Major Progress on Tore Supra toward Steady State Operation of Tokamaks

Equipe Tore Supra*

Euratom-CEA Association, CEA/DSM/DRFC,
CEA Cadarache – F-13108 Saint-Paul-Lez-Durance

e-mail contact of main author: saoutic@drfc.cad.cea.fr
** (see appendix)*

Abstract. During winter 2000-2001, a major upgrade of the internal components of Tore Supra has been completed that increased the heat extraction capability to 25 MW in steady state. Operating Tore Supra in this new configuration has produced a wealth of new results. The highlights of the 2002 long duration discharges campaign are: 4 minutes 25 seconds long discharges with an integrated energy of 0.75 GJ, which is three time higher than the old Tore Supra world record; recharge of the primary transformer by Lower Hybrid Current Drive (LHCD) for about 1 minute; 4 minutes long LHCD pulses; 1 minute long Ion Cyclotron Resonant Heating (ICRH) pulse (0.11 GJ of ICRH injected energy). Beyond the quantitative step, significant qualitative progress in the steady state nature of the discharge has been accomplished: contrary to the situation in the old Tore Supra configuration, the plasma density is perfectly controlled by active pumping over the overall shot duration. The duration of Tore Supra discharges is sufficient to allow the complete diffusion of the resistive current. Surprising new physics is revealed in such discharges when approaching zero loop voltage. Slow central electron temperature oscillations have been observed in a variety of situations. Such oscillations are not likely to be linked to any MHD instabilities and probably results from an interplay between current profile shape, LHCD power deposition and transport. Analysis of the temperature gradient in the core region shows a very interesting behaviour and the normalised temperature gradient length is compared to the critical thresholds. Finally, the performance of heating and current drive systems and the observations made of the interior of Tore Supra after the long duration discharges campaign are reported.

1. Introduction

Achieving long-duration high performance discharges in a magnetic fusion device is one of the most important challenges "en route" to a fusion reactor [1]. The mission of Tore Supra as the largest super-conducting tokamak (minor radius up to a=0.78 m, major radius R=2.40 m, plasma current up to I_p=2 MA) is devoted to the study of such discharges. In the past, discharges up to 2 minutes have been obtained on Tore Supra and have allowed us to understand of the main limitations that were preventing further increase of the discharge duration. This led to a strong development programme that culminated in the CIEL project (French acronym for Inner Components and Limiter, ‘*Composants Internes Et Limiteur*’) [2]. This major upgrade of the internal components of Tore Supra aims at increasing the heat removal capability up to 25 MW (15 MW convected/10 MW radiated) and particle exhaust in steady-state. During the winter 2001-2002, the CIEL project was completed. This paper describes the new results obtained on Tore Supra in its new CIEL configuration. It first gives the highlights of the 2002 experimental campaign and the main parameters of some of the longest discharges. Then, it addresses the physics that has been observed when operating close to zero loop voltage over sufficient durations to allow full resisitive current diffusion. Finally, it presents the heating and current drive systems performance and the observations made inside Tore Supra after the long duration discharges campaign.

2. Highlights of the 2002 Experimental Campaign

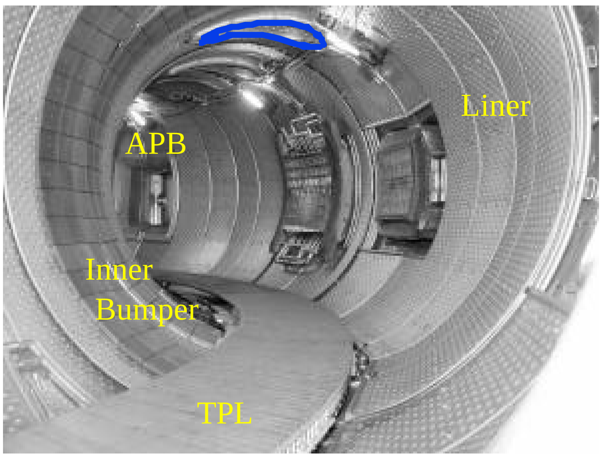
Picture 1 illustrates the new configuration of the internal components of Tore Supra that were installed in winter 2001-2002. The main components are:

- The toroidal pump limiter (TPL) that consists of 576 actively cooled fingers. This limiter has been designed to exhaust 15 MW of convected power, with a maximum flux density of 10MW/m^2.

- The liner composed of actively cooled stainless steel panels that protect the inner vessel of radiated power.
- Inner bumpers designed to cope with transient load at the beginning and end of the discharge.
- Protection against electron ripple losses.
- Antenna protection outer bumper limiter (APB) that is designed to protect the actively cooled antenna edge limiters from runaway electrons at the beginning of the discharge and is slowly recessed from the plasma after some seconds of operation.

This new configuration has allowed us to explore a new domain of performance, as shown in figure 2 where total integrated energy versus injected power is shown. Performance of the present machines for pulse duration longer than 30 seconds are also displayed in this figure. Highlights are:

- 4 minute 25 second long discharges with an integrated energy of 0.75 GJ, three time higher than the old Tore Supra world record.
- Recharge of the primary transformer by LHCD for about 1 minute.
- 4 minutes long LHCD operation on plasma
- 1 minute long ICRH operation on plasma (0.11 GJ of ICRH injected energy)



Picture1: Tore Supra new configuration. The blue line identifies one of the ripple losses protections.

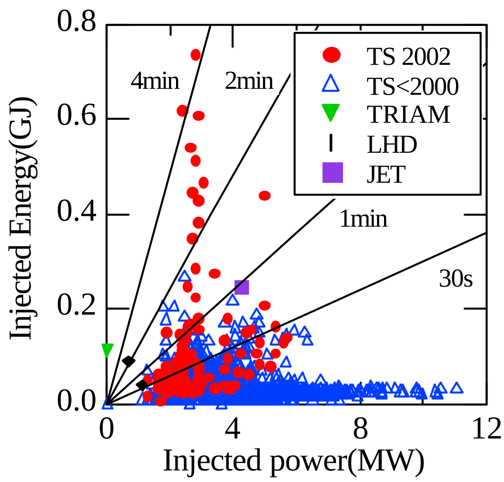


Figure 2: injected energy vs injected power

3. Main Plasma Parameters of Long Duration Discharges

The main parameters of the longest discharge, as displayed in Figure 3, were: major radius R=2.42m, minor radius a=0.71m, working gas Deuterium, I_p = 0.52 MA, toroidal magnetic field 4 T, edge safety factor 9.3, central line integrated density 2.5 $10^{19}m^{-2}$, central electron temperature T_{e0} = 4.8 keV, central ion temperature T_{i0} =1.3 keV, effective ion charge 2, radiated power fraction 20%. Note that in this discharge, the low and high Z impurities were maintained at low stationary levels. Loop voltage is less than 0.01 V corresponding to a non inductively driven current fraction of 96 %. At such a low loop voltage, this discharge could have been maintained for several more minutes. However, after 3 minutes of operation, the LHCD power decreases from 3 MW to 2.4 MW, due to klystron problems. Following this drop of LHCD power, MHD activity appears, which further decreases the LHCD efficiency. In consequence, the duration of this discharge was limited by the available poloidal flux.

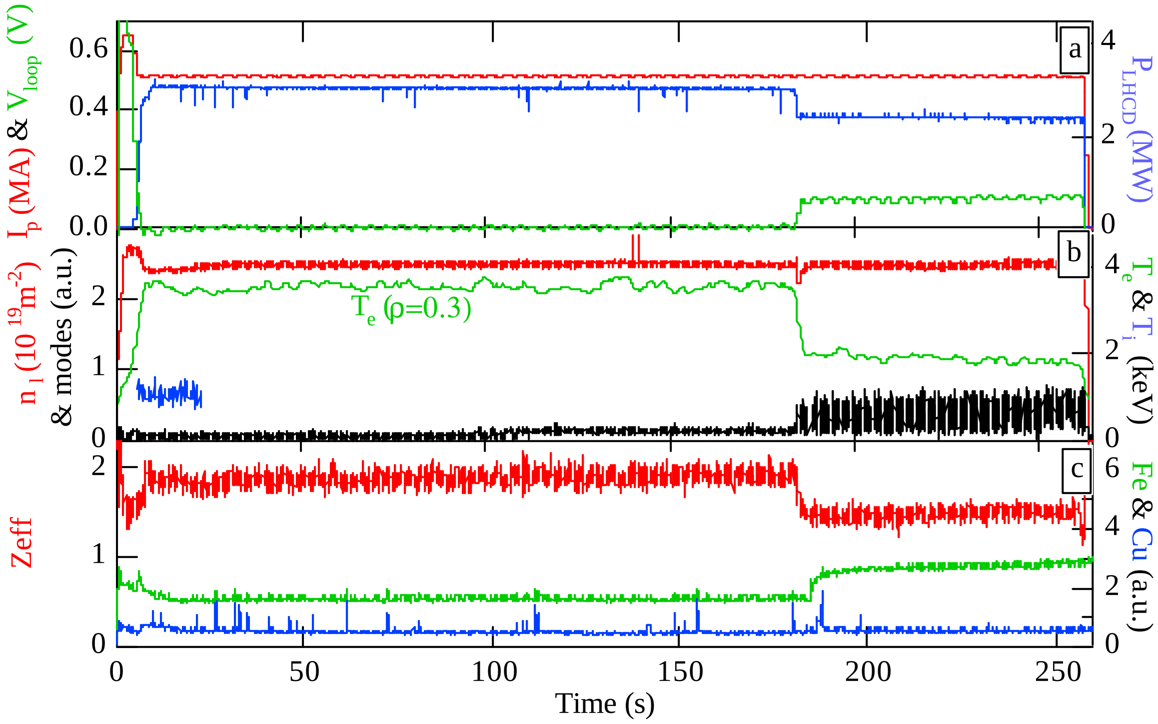


Figure 3: discharge # 30414. Time evolution of: (a) plasma current (red), loop voltage (green) and LHCD power (blue); (b) central line integrated density (red), Mirnov coil signal (black), electron temperature at normalised radius 0.3 (green), central ion temperature (blue); (c) effective charge (red), FeXV (green) and CuXIX (blue) line brightness.

The deleterious effect of MHD activity on LHCD efficiency can also be seen in discharge #30448, where the LHCD power was sustained at a level of 3.2 MW over the whole discharge (see Figure 4). A first phase at negative loop voltage is maintained for almost one minute, saving 0.9 Wb on the primary transformer. Though all plasma parameters look stationary, this phase ends with the appearance of an m=2, n=1 double tearing mode, linked to the occurrence of a Copper UFO and accompanied by a redistribution of the current profile clearly visible on the time evolution of the internal inductance. This MHD mode remains for 1 minute 30 seconds up to the end of the discharge and is accompanied by a decrease of the LHCD efficiency as can be inferred from the primary flux consumption.

Experiments combining ICRH and LHCD have also been carried out up to a total injected power of 6 MW (3.1 MW LHCD, 2.7 MW ICRH, 0.2 MW ohmic). The present highest injected energy in this scheme was achieved on discharge #30348: duration 124 seconds, total injected energy 0.42 GJ, ICRH pulse duration 65 seconds, ICRH total injected energy 0.11 GJ. Plasma current and LHCD power were the same as for discharge #30414. The central line integrated density was higher (3.5 $10^{19} m^{-2}$) in order to provide a reasonable ICRH power coupling. During the ICRH phase, T_{e0} rose up to 4 keV, and T_{i0} up to 1.8 keV. A weak increase of the effective charge (10%) was observed. Note that this type of discharge was performed at high Greenwald fraction (0.8) and relatively high β_p (0.8). The operating loop voltage was lower than 80 mV corresponding to 63% of the current driven by LHCD and 15-20% by bootstrap current.

Beyond the quantitative step, one should stress a huge qualitative progress in the steady-state nature of the discharge as illustrated in Figure 5 comparing the behaviour of density during long duration discharges in the old and new configurations of Tore Supra. In the discharges performed in the old configuration [3], there always was a steady increase of density after one minute of operation. This was attributed to outgassing of inadequately cooled components located far from the plasma and heated by radiated power. In the present configuration, with all the plasma facing components actively cooled and active pumping, the plasma density is perfectly controlled over 4 minutes despite a higher level of injected power. It is worth noting that particle balance carried out for this discharge indicates that the "wall" is not yet saturated at its end [4] despite the large amount of particle trapped in the walls (>127$Pa.m^3$). This emphasizes the need to perform longer duration discharge in order to assess the issue of particle control in the presence of a saturated wall.

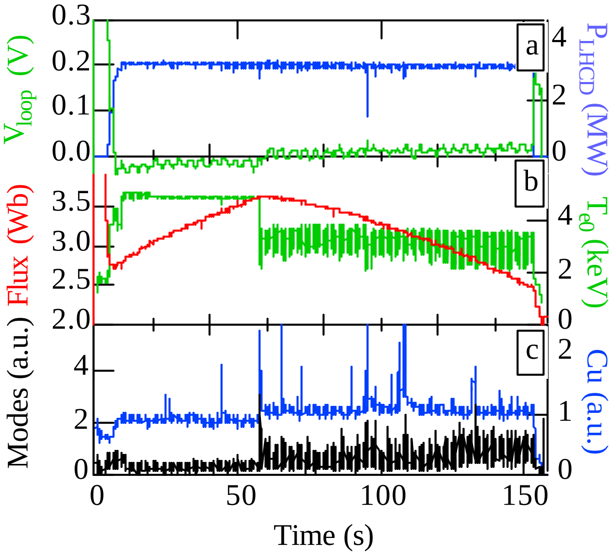


Figure 4: discharge #30448. Time evolution of: (a) loop voltage (green) & LHCD power (blue); (b) Poloidal flux (red) & central electron temperature (green); (c) Mirnov coil signal (black) & Cu line brightness (blue).

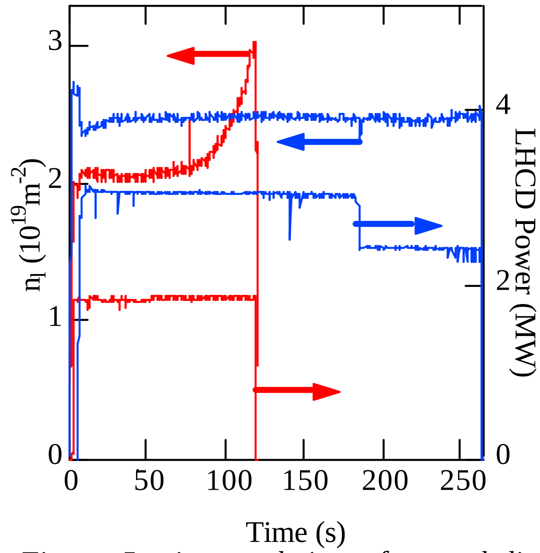


Figure 5: time evolution of central line integrated density (solid line) and LHCD power (dashed line) for discharges #19622 (red, old configuration) and #30414 (blue, new configuration).

4. Physics Issues at Loop Voltage Close to Zero

The duration of Tore Supra discharges are long enough to allow the complete diffusion of the resistive current. Surprising new physics reveals itself in such discharges, when zero loop voltage is approached. Slow oscillations of the central electron temperature were observed in a variety of situations: LHCD alone, combined LHCD/ICRH and combined LHCD/electron cyclotron current drive (ECCD). Figure 6 displays such oscillations that appear 45 seconds after LHCD power application. These oscillations only affect a narrow central region, inside a normalised radius ($\rho = r/a$) of 0.2. Their frequency ranges from 4 to 8 Hz, with amplitude between 0.5 keV and 1 keV. Analysis of the soft X-ray tomographic system data shows that these oscillations are poloidally symmetric corresponding to a poloidal mode number m = 0 (see Figure 7). As such, they do not reflect the local helicity of the magnetic field (central safety factor, $q_0 = 1.5$). Furthermore, the Mirnov coil signal does not change during these oscillations, whatever the heating scheme. For these reasons, this phenomenon is not likely to be linked to any MHD instability. A natural interpretation would be that we observe the interplay between current profile shape, LHCD power deposition and transport.

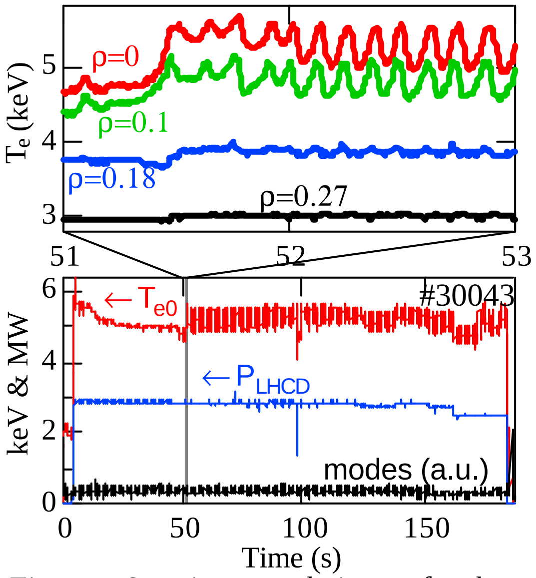


Figure 6: time evolution of electron temperature at normalised radius 0, 0.1, 0.18, 0.27 (top), of central electron temperature (red bottom), LHCD power (blue bottom) & Mirnov coil signal (black bottom).

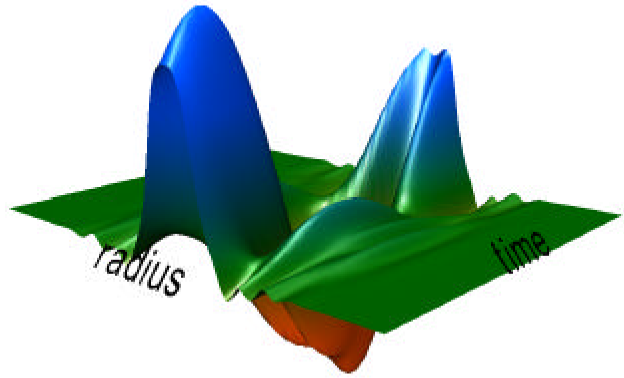


Figure 7 : tomographic reconstruction of soft X-ray data during one oscillation.

A typical combined LHCD/ECCD discharge (#30559) is displayed in Figure 8. In this discharge, sustained by 2.5 MW of LHCD power, four pulses of central ECCD (300kW / 5s) were applied, corresponding to the injection of 6 MJ of integrated ECCD energy. Fig. 8a shows that the electron temperature at ρ = 0.3 is stationary with an additional heating effect by ECCD application. In contrast, the behaviour of the central temperature T_{e0} is very different, exhibiting various phenomena. When the first pulse of ECCD is applied at t = 14s, e.g. 9s after LHCD application, T_{e0} rises from 4.8 keV to 5.6 keV with the slow oscillations (type 1) described above (amplitude 0.8 keV). Then, one second later, another type of oscillations (type 2) with small amplitude (0.2keV) appears for more than one second, followed by a phase with type 1 oscillations, up to the end of this ECCD pulse. During the second ECCD pulse (beginning at t = 29s), type 1 oscillations first appear (Figure 8b). Then, at t = 30 s, T_{e0} collapses, and type 2 oscillations continue until the end of the second ECCD application. During the following LHCD only phase, T_{e0} further decreases. A recovery phase then begins (t = 35.3 s), preceding type 1 oscillations, and ends when T_{e0} reaches its initial level during LHCD. The two last ECCD pulses only exhibit type 1 oscillations. At t = 35s, the temperature profile is found to be flatter than that at t = 28.5s, inside the core region of the plasma (Figure 8d). This difference is correlated with the change of the measured Hard-X rays profile within the same core region. These observations strongly suggest interplay between the local heat transport and the LH power deposition linked through the safety factor profiles. Thus, the results figure out the crucial role of the current profile control for steady-state operation.

Analysis of the temperature gradient in the core region shows a very interesting observation. In some phases, the normalised electron temperature gradient length R/L_{Te} ($L_{Te} = |T_e/\nabla T_e|$) was found to exceed the critical threshold $(R/L_{Te})_c$ by a factor of about 2. In Figure 8d, R/L_{Te} at ρ = 0.25 is displayed together with both the empirical [5] and theoretical [6] values. The empirical value was determined from a wide database of Tore Supra with Fast Wave Electron heating: $(R/L_{Te})_c = 5 + 10\ s/q$, s being the magnetic shear. The theoretical threshold corresponds to electron temperature gradient (ETG) turbulence, including an offset term according to the results of gyro-kinetic simulations [7]. In this discharge (#30559), R/L_{Te} dithers between phase in excess or not of ETG critical threshold. In contrast, discharge #30414 exhibits a stationary phase where R/L_{Te} is maintained above twice the critical threshold for over 3 minutes.

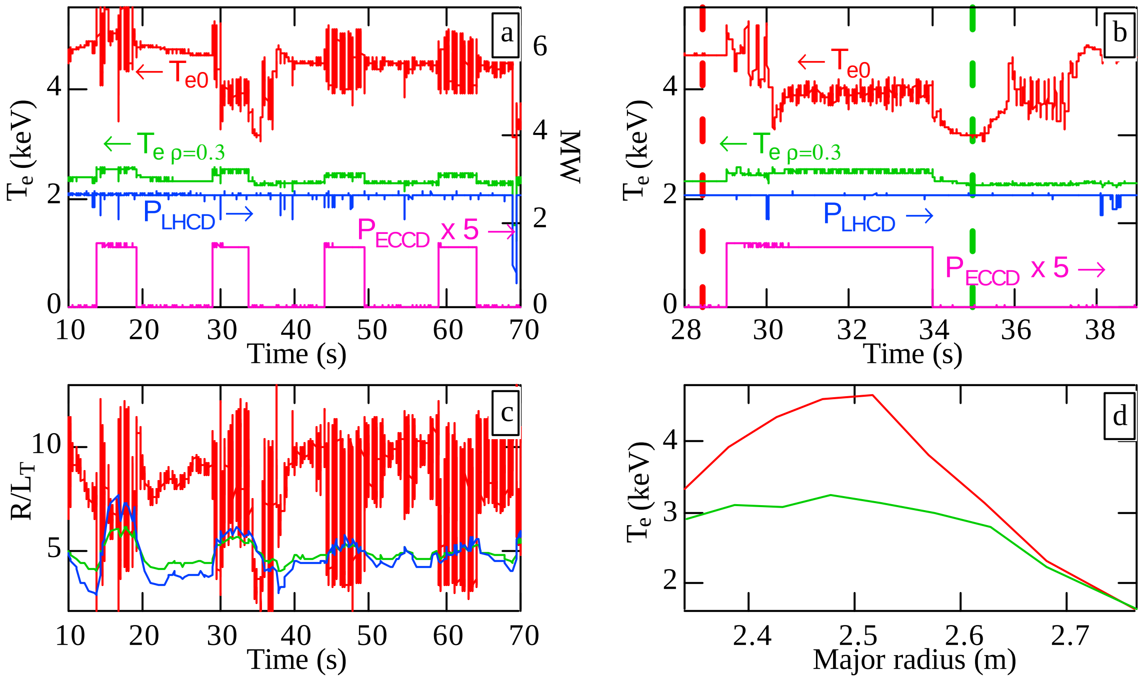


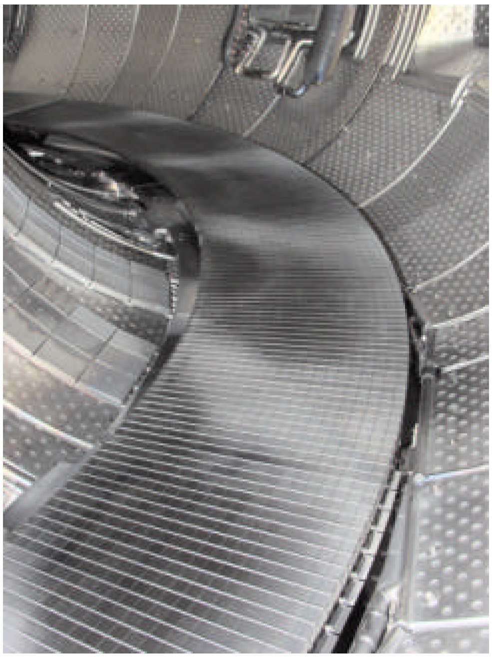
Figure 8: discharge #30559. a) & b) time evolution of central electron temperature (red), electron temperature at normalised radius 0.3 (green), LHCD power (blue), ECCD power multiplied by 5 (magenta); c) time evolution of normalised electron temperature gradient (red), experimental (green) & theoretical (blue) ETG critical threshold; d) electron temperature profile at 28.5 s (red) and 35 s (green).

5. Heating and Current Drive System Performance

Performing such long duration discharges has allowed us to thoroughly test the additional heating systems of Tore Supra. The LHCD system has been able to deliver up to 3 MW of RF power for 3 min. The ICRH system has been operated for 30 s at a voltage level on the antenna higher than 35 kV, which is the operating voltage foreseen for ITER. One ICRH antenna has delivered 1 MW for 1 minute. Having all plasma facing components of Tore Supra actively cooled has allowed the validation of these performance levels by calorimetric measurement [8]. However, despite these good results, progress has still to be made on the reliability of the heating systems. Indeed, most of the discharges having duration more than 2 minutes, carried out with about 3 MW of LHCD, exhibit a decrease of the LH power during their final phase (Fig. 3, 6), due to problems on klystrons. Knowing that such klystrons have been able to deliver 450 kW for 1000 s on the test bed (compared to 250 kW into plasma during long discharges), one can appreciate the step to be taken when going from test bed to real operation on plasmas. This will be one of the major challenges of the CIMES project (refurbishing of the Tore Supra LHCD system to make it capable to deliver to the plasma 8 MW of power for 1000 s [9]) and certainly a very important lesson to learn for ITER operation.

6. Observation inside Tore Supra after the Long Discharges Campaign

A short programmed opening of Tore Supra took place in August, just after long duration discharge operation at 3 MW injected power level. This opening allowed the verification that the general state of the internal components of Tore Supra was excellent (see picture 9). This observation was confirmed in an opening in October, following a water leak due to the clogging of a water pipe. However, these openings also revealed two interesting phenomena:



Picture 9: internal components of Tore Supra after the long duration discharges campaign. Darker areas on the TPL correspond to zone of maximum interaction with the plasma.

- the development of carbon flakes and deposited layers observed in low and medium recycling zone. The redeposition mechanism and the impact of these flakes on the "wall pumping" are under investigation. It is also worth to note that such layers are thermally insulating, thus leading to very high surface temperatures and therefore preventing the actual surface temperature of plasma facing components below these layers to be measured [4].
- some small damage due to losses of fast electrons trapped in the magnetic ripple well were observed in unexpected places (in fact behind actively cooled protections designed to cope with these ripple losses!). The most probable explanation is that due to the resistivity of the B_4C covering, the protections get polarised and the particle trajectories are locally modified. B_4C has been removed on one protection in order to check this hypothesis. Besides demonstrating the adverse effects that can appear when integrating weak power load over a long duration, this observation also stresses the importance of performing long pulse experiments in a realistic tokamak environment in order to identify all the possible sources of spurious heat loads, even the most complex and unexpected.

7 Conclusions

In its new configuration, Tore Supra can now routinely address the physics and technology of very long duration discharges. This allows the study of a whole set of new and exciting physics. Two major fields of investigation will certainly be:

- The physics of discharge at vanishing loop voltage in a situation where the resistive current diffusion has fully taken place,
- Plasma wall interaction on long time scales in a situation where the plasma facing components work at steady-state temperature.

For these first long duration discharges, the operating scenario was deliberately chosen to be L mode and, in order to avoid difficulties linked to MHD instabilities, the lower hybrid launcher phase was selected to get a monotonic current profile. Despite these measures, the early part of the discharge had to be carefully tailored to avoid MHD activity when reaching low loop voltage. Obviously, the next major challenge for the Tore Supra experimental programme of long duration discharge study will be the feedback control of the current profile for the study of physics at zero loop voltage in advanced scenarios.

Performing long duration discharges requires the integration of various fields of physics and technology. Doing such an integration on Tore Supra has already produced a whole set of key results for ITER and the coming years will certainly produce a full harvest of new results.

1 B. Saoutic, Plasma Phys. Control. Fusion **44,** 1-12 (2002)
2 J.J Cordier, 22th SOFT (Helsinki, 2002), to be published in Fusion Engineering and Design
3 Equipe Tore Supra, IAEA-CN-64/O2-2, Montreal, 1996
4 J. Jacquinot, IAEA-CN-94/OV/1-2, Lyon, 2002
5 G. T. Hoang, *et al.*, Phys. Rev. Lett. **87**(12), 125001-1 (2001)
6 W. Horton, *et al.*, Phys. Plasmas **7**, 1494 (2000)
7 F. Jenko, *et al.*, Phys. Plasmas **8** (9), 4096 (2001)
8 R. Mitteau et al., IAEA-CN-94/EX/D1-5, Lyon, 2002
9 Beaumont, B., *et al*., Fusion Engineering and Design, vol.56-57 (2001) p.667-672.

Appendix: Equipe Tore Supra

G. Agarici , J.C. Alliez, D. Alpe-Conchy, J.M. Ané, T. Aniel, J.F. Artaud, S. Assas, S. Balme, V. Basiuk, P. Bayetti, B. Beaumont, A. Bécoulet, M. Bécoulet, L. Begrambekov, G. Berger-By, B. Bertrand, Ph. Bibet, D. Boilson, G. Bosia, J.M. Bottereau, F. Bouquey, C. Bourdelle, S. Bremond, C. Brosset, R. Brugnetti, J. Bucalossi, Y. Buravand, A. Cambe, H. Capes, P. Cara, M. Chantant, Ph. Chappuis, E. Chatelier, M. Chatelier, D. Ciazynski, F. Clairet, J. Clary, C. Clément, L. Colas, J.J. Cordier, Y. Corre, L. Costanzo, B. Couturier, C. Darbos, B. De Gentile, C. De Michelis, H. De Esch, P. Decool, R. Dejarnac, E. Delchambre, C. Desgranges, P. Devynck, L. Doceul, H. Dougnac, J.L. Duchateau, B. Dugué, R. Dumont, A. Durocher, A. Ekedahl, D. Elbèze, E. Eriksson, A. Escarguel, F. Escourbiac, G. Falchetto, J.L. Farjon, C. Fenzi, E. Fleurence, C. Fourment, P. François, B. Franel, C. Friant, X. Garbet, R. Garbil, L. Gargiulo, P. Garin, E. Gauthier, A. Géraud, Ph. Ghendrih, R. Giannella, C. Gil, G. Giruzzi, M. Goniche, V. Grandgirard, B. Gravil, C. Grisolia, A. Grosman, O. Guérin, D. Guilhem, B. Guillerminet, R. Guirlet, J. Gunn, R. Hemsworth, P. Hennequin, D. Henry, P. Hertout, W. Hess, G.T. Hoang, C. Honoré, J. Hourtoule, J. How, T. Hutter, G. Huysmans, F. Imbeaux, J. Jacquinot, M. Jaunet, E. Joffrin, J. Johner, J.Y. Journeaux, M. Ju, F. Kazarian, V. Krivenski, A. Krylov, B. Labit, J. Lasalle, C. Laviron, A. Le Bris, M. Lennholm, F. Leroux, P. Libeyre, M. Lipa, X. Litaudon, T. Loarer, P. Lotte, C. Lowry, C. Lyraud, A. Maas, P. Magaud, P. Maget, R. Magne, G. Marbach, G. Martin, A. Martinez, R. Masset, P. Massmann, D. Mazon, L. Millon, J. Misguich, M. Missirlian, R. Mitteau, P. Mollard, P. Monier-Garbet, D. Moreau, P. Moreau, D. Moulin, M. Moustier, P. Navarra, F. Nguyen, S. Nicollet, M. Ottaviani, Z. Ouyang, H. Parrat, A.L. Pecquet, B. Pégourié, Y. Peysson, P. Platz, C. Portafaix, D. Protas, M. Prou, R. Reichle, J.D. Reuss, G. Rey, P. Reynaud, F. Rimini, F. Rochard, L. Rodriguez, B. Rothan, G. Roupillard, F. Sabathier, R. Sabot, F. Saint-Laurent, F. Samaille, A. Santagiustina, B. Saoutic, Y. Sarazin, J. Schlosser, B. Schunke, J.L. Schwob, J.L. Ségui, J. Signoret, A. Simonin, F. Sourd, F. Spineanu, P. Spuig, P. Stott, F. Surle, L. Svensson, M. Tena, J.M. Theis, P. Thomas, J.M. Travère, G. Tresset, E. Tsitrone, N. Utzel, J.C. Vallet, D. van Houtte, L. Vermare, M. Vlad, K. Vulliez, V. Waller, Z. Wang, L. Zani, G. Zhuang, X.L. Zou, K. Zunino, W. Zwingmann.