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Recent developments towards Steady State physics and technology of Tokamaks in Cadarache

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Abstract. Operations of Tore Supra have resumed after a major upgrade of internal components in order to increase the heat extraction capability to 25 MW for 1000 s and address long pulse research at a level of power density flowing through the separatrix relevant for next step. The overview highlights first the related technology developments : industrial realization and tests with plasma of about 600 plasma limiter components made of some 12000 actively cooled CFC tiles. World record breaking discharges with a coupled energy of 0.74 GJ have been obtained with durations exceeding 4 minutes only limited by the long pulse capability of the heating and current drive systems. Particle balance analysis shows that the in-vessel Deuterium inventory never reached saturation possibly in connection with heavy carbon deposit seen in the neutralization zone. The in-vessel inventory is reduced when efficient supersonic gas injection is used. New physics is observed when the loop voltage vanishes for long times : density remains peaked in absence of the Ware Pinch effect and, independently, the response to additional heating becomes dominated by complex interplay between transport and current drive. The contributions of the Euratom-CEA Association to fusion energy research also include new developments in the field of Negative Ion Beam Injection (1000 s H source and Singap acceleration to 1 MeV) and in the field of superconductors (cable in conduit concept, connections, testing). Finally, European studies for Cadarache as a site for ITER conclude that all ITER technical requirements are met.

1. Introduction

Tore Supra is a 1.5 MA class tokamak constructed in the 1980 with a steady-state magnetic field using large scale superconducting magnets and water cooled plasma facing components in view of high performance long pulse plasma discharges. At this occasion a new fusion laboratory was created, gathering the French activities in magnetic fusion at the CEA Cadarache site with the aim to offer an attractive option to host the “next step” after JET. Today the Euratom-CEA Association co-ordinates a comprehensive range of contributions to magnetic fusion by CEA, CNRS, Universities and Industry. The superconducting magnets of Tore Supra have operated with high reliability during fourteen years and the machine has progressively extended the data base for steady state technology and physics of tokamaks.

When plasma facing components (PFC) are not actively cooled, they can only accumulate a limited amount of energy and the temperature of PFCs increases continuously during the discharge. In such conditions, some long pulse research has been performed on JET [1] in ELMy H-mode with the MKI divertor (P_{tot}~7MW limited to 20sec, i.e. 140MJ), on JT60U [2] (230 MJ injected) and on TRIAM [3] which has established a world record for pulse duration of 3h10' and a total injected energy of 100 MJ. In this paper we report the recent results of Tore Supra taking advantage of both superconducting magnets and actively cooled PFCs.

Recently the machine has undergone a complete renewal of internal components with the aim to provide a heat extraction capability of 25 MW for 1000 s (CIEL project). This change has been performed in two stages each followed by an experimental campaign in 2001 and 2002. This paper gives an overview of the experimental results and highlights related technology developments. It is organized as follows : Firstly the technical aspects of the upgrade of the in-vessel components are described. For the first time, it has been necessary to realize on an industrial scale actively cooled components with heat flux power density and reliability requested by ITER. After having given detailed accounts on exhaust power flux to the components and on the particle balance, we address the physics of very long pulse discharges with essentially zero loop voltage where new phenoma can develop over large time scales not normally accessible with inertially cooled devices. Finally a brief account is given on other developments directly relevant to ITER most notably negative ion formation and acceleration with a single gap, superconductor coil technology and last but not least technical validation of Cadarache as a European site for ITER.

2. The CIEL project realization

A new goal of 25 MW injected power for discharge heating of more than 300s, was assigned to the machine in 1996, in order to study conventional and advanced scenarios (CIEL Project). Handling power and particles over such long discharges requires a profound modification of the in-vessel environment and naturally led to the design and construction of a flat and continuous toroidal limiter (area $7m^2$) configuration, the "Toroidal Pump Limiter" (TPL). The concept included fine adjustment with respect to the magnetic axis using a set of independently movable modular limiters.

In addition to these geometrical improvements, the new generation of Tore Supra High Heat Flux Components (HHFCs figure 1), took advantage of the considerable progress achieved by the European industry in the fabrication process of these components, particularly the reliability of bonding techniques of CFC with copper. This progress made the handling of power densities in the range $10MW/m^2$ over broad areas a reality.[4].

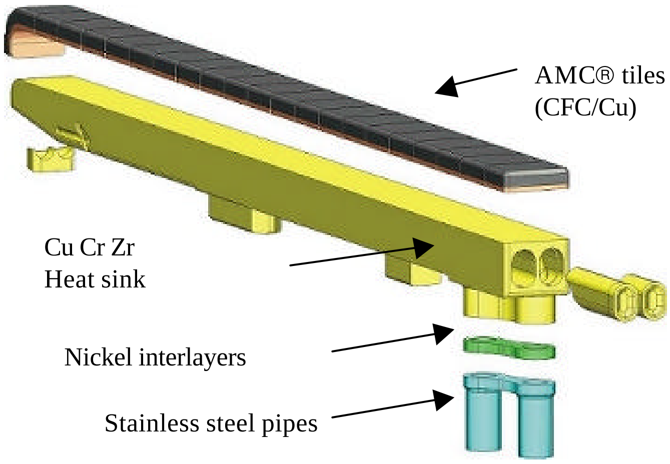

FIG. 1: Schematics of the high heat flux TPL finger element (length 0.5m,2.5cm depth and width). The 21 AMC tiles (6mm thickness), 3 plugs and Ni/SS cooling pipes are EB welded to the heat sink

The CIEL project consists of:

a set of high heat flux plasma facing components, forming the TPL, able to exhaust 15 MW of convected power at a power density of $\sim 10MWm^{-2}$ relevant to ITER's highest loads.

- a completely redesigned inner vessel protection with a set of water cooled panels covering entirely the inner wall of the vessel in order to protect the cryostat against thermal radiation and poloidal bumpers against transients (figure 2).
- A set of 10 neutralizers below the TPL where the convected particle flux in the scrape off layer is neutralized, each connected to turbomolecular pumps through the vertical ports. These neutralizers are also actively cooled high flux components. The

maximum flux on the neutralizers edge can reach 15 MW/m^2.

- Monitoring of PFC surface temperature during the entire discharge, performed by a set of actively cooled infrared endoscopes [4].

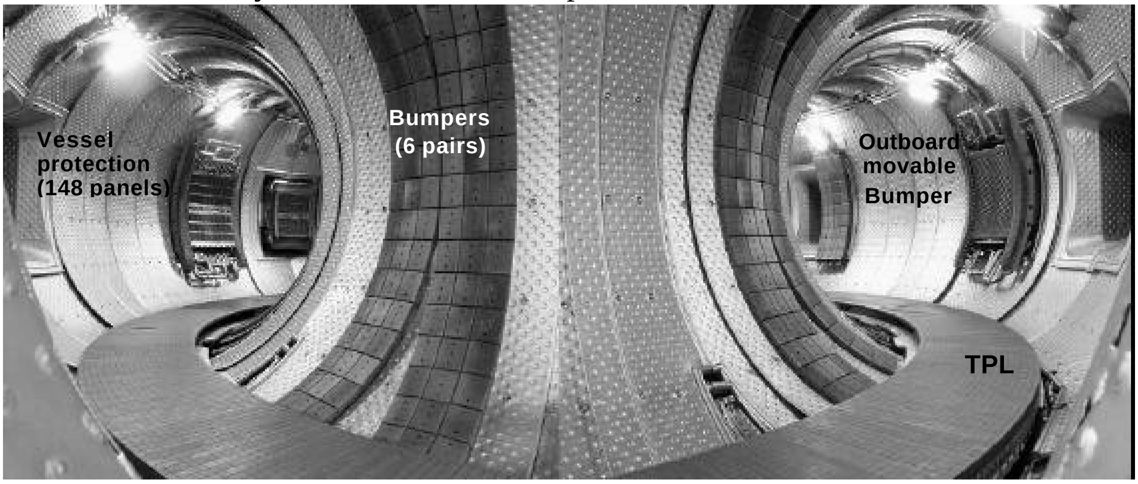

FIG. 2: Tore Supra in the CIEL configuration

The main characteristics of CIEL are the following [5]:

The major component, the **Toroidal Pump Limiter (TPL),** consists of a flat toroidally continuous disk (R_i=2.22m, R_e=2.71m) made of 12000 CFC tiles assembled in 574 radial high heat flux elements called “fingers” (see figure 1). This disk allows a plasma minor radius a=0.72m and covers a 7.6 m^2 area. It is supported by a full ring made of 12 toroidal 30° stainless steel sectors (machining accuracy is submillimetric), also used as the manifold. The whole active part of the limiter is cooled by a pressurized hot water loop. It is movable vertically using six electric jacks (70mm). The vertical axis and the horizontal position of the limiter can be adjusted remotely to best fit a toroidally uniform heat distribution at the leading edge.

Since the beginning of machine operation (1988), hydraulically inflated stainless steel (SS) panels covering the vessel (Figure 2) have proven to be very reliable. Therefore, this technology has been maintained for CIEL. The radiated plasma power losses (i.e. 0.2 MW/m^2) is absorbed by a set of **144 SS panels** covering without gap the entire surface of Tore Supra’s inner vessel (see Figure 2). It includes the screening of the 12 vertical upper and 6 horizontal midplane ports equipped with diagnostics [6]. A set of **12 poloidal bumpers** (CuCrZr heat sink covered with thick CFC tiles) has been added on the high field side, in order to sustain transient events (disruptions). A movable **outboard limiter** (Fig. 2) has been added on the low field side in order to protect the five RF antennae from the impact of disruption induced runaway electrons that could occur during plasma ramp-up. Tightness reliability of this new protection wall, was demonstrated under thermal baking cycles and plasma radiated power, during the 2001 and 2002 experimental campaigns.

The ***water*** **cooling loop** of Tore Supra has been completely upgraded to enable a total water flow of 1100 tons/hour, for the cooling of the CIEL plasma facing components, RF antennae and diagnostics at a maximum pressure of 3 MPa [7]. The pressure drop of the loop (i.e. 0.7 MPa) allows a water speed in the TPL finger elements of about 10 m/s. Calorimetric measurements of the actively cooled components are now provided for each important sector and benefits from improved sensitivity. Each independent component is equipped with an output thermometer (sensitivity 2 10^{-2} K). This diagnostic ensures the overall energy removal balance in the water cooled PFCs during the pulse, within an accuracy better than 3% [8].

3. The physics of CIEL

3.1. Overview of the experimental campaign

Tore Supra was restarted in the full CIEL configuration in 2002 and the experimental campaign was oriented towards the achievement of long pulse steady state discharges. A low density, and low plasma current scenario sustained by lower hybrid current drive only (3 MW - 300 s) was chosen for this purpose. So far, a steady state 265 s record discharge has been obtained, allowing to reach an injected/extracted energy of 0.74 GJ (#30414, fig.3). The previous record from the 1996 campaign was a 120 s discharge with 0.28 GJ [9]. A scenario at higher current and higher density , up to a Greenwald fraction of 0.8, was also developed with combined lower hybrid current drive and ion cyclotron heating. So far, it allowed to reach 0.42 GJ of injected energy (#30438, fig.3).

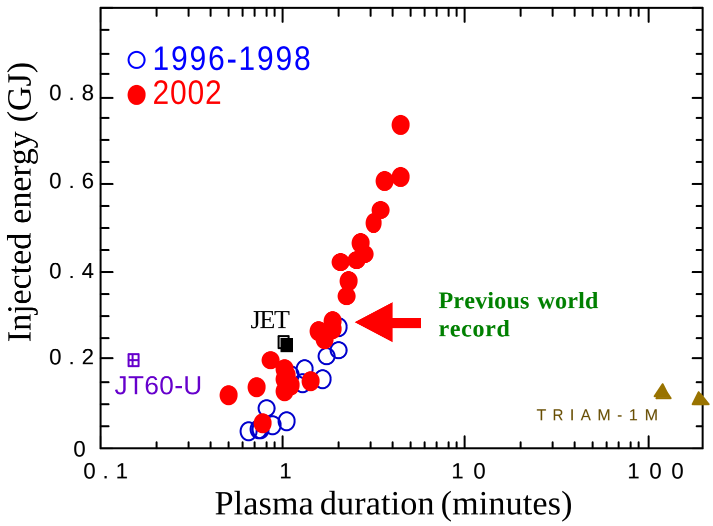

FIG. 3 : Total energy injected versus plasma duration, showing the new domain reached in the Tore Supra 2002 campaign

In shorter discharges (20s), up to 6 MW of power have been successfully coupled to the plasma, demonstrating that the power density limit of the TPL was not reached. In most of these discharges, zero loop voltage has been maintained for about 3 minutes on #30414. Discharges with negative loop voltage have also been obtained for about 1 minute on #30448 [10]. A careful shaping of the plasma current profile has to be performed to prevent MHD activity from occuring when the power is applied. This is achieved through the initial current ramp phase and the precise timing of the LHCD power application. These long discharges terminate when the klystrons feeding the LHCD system reach the maximum rating of their specification. The loss of LHCD power results in an “early” termination of the discharge when the maximum available magnetic flux of the transformer is reached. This underlines the importance of the upgrade of the Tore Supra lower hybrid system [11], currently underway. Figure 3 presents the new domain of performance reached during 2 month of the 2002 campaign, with reference to the previous experiments in 1996 and 1998 campaigns.

ECRH power at 118 GHz was also successfully coupled to Tore Supra long pulse discharges. The present availability of the ECRH system allowed us to couple up to 6MJ of ECRH through 4 successive pulses of 5 seconds from one 300kW gyrotron in a single plasma discharge. The Tore Supra vacuum chamber was used as a high frequency load in between plasma shots and in presence of the toroidal magnetic field to speed up considerably the gyrotron conditioning time.

3.2. Plasma facing components and heat flux deposition

The behaviour of the toroidal pump limiter (TPL) has proven very satisfactory all along this long discharge campaign.

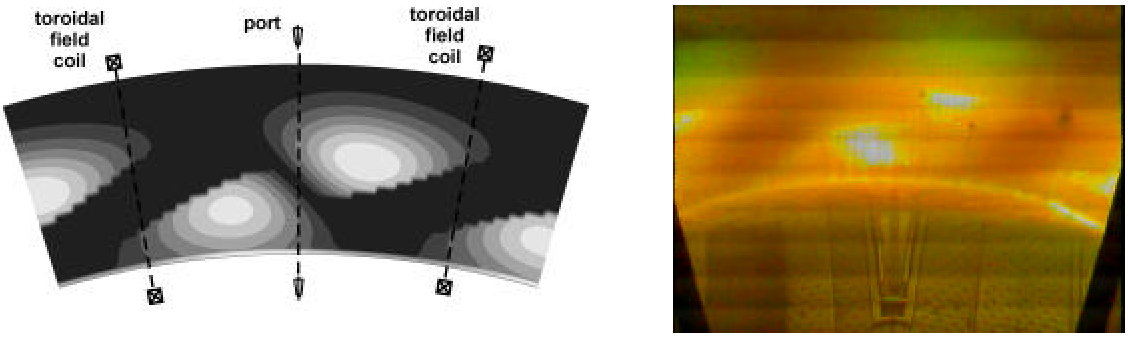

FIG. 4 : Comparison of heat flux pattern as calculated from simulations (left) and recycling pattern measured by a CCD camera (right). The main experimental features (loaded areas alternating with shadowed areas) are well reproduced by the simulations.

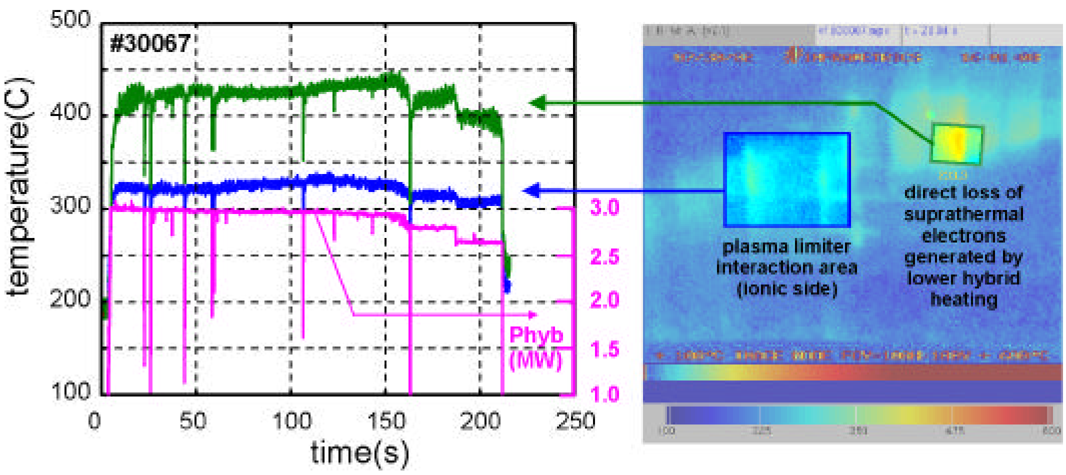

FIG 5 : Typical time evolution of the TPL surface temperature in the convective zone (blue) and in the hot spot zone (green). The lower hybrid power is also indicated [13].

The experimental heat flux pattern on the TPL exhibits bright areas corresponding to convective heat flux deposition and dark areas corresponding to shadowed areas both correlated with the magnetic field ripple, as expected from simulations [12].
This can be seen in figure 4 where a simulated heat flux deposition pattern is compared with a CCD view of the recycling pattern on the TPL. The typical temperature increase of the convective zone (about 200 °C for 3 MW of additional power) as well as the thermal response of the tiles (time constant around 0.8 s) are in good agreement with design calculations [13]. A time evolution of the TPL temperature is shown in figure 5 for a typical discharge. When lower hybrid is applied, localized hot spots appear on 4 tiles on the electronic side. This observation is consistent with suprathermal electrons generated in the core plasma and drifting radially outward, hitting the TPL close to the last closed flux surface. So far, the surface temperature of the TPL in response to auxiliary heating (LHCD and ICRH) has shown tolerable heating of the components in all cases [13].

Calorimetry has proven to be a valuable tool to confirm injected energy values, as all actively cooled components are equipped with temperature sensors. The balance between injected and extracted energy is presented in figure 6, showing an excellent agreement : more than 95% of the injected energy is recovered. In typical discharges, the TPL extracts more than 60% of the total injected energy while the vessel protections handle around 21 %.

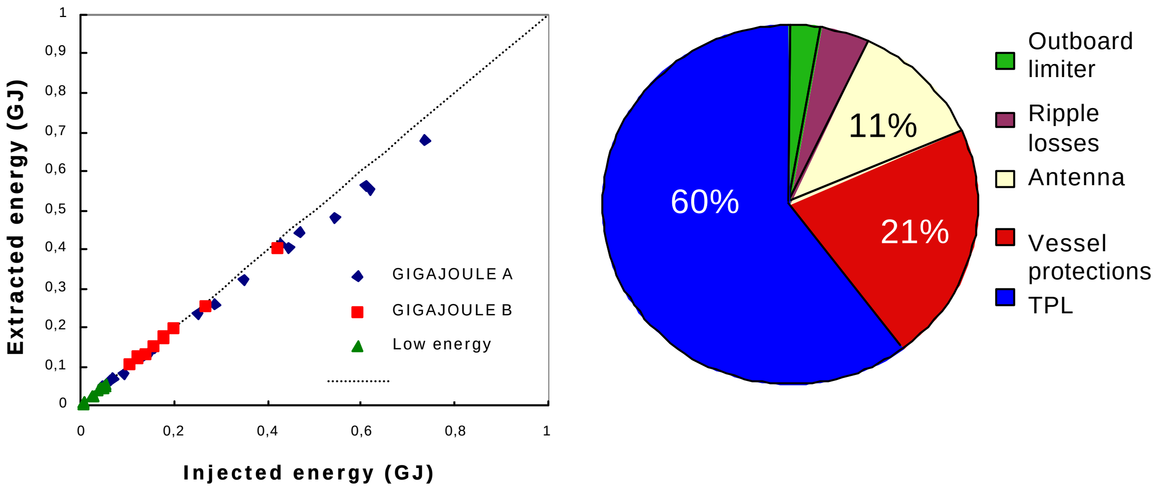

FIG 6 : extracted energy as measured by calorimetry versus injected energy.

The remaining part of the injected energy is evacuated by the outboard limiter, the ripple protections and the antenna lateral protections. Calorimetry has also been used to adjust the position of the 12 different TPL sectors with a sensitivity of about 0.2 mm in height.

During this campaign, high temperatures were measured on the neutralizers located below the TPL by a system of (infra red) optical fibers [14]. These high temperatures (above 1200 °C for 3 MW of lower hybrid power) appeared when lower hybrid heating was applied and seem to be linked to suprathermal electrons generated in front of the launcher and magnetically connected to the neutralizers. The location of the hot spots is very sensitive to the plasma current, and a plasma current sweeping of a few tens of kA was generally applied during long discharge in order to distribute the heat load. However, even in ohmic plasmas, the measured temperatures are already quite high (400-600°C). This is attributed to a deposited layer, which has been observed on all the neutralizer surfaces and which is loosely connected to the actively cooled substrate. The flaky deposited (see figure 7) layer is currently under analysis, to characterize its thermal behaviour as well as its deuterium retention properties.

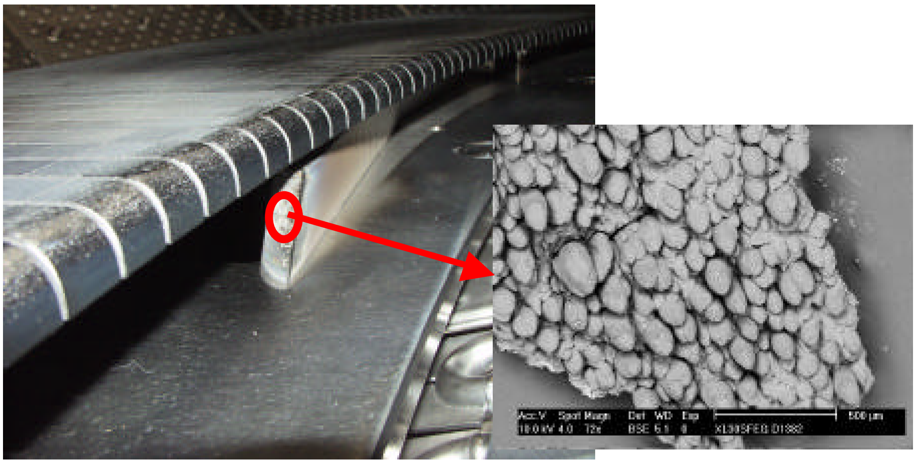

FIG.7 :View of the layer deposited on the neutralizer surface in the machine and imaging of this layer by electronic microscopy

Comparison has been made between measurements on a neutralizer cleaned up during a shutdown and a neutralizer where the deposited layer was left on. First results show that for a given plasma the temperature measured on the "clean" neutralizer is well below the temperature measured on the "dirty" one (200 °C less for a ohmic plasma). The discrepancy between the clean and the "dirty" neutralizer tends to diminish as the campaign proceeds. However, the time constant of the temperature on the two neutralizers does not show any significant difference and is rather close to the time constant expected for the neutralizer itself (around 1 s), which has still to be understood. The spectrum emitted by the "dirty" neutralizer is closer to black body radiation than the spectrum from the clean one.

The analysis of the heat flux deposition on the different plasma facing components of the machine indicates that the simple exponential decay model of the heat flux in the scrape off layer is not appropriate, as several characteristic decay length λ_q have been identified with different diagnostics observing in different regions (λ_q = 5 mm from CCD imaging of the limiter footprint, λ_q = 10 mm as deduced from calorimetric measurements on the TPL, λ_q = 20 mm as measured by a mobile Langmuir probe scanning the SOL at the top of the machine). The decay length appears to be shorter near the last closed flux surface than in the far SOL. Possible link to edge avalanche transport phenomena given by calculations are under consideration [15].

3.3. Density control and particle balance

Strong and uncontrolled density increase was always observed typically after 1 minute in previous 1996 long discharges experiments and was a serious issue limiting the performances and pulse duration. It was attributed to components located far away from the plasma, thermally loaded by the plasma radiation and outgassing as their temperature gradually increased [16]. Solving this problem in the CIEL configuration was twofold : inhibiting the wall particle source by a complete coverage of the vessel with actively cooled components (see section I) and maximizing the particle sink with a continuous active pumping system installed under the TPL [17]. For the 2002 campaign, the pumping system of the TPL was fully operational with 10 neutralizers connected to turbomolecular pumps (total installed pumping speed 20 m^3s^{-1}). The resulting plasma density time evolution is presented in figure 8, where the plasma density is shown to be very efficiently controlled, for duration longer than 4 minutes, at a higher level of lower hybrid power.

Typical injected fluxes are around 1 Pam^3s^{-1} while the extracted flux is around 0.4 Pam^3s^{-1}. The injected flux is seen to decrease slowly in the first phase of the discharge where full lower hybrid power is available (for t < 120 s). In the second phase of the discharge with reduced lower hybrid power, the injected flux needed to maintain the plasma density decreases, possibly due to a somewhat better confinement, and stays constant.

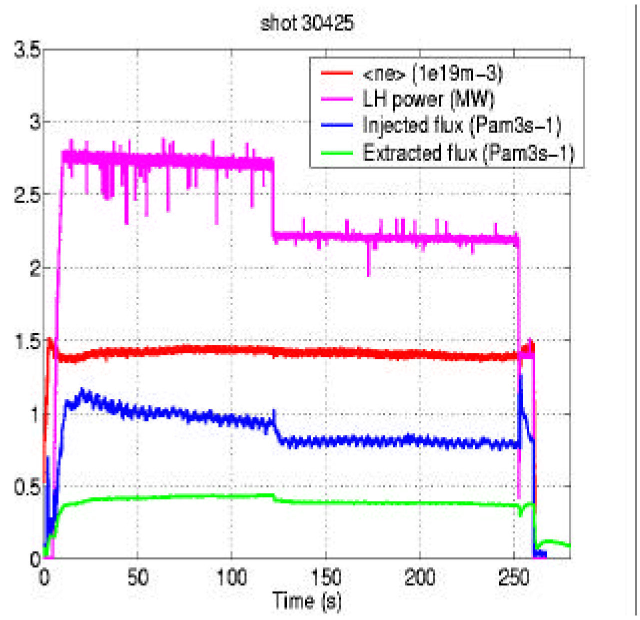

FIG. 8 : typical time evolution of the plasma volume averaged density during a long discharge. Also shown is the lower hybrid power and the fluxes injected by gas puff and extracted by the TPL

For all the long pulses, the spectral line brightnesses of low Z impurity ions (C and O) as well as of metals (Fe, Ni, Cu) are perfectly stationary during the flat top phases of the plasma, as is Z_{eff}, deduced from the Bremsstrahlung measurements, which is close to 2 for a total input power of 3MW (#30414). It is worth noting that boronization does not seem to affect the time behaviour of impurities, although it reduces significantly oxygen and iron contents in the discharge.

It is important to note that the in-vessel gas inventory does not show any sign of saturation, even after 4 minutes, although significant quantities of gas have been injected (close to 300 Pam^3) and is still strongly pumping after 4 minutes of discharge. This can be seen on figure 9, where the particle balance, calculated as described in [18], is presented for a long discharge. As usual, the plasma inventory is very small compared to the injected gas. At the end of the discharge, the TPL has extracted 40 % of the injected gas while the in-vessel components have trapped the remaining 60% (130 Pam^3). Taking into account the 15 m^2 of carbon surface in Tore Supra, and its saturation at a ratio of 0.4 deuterium per carbon atom, one finds 1 to 3 10^{22} atoms of deuterium (corresponding to 20 to 60 Pam^3), far below the experimental retention. The metallic surfaces are estimated to be a negligible deuterium sink (10^{16} to 10^{17} deuterium atoms). Other mechanisms must be involved, such as retention in the graphite pores or in films of hydrocarbons growing on the graphite surface, and are currently under investigation.

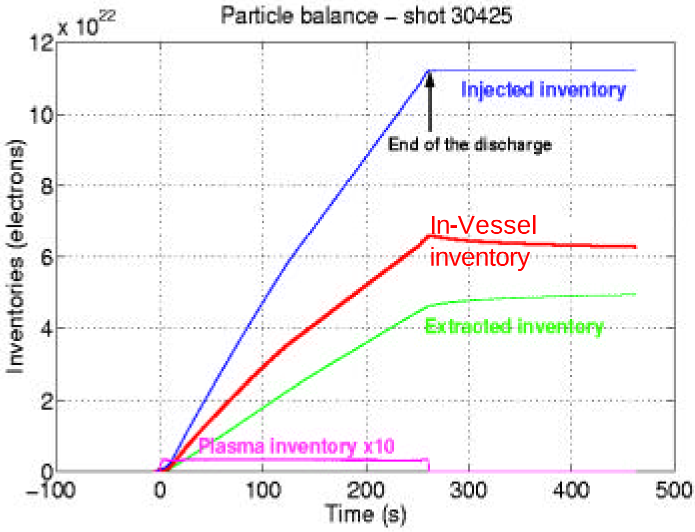

FIG 9 : Typical particle balance for a long discharge, showing the injected, extracted, plasma and wall inventories Note that the plasma inventory is multiplied by 10 to be seen on the figure.

In order to minimize the quantity of gas injected and therefore the in-vessel inventory, an original fueling method by supersonic pulsed gas injection (SPGI), launching a series of very dense and short gas puffs, has been developed and tested on Tore Supra. It allows to reach a Mach number up to 5, and to inject 0.4 Pam^3 of D_2 molecules within an injection time τ_{nj} = 2-4 ms [19]. As seen on figure 10 experimental fueling efficiencies of SPGI are found to be 3 to 4 times higher than for conventional gas puff (30-60% instead of 10-15 % respectively). According to modeling, this increased efficiency can be solely attributed to the very short injection time (τ_{nj} << τ_p) and to the strong edge plasma cooling linked to the injection of matter [20]. It has recently been applied to long discharge fueling [21].

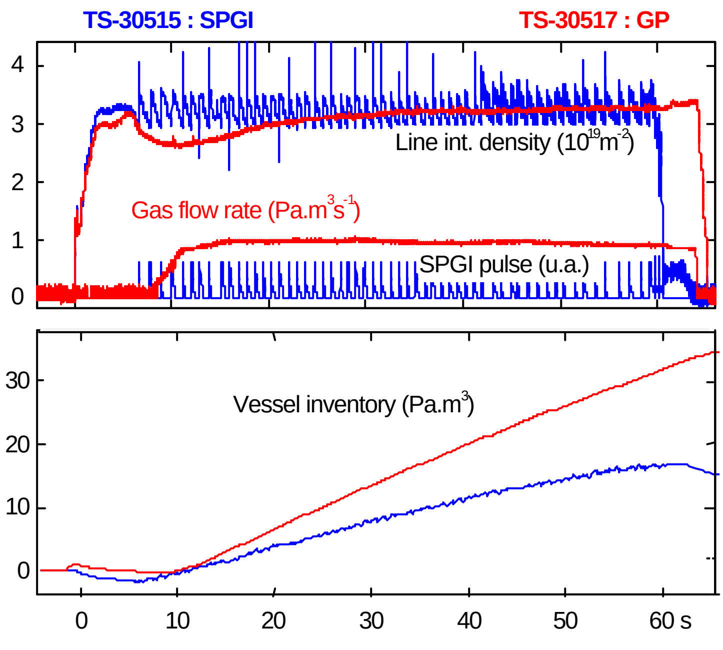

FIG. 10: Comparison of feedback gas injection from conventionnal gas puff (GP) and supersonic pulsed gas injection (SPGI) for the same plasma density target (I_p=0.67MA and P_{LHCD}=2.8MW).

The feedback control of the density with SPGI was very satisfactory (the injector worked at 1.2 Hz), and the total quantity injected was 30% lower with this system than for a conventional gas puff fueling, as can be seen in Figure 10. Moreover, the in-vessel inventory is halved at the end of the shot. Finally, it has also been shown that the coupling of the lower hybrid or ICRH powers was not degraded by applying SPGI, although the edge plasma is strongly perturbed.

4. Physics issues linked to very low loop voltage operation

Full non inductive current drive is mandatory for such very long pulse operation. According to the present Tore Supra heating and current drive capability, two possible scenarios have been investigated, namely scenario A at low density when the LHCD current fraction is maximum, and scenario B when a certain balance between LHCD and bootstrap current is realized. In the present very long pulse operation, the scenario A target at 3.85T was located at 3MW LHCD, a plasma current of about 600-650 kA, and a volume averaged density of about 1.5 10^{19} m^{-3}. This type of discharge is sustained at 80-90% by LHCD. Scenario B was achieved by increasing the volume averaged density up to about 2 10^{19} m^{-3}, adding 3 MW of ICRH and decreasing the plasma current down to 500-550kA, achieving deuterium discharges at 80% of the Greenwald density limit. Bootstrap current fractions up to 20% were obtained. Figure 11 shows a summary of some of the longest pulses obtained during the last campaign.

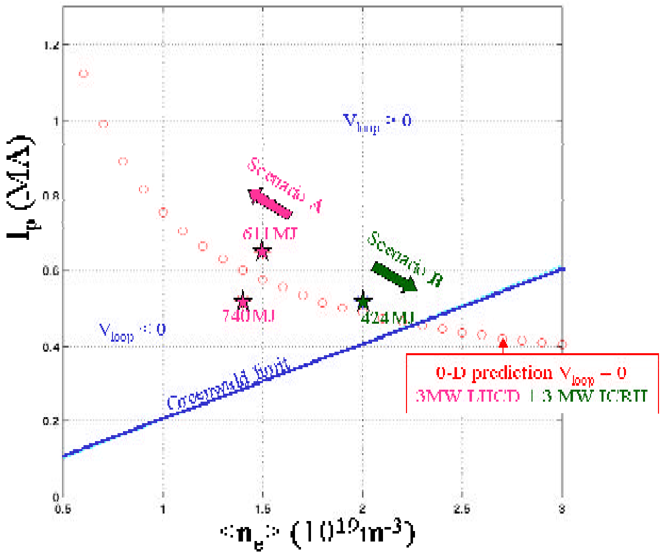

FIG. 11: Tore Supra operational domain for long pulses. The circles display the 0-D prediction of zero loop voltage at 3MW LHCD + 3MW ICRH. The stars represent actual 2002 Tore Supra discharges labelled with their total coupled energy.

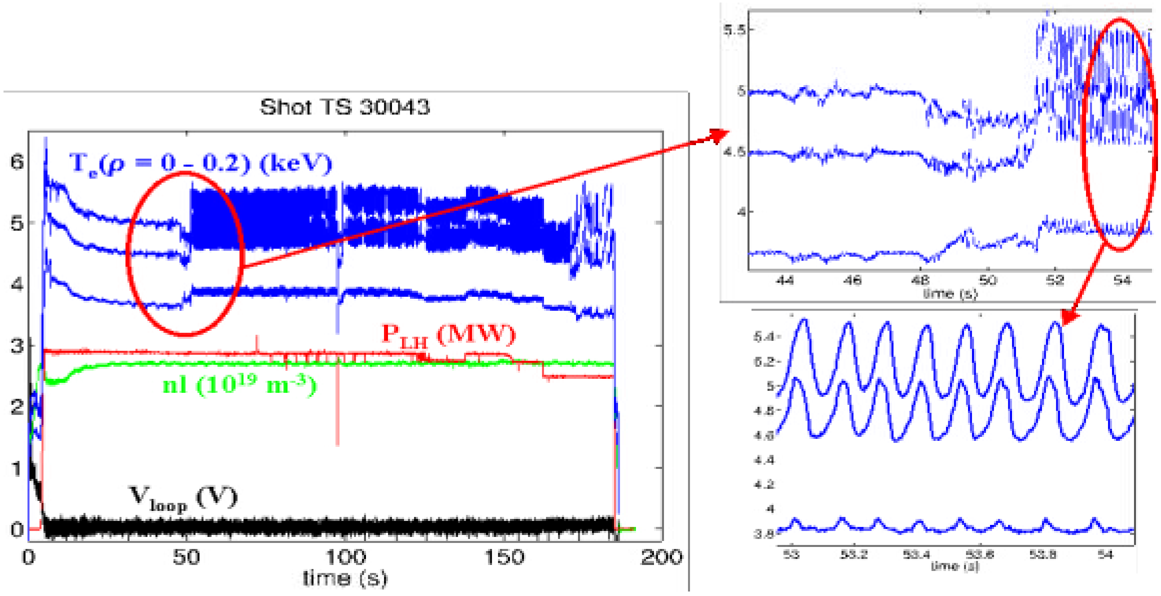

FIG. 12: Tore Supra #30043. Zoom on the central electron temperature behaviour.

A detailed analysis in terms of confinement, transport and profiles of such discharges was performed using the CRONOS package [22]. It should be noted that in such simulations the current density profile is strongly constrained by the detailed measurements of hard-X rays emitted by the fast electrons driven by LHCD [23, 24], together with the bootstrap current deduced from a neoclassical simulation. This particular combination provides a unique determination of the current density profile with a high degree of confidence. The first conclusion drawn from these simulations is that the discharges exhibit basically an L-mode confinement, associated to a monotonic and/or centrally flattened q-profile. Variations with higher central temperatures possibly associated with a so-called LHEP behaviour are also observed in certain discharges. What becomes obvious in most of those highly steady-state discharges is the unusual behaviour of the central electron temperature whenever the loop voltage vanishes. Such a behaviour is first illustrated on figure 12, displaying #30043 (3MW LHCD) when after almost one minute of a stationary discharge, the core electron temperature suddenly experiences a bifurcation (possibly linked to the occurrence of a very central ITB structure) towards a stationary slowly oscillating behaviour (frequency ~ 8Hz, observed for more than 2 minutes). The soft X-ray measurements definitely show that no central MHD activity can be associated to this m=0 behaviour of the plasma core, leading more likely to an interpretation in terms of an interplay between the LHCD power deposition profile and the local heat transport properties connected through the temperature and q profiles. This behaviour was confirmed on most of the vanishing loop voltage discharges, including when (centrally deposited) ICRH or ECRH power were superimposed [10]. Finally, the global energy balance is not affected by this type of core behaviour, contrary to some discharges which eventually developed a 3/2 double tearing MHD activity and a dramatic reduction of the overall performance.

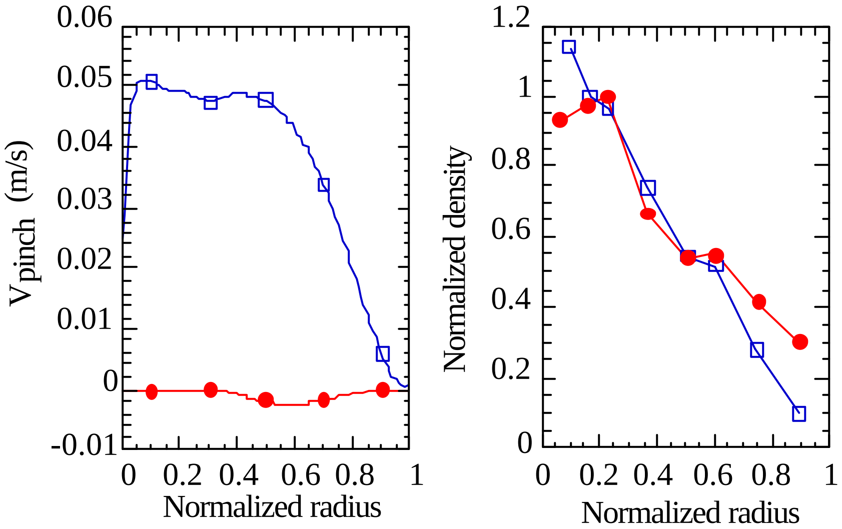

Fig. 13: Radial profile of neoclassical pinch (left) computed with NCLASS and normalized density (right), for ohmic (squares) and full LHCD phases (circles) in discharge shown in Fig. 14

In JET [25] and ASDEX [26], finely tuned gas puff experiments show a particle pinch close to the neoclassical prediction. In TCV, density profiles are more peaked than expected from the Ware pinch alone [27]. In the latest long Tore Supra plasmas, the plasma current is fully driven by Lower Hybrid waves therefore the Ware pinch vanishes everywhere, see figure 13 where the neoclassical pinch is calculated by NCLASS [28]

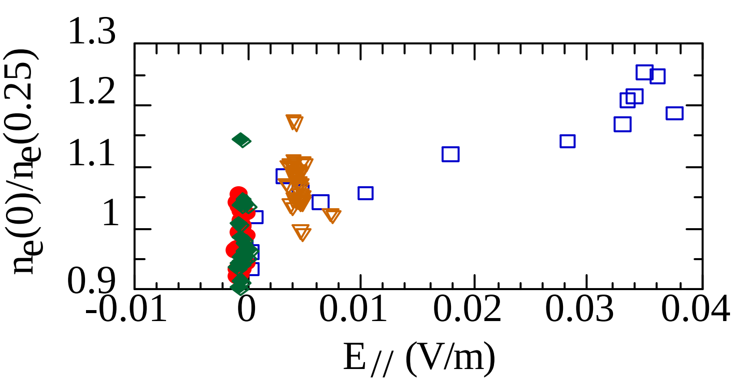

Fig. 14 : Normalized density versus toroidal electric field

for a Tore Supra plasma. However as shown on figure 13, the density profiles are still peaked. This suggests the existence of an anomalous particle pinch, as addressed by different theories [29-31]. On figure 14, we see that when the LH power is decreased, the loop voltage increases above zero, and the central density peaking is enhanced. This peaking is expected from the re-aparition of the Ware pinch.

5. Other developments for ITER

The contributions of the Euratom-CEA Association to fusion energy research also include new developments in the field of Negative Ion Beam Injection (1000 s H source and Singap acceleration to 1 MeV) [32]. A specific contribution of CEA to the R&D for the ITER magnets was the active participation to the development of high-current, high-field cable-in-conduit conductors, cooled by forced flow supercritical helium, and in particular the development of the twin-box joint concept. The successful transfer of this technology to industry is now achieved both for Nb3Sn conductors and for NbTi conductors, as demonstrated in the ITER model coil testing [33]

Finally, we note that Cadarache is the main CEA centre for power-oriented research with experimental reactors, specialized laboratories, workshops and test facilities. Work is also carried out on plant safety, waste disposal and on the protection of the environment. Cadarache is now proposed as a possible European site for ITER [34]. Figure 15 shows the integration of ITER in the landscape. The site offers a considerable infrastructure in fusion and nuclear science and technology while the ITER requirements are found after detailled studies to be met in full.

FIG. 15 : Aerial view of the integration of ITER in the landscape and Tore Supra site (~ 350x350m).

6. Final remarks

The Euratom-CEA Association has specialized for 20 years in the physics and technology of steady state operation of tokamaks. Few research groups have taken the challenge of developing this difficult technology despite the obvious need of such studies for the construction of ITER. The recent upgrade of Tore Supra has allowed to operate in unchartered territory. A wealth of new results are now available and require detailed analysis. It is clear that new understanding already emerges in the most important areas of industrial realization of high heat flux systems, of energy and particle balance, on the challenging aspect of hydrogen inventory and on new intriguing physics which appear when the inductive drive vanishes. The Association has also prepared the case for construction of ITER in Cadarache with the view of an attractive scientific and technical infrastructure for the benefit of ITER partners.

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