

Steady state density control in Tore Supra long discharges

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1-Introduction

Particle control is a crucial point for next step machines, in particular in terms of He exhaust, impurity core plasma contamination and tritium wall retention. With its ability to pursue long discharges (> 200 s), Tore Supra offers a unique opportunity to study these issues in steady state, with a focus on long time scale phenomena, such as wall deuterium retention, or carbon erosion and redeposition. In previous long pulse experiments, an uncontrolled plasma density increase was observed after about 1 minute, which was attributed to outgassing from uncooled components, located far from the plasma and slowly heated by radiation [1]. In the new CIEL configuration of Tore Supra, where the whole vacuum vessel is actively cooled (with a cooling loop at 120°C), density control has been demonstrated for durations over 4 minutes. This paper presents the results obtained during these long discharges in terms of particle balance and wall retention.

2-Tore Supra long discharges

In Tore Supra long pulse experiments, the current is provided by lower hybrid (LH) current drive. These discharges are restricted to low current ($I_p = 0.5$ MA) and low density ($f_{\text{GW}} = 0.6$) in order to sustain non inductively the current ($V_{\text{loop}} \sim 0$) with a limited amount of LH power (3 MW). As a consequence, the edge temperature is rather hot (in the range $T_e = 100$ eV at the last closed flux surface). This scenario allowed to reach a record of pulse duration of 4 min 25 s and to couple 0.75 GJ of energy to the plasma. The injected gas is feed back controlled to maintain the target density ($\langle n_e \rangle = 1.5 \cdot 10^{19} \text{ m}^{-3}$). After a first phase (roughly 50 s) where it slowly decreases until the target density is reached, it is stationary (around $1 \text{ Pa m}^3 \text{ s}^{-1}$) all along the discharge. It depends only on the level of power coupled to the plasma (when some of the LH power is lost, it decreases to compensate a higher particle confinement time). Particle pumping is ensured by neutralisers located below the main plasma facing component, the toroidal pump limiter (TPL), which collects the plasma outflux and directs it to turbo-molecular pumps.

3 - Particle balance

Particle balance has been performed on these shots using the following equation :

$N_{\text{wall}} = \int \Phi_{\text{inj}} dt - \int \Phi_{\text{pump}} dt - N_p$ where N_{wall} is the wall inventory, Φ_{inj} the injected particle flux, Φ_{pump} the extracted flux by the TPL and the vessel pumps and N_p the plasma particle content. Typical results for a long discharge are shown in Figure 1. At the end of the discharge, 40-50 % of the injected particles have been extracted by the pumping system while the remaining 60-50 % are trapped in the vessel, leading to a wall inventory of 6.3×10^{22} particles in the case shown in Figure 1. This corresponds to a retention rate of $2.5 \times 10^{20} \text{ D s}^{-1}$ or $0.8 \text{ mg of D s}^{-1}$, which does not show any sign of saturation, even after more than 4 minutes of discharge.

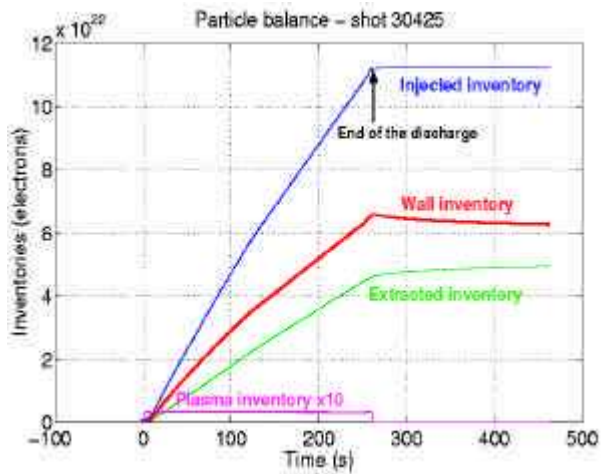


Figure 1 : Typical particle inventory for a long pulse experiment in Tore Supra.

Two main mechanisms can be invoked to explain this large experimental retention. The first is the direct deuterium implantation in zones in strong interaction with the plasma ($\sim 3.5 \text{ m}^2$ on the TPL surface, see Figure 2, where alternating plasma loaded zones and shadowed zones due to the magnetic field ripple are shown). The maximum D concentration expected for incident particles hitting the TPL with energies below 1 keV is $2 \times 10^{17} \text{ D/cm}^2$ [2], leading to a capacity of 7×10^{21} particles, far below the experimental wall retention.

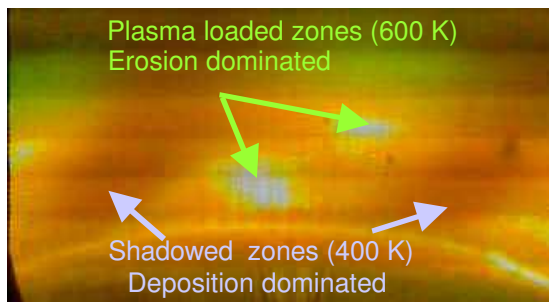


Figure 2 : Top view of recycling on the TPL in visible light (CCD camera). Bright zones : plasma loaded zones, dark zones : shadowed zones.

Moreover, the saturation of this area is estimated to take place in $\sim 30 \text{ s}$ while the experimental data do not show any sign of saturation after 260 s. Diffusion of deuterium in the bulk carbon could enhance this reservoir capacity. However,

preliminary rough estimates with the available diffusion data of deuterium in carbon seem to indicate that this effect is rather small (diffusion of $10 \text{ \AA}$ after 260 s for a diffusion coefficient $D = 10^{-16} \text{ cm}^2 \text{ s}^{-1}$ at 600 K compared to implantation depth in the $100 \text{ \AA}$ range [2]). However, this point should be further investigated as previous studies in Tore Supra have evidenced possibly larger values of D [3]. The second mechanism is codeposition of deuterium with carbon in the shadowed areas shielded from the plasma particle flux (see Figure 2), after chemical erosion and formation of C_xD_y radicals sticking to the walls. This effect, which does not saturate, is thought to be the main responsible for the continuous wall deuterium inventory build up during long discharges. Indeed, numerous carbon deposits have been identified after inspection of the machine. Thin deposited films have been

localised on surface and on the lateral sides of the tiles of the TPL. These deposits are also evidenced by IR imaging of the TPL, where they appear gradually as hotter zones. A thick deposited layer ($800\text{ }\mu\text{m}$, growth rate estimated around 20 nm s^{-1}) has been found on the neutralisers located below the TPL [4]. Dust and flakes have been found on the TPL surface and its surroundings, with dust mainly concentrated in the transition region between the shadowed and the loaded areas shown in Figure 2. It is postulated that when the deposited layers get thick enough, this leads to flaking and dust production. Modelling of the carbon erosion, transport and redeposition is currently underway in order to estimate the deuterium retention associated with these processes [5]. Analysis of the deuterium content of various deposits and flakes has also been undertaken.

4 – Reducing the wall inventory

In JET long H mode discharges recently performed with a 16 s flat top, the fraction of the injected gas puff going into the wall is similar to the Tore Supra case (from 50 to 60 %, increasing with the gas puff rate) [6]. As the gas puff rate is much stronger in JET, this leads to a significant deuterium retention rate (from 22 mg of D s^{-1} for a $25\text{ Pam}^3\text{s}^{-1}$ gas puff up to $167\text{ mg of D s}^{-1}$ for $150\text{ Pam}^3\text{s}^{-1}$). Present predictions for ITER indicate a tritium (T) retention of 1 to 4 g for a reference 400 s pulse [7]. This would allow for ~ 100 to 350 shots before reaching the T in vessel inventory safety limit of 360 g. However, validation of the code package used for the ITER studies against experimental data is still underway (when applied to the JET DTE1 campaign, it tends to underestimate the T retention [7]). A simple extrapolation of the JET long discharge results for a $50\text{ Pam}^3\text{s}^{-1}$ injection (retention of 50 mg of D s^{-1}) to an ITER case, where the gas puff rate is expected to range between 50 and $100\text{ Pam}^3\text{s}^{-1}$ (and even higher in the start up density rise phase) would lead to a tritium retention of 10 g T for a 400 s pulse, assuming that the wall inventory is half tritium and half deuterium. This illustrates the need for developing tools to reduce the wall retention. In Tore Supra, two methods have been tested. First, the role of active pumping has been investigated. Two similar discharges have been performed, one with the pumping activated, one without. The resulting wall inventory is the same, as can be seen on Figure 3, while the gas injection necessary to maintain the density is simply increased by the exhausted flux value when the pumping is

activated. Therefore, in Tore Supra, active pumping has no effect on wall retention and is simply an offset on the gas injection needed to maintain a given density. Second, the role of

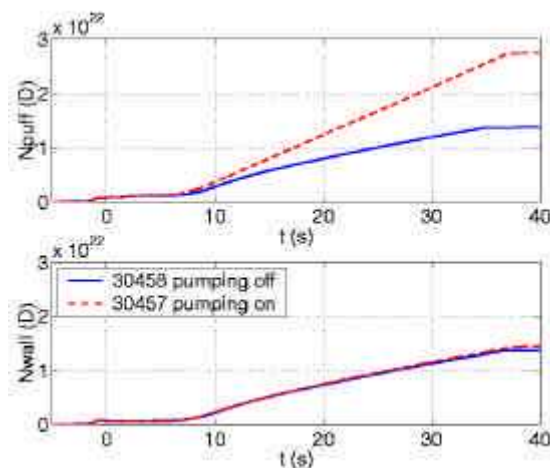


Figure 3 : Comparison of 2 similar discharges with (dotted red) and without (blue) active pumping. Top : injected particles inventory, Bottom : wall inventory

fuelling has been investigated. Tore Supra is equipped with a supersonic pulsed gas injection

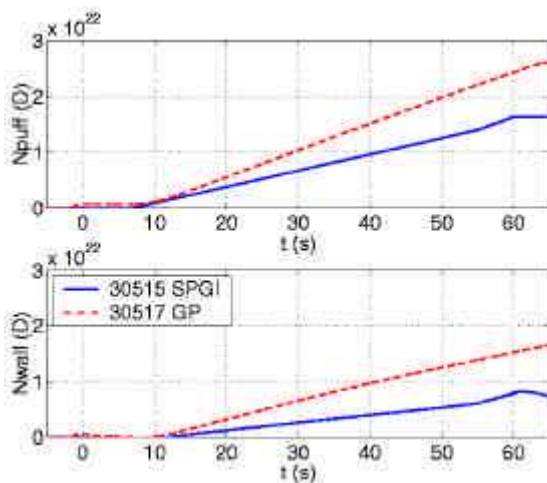


Figure 4 : Comparison of 2 similar discharges fuelled by gas puff (dotted red) and supersonic injection (blue). Top : injected particles inventory, Bottom : wall inventory

(SPGI) system, which allows to send very short and intense gas puffs ($200 \text{ Pam}^3\text{s}^{-1}$ within 2 ms). This system has shown an improved fuelling efficiency of a factor 2-3 with respect to conventional gas puff (GP) [8]. A preliminary experiment has been performed with two similar long discharges, the first fuelled with GP, the second with SPGI. Feed back control of the density with SPGI was proven satisfactory, with the injector working at 1 Hz. As can be seen on Figure 4, gas injection needed to maintain the density is reduced by 30% with SPGI, due to its improved fuelling efficiency. The

resulting wall inventory is reduced by 50%, which might be due to a change in the plasma edge properties, as SPGI leads to a strong edge plasma cooling and a short semi-detached phase (~ 20 ms) following each gas pulse [8].

5 – Summary and prospects

Long pulse experiments in Tore Supra exhibit a large wall retention (up to 60 % of the injected gas puff), showing no sign of saturation after 4 minutes of discharge. Codeposition of deuterium with carbon in plasma shadowed areas is thought to be the main mechanism. Deposited carbon layers have been observed at several locations in the machine. In JET as in Tore Supra, the wall retention rate is shown to be correlated with the gas puff rate. Therefore, in next step machines such as ITER where tritium inventory is limited for safety reasons, gas puff should not be considered as a freely adjustable parameter to compensate for the fuel throughput necessary to ensure He exhaust, as it has a price to pay in terms of wall retention. Fuelling optimisation, using methods with improved fuelling efficiency (pellets and/or supersonic injection), as well as in situ detritiation techniques should be further developed.

References :

- [1] : C. Grisolia et al., J. Nucl. Mater. 266-269 (1999) 146
- [2] : K. L. Wilson et al., in “Atomic and Plasma Material interaction data for fusion”, Supplement to Nuclear Fusion, IAEA (1991) volume 1, p 31
- [3] : C. Grisolia et al., J. Nucl. Mater. 196-198 (1992) 281
- [4] : E. Delchambre et al., these proceedings
- [5] : J. Hogan et al., these proceedings.
- [6] : T. Loarer et al, these proceedings
- [7] : G. Federici et al., J. Nucl. Mater. 313-316 (2003) 11
- [8] : B. Pégourié et al., J. Nucl. Mater. 313-316 (2003) 539