power increase phases in 2008. A comparison of this power increase phase with one the presence of carbon deposits (2006) is shown in Fig. 5. The sequence of discharges in the DITS campaign (2007) is also shown. The filled points correspond to discharges ending in disruption or early termination. In 2008, the power increase phase was much faster, due to the absence of disruptions. As a result, a discharge with close to 12MW of total heating power, with duration of 10s has been obtained, which is a new record for Tore Supra (Fig. 6). This result has demonstrated the importance of operating with clean PFCs, at least in limiter plasmas using RF heating.

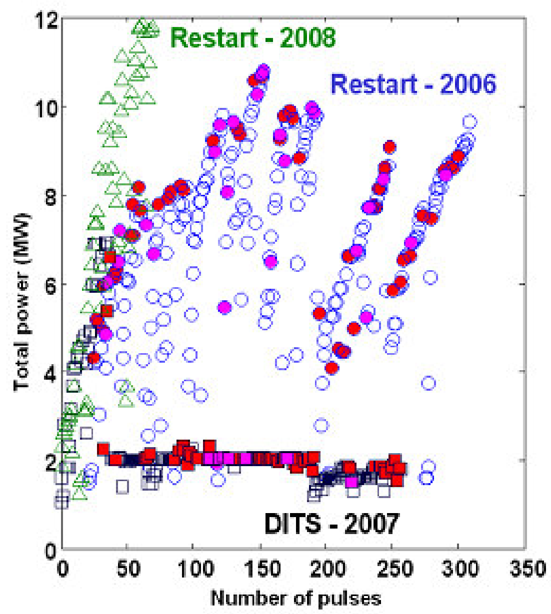

FIG. 5. Injected power versus number of pulses for two plasma restart campaigns: Before cleaning (2006) and after cleaning (2008).

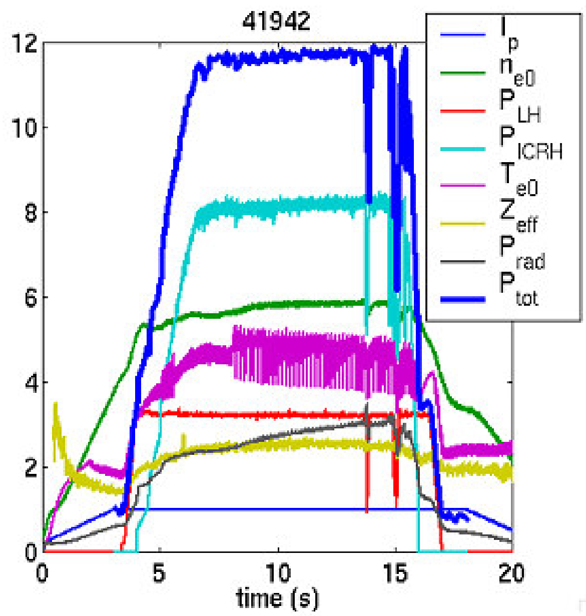

FIG. 6. Time evolution of plasma parameters in the highest power discharge obtained in 2008, with close to 12MW during 10s.

6. Antenna heat load during high power operation

Another subject relevant to long pulse RF operation (although not related to the issue of carbon deposits), are localised heat loads on antennas due to RF sheath effects and interaction by fast particles. In particular, ripple induced losses of energetic ions, due to the strong magnetic ripple in Tore Supra, can cause heat load on the plasma facing components. There are two loss mechanisms: firstly the direct ripple losses, which in the Tore Supra CIEL configuration are directed towards the bottom of the tokamak, and secondly stochastic diffusion of the fast ion orbits due to the magnetic ripple [11]. The latter effect can produce fast ions that impinge on the low field side, below or at he mid-plane. This is in particular evident on the IR images of the LHCD grills [1], and as already observed in JT60-U [12]. The extra heat flux on the Tore Supra LHCD launchers can be ~1MW/m^2 in scenarios at low current (I_P = 0.6MA) and low density ($n_e < 3*10^{19}m^{-3}$).

In order to optimise the further the high power scenario (at 0.9MA) and reduce antenna heat loads, a scan in the hydrogen minority concentration was performed in 13 consecutive discharges at identical power levels (2.8MW LHCD + 4.8MW ICRH). The highest ratio of $n_H/(n_H+n_D)$ injected was 14%. This corresponded to ~11% measured by the neutral particle analyser (NPA). Fig. 7a shows the temperature increases of the ripple protections located at the bottom of the tokamak, which are subject to the direct ripple losses. The dependence on the hydrogen minority concentration seems in qualitative agreement with the modelling carried out for Tore Supra [13]. The temperature increase of the hot spot on the LHCD launcher, identified as interaction by fast ions, has the opposite behaviour (Fig. 7b). As expected, the heat load decreases when increasing the hydrogen concentration from low values to intermediate values (from ~3% to ~7%). The fact the heat load increases again when going above ~7% could possibly be due to finite larmor radius effects [14]. Fig. 7 indicates that an optimum in hydrogen minority concentration allows minimising the heat load on the antennas, which may be required if extending the pulse duration to hundreds of seconds.

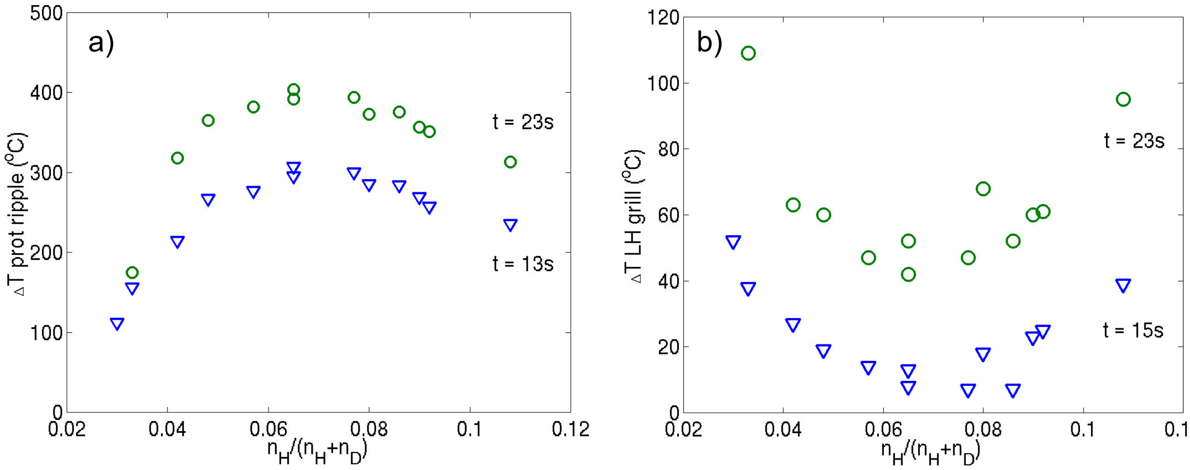

FIG. 7. Temperature increase of an ion ripple protection (a) and on a LHCD grill (b) during a scan in hydrogen minority concentration.

Increased metallic impurity content of the plasma, in particular iron, was seen as more hydrogen was puffed in the discharges (Fig. 8). Bursts of metallic impurities were occasionally observed, as well as a higher base level. The single pass absorption, calculated with the METS code [15], indicates that good absorption is (~90%) would be expected if a fast ion tail has developed. However, in absence of a fast ion tail, the single pass absorption drops to ~30%. It is possible that parasitic absorption in front of the antenna can take place in such conditions. Fig. 9 shows that both the coupling resistance and the temperature of the upper left antenna corner, i.e. the zone sensitive to heat loads due to sheath rectification [16], increase when going to high higher minority concentrations. These two measurements could indicate that the density in front of the ICRH antenna is increasing. It has to be noted that no increase in density is observed in front of the LHCD launchers during the phase with LHCD alone. The modification observed seems therefore to be an effect purely due to ICRH.

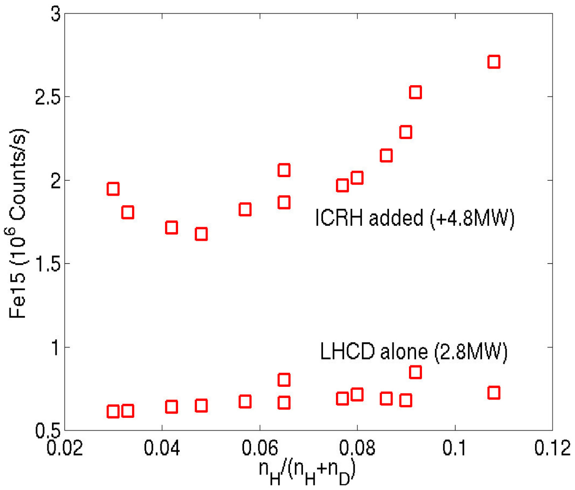

FIG. 8. FeXV line brightness as a function of hydrogen minority concentration. An increase is seen at high concentrations during ICRH.

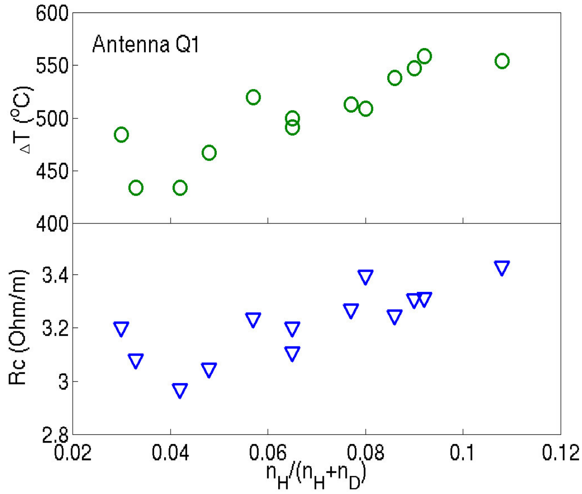

FIG. 9. Coupling resistance and temperature (from IR measurements) of the upper left corner of an ICRH antenna.

7. Summary and outlook

The Tore Supra tokamak is still a unique device for studying plasma-wall interaction issues in true steady state conditions, in an actively cooled machine. In view of future devices, reliable tokamak operation is becoming an increasingly important research issue. In this domain, the recent Tore Supra experiments have given a crucial insight to the impact of carbon deposits on the tokamak operation. Indeed, after removing the carbon re-deposition layers from all PFCs, a remarkable improvement in the injected power capability was obtained. This indicates that deposits, as accumulated over a long time of plasma operation, could become a serious concern in next step devices, running repetitive discharges over long durations.

Due to its long pulse capability, Tore Supra offers a good opportunity to investigate power handling of RF antennas and plasma-antenna interaction phenomena in long discharges. Knowledge in this area is essential in order to extrapolate to the requirements needed for RF systems in next step devices. Experience has been gained in the understanding of localised heat loads due to interaction by fast particles and RF sheath effects. The Tore Supra programme is soon entering a new phase, consisting of an upgrade of the LHCD system (the CIMES project [17]). This upgrade will provide ~6MW of CW LHCD power and will allow to perform full non-inductive discharges at higher plasma current and/or density than before.

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