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Particle control in high power, high density long pulses on Tore Supra

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Introduction

Long pulse operation, and the related issues such as non inductive current drive, particle control and power exhaust, is a crucial point to investigate for next step machines. On the tokamak Tore Supra, equipped with superconducting magnets and actively cooled plasma facing components, 6 minutes discharges, coupling 1 GJ of energy to the plasma, have been obtained [1]. In these discharges, the plasma current is driven by LH wave power while the loop voltage is maintained constant at zero (bootstrap fraction ~10%). Typical characteristics are: B_T = 3.4 T, I_p = 0.5 MA, LHCD = 3 MW, and line integrated density nl = 2.6×10^{19} m^{-2}. The plasma density and impurity level (Z_{eff}~2) are perfectly controlled all along the discharge, the main limitation coming from the LH power source. Particle balance studies have been carried out taking benefit from the long duration of the pulse, current breakdown, ramp-up and ramp-down phases playing a negligible role in the balance. The figure 1 shows the particle flux and the particle inventories evolution measured for one GJ discharge.

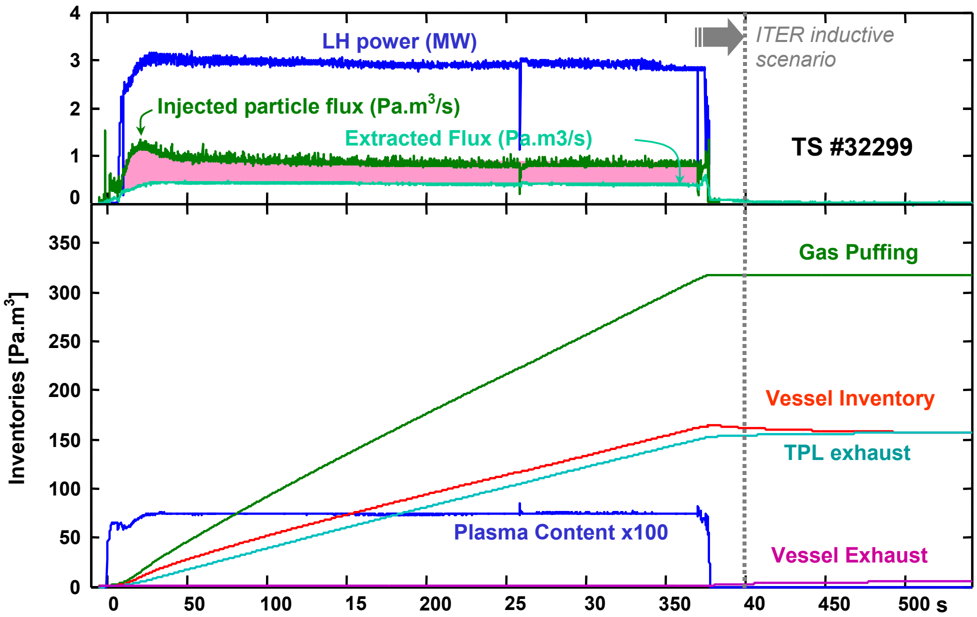

Figure 1: Particle balance for the GJ discharge TS#32299. Upper panel: time evolution of the LHCD power, of the flux of injected deuterium (gas puff) and the extracted flux (Toroidal Pumped Limiter [TPL] + vessel exhaust). The in-vessel retention is shadowed. Lower panel: time evolution of the different inventories.

After ~60 s, the particle injection rate and the particle exhaust rate are constant. Therefore the retention rate, defined as the difference between these two quantities, is also constant at about 3 10^{20} D/s. Moreover, three consecutive discharges with same parameters, accounting for more than 15 minutes of plasma, exhibit the same retention rate evolution indicating that there is a weak influence of previous discharges and of pumping between discharges [2].

High power, high density long pulse operation

The GJ discharges were performed at low density and with LHCD only. A new scenario has been recently developed combining ICRH and LHCD up to a total power of 10 MW at higher density (up to 90% n_{GW}), limited in time to 60 s by the capability of the ICRH heating systems. Figure 2 shows the time evolution of the main parameters of one ICRH+LHCD discharge (500 MJ of injected/extracted energy). The fraction of non inductive current is close to 80%, loop voltage ~0.05 V and bootstrap fraction ~20% [3].

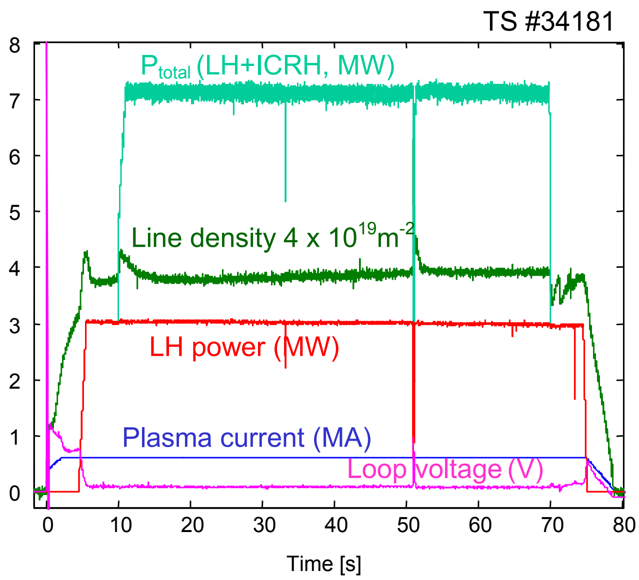

Figure 2: Main parameters for TS#34181.

The density is maintained by a feedback control on the gas injection system and do not exhibit any uncontrolled excursions. The radiated power fraction is stable and remains around 25% all along the discharges (Z_{eff}~2.5).

During combination of ICRH and LHCD, the IR imaging protection system reveals lots of hot spots on the plasma facing components. These localized heat loads are attributed mainly to the fast particles which are accelerated in the near field generated by the IC and LH launchers [4]. Therefore, careful choices of the magnetic field and of the respective launcher positions were necessary in order to safely increase the power and the density. However, due to these inhomogeneous heat loads, even after 1 minute of plasma, the surface temperature in

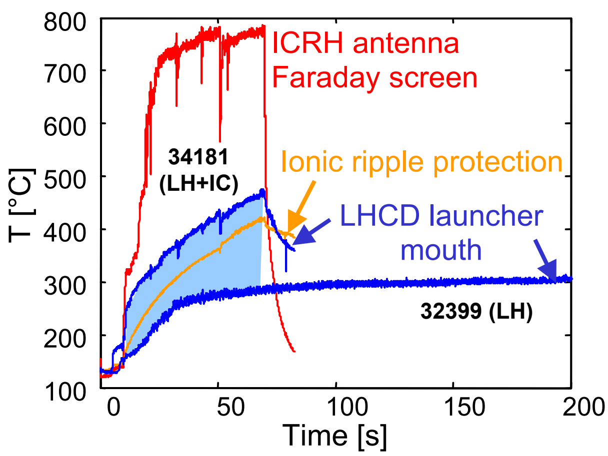

Figure 3: time evolution of the surface temperature of several plasma facing components measured by infrared imaging.

some areas has not reached a steady-state value as illustrated in figure 3. As the wall outgassing is dependent on wall temperature an extended conditioning of the component in a given scenario is required to access the retention rate. The figure 4 shows the injected and extracted fluxes during two consecutive discharges at 10 MW of additional power. In both cases, the gas injection rate is strongly decreased at the application of LH power (t~4 s) and later on at the application of IC power (t~6 s) mainly because of the transient outgassing induced by the temperature rise of the PFC. In the full power phase (t>8 s), a net wall outgassing (negative retention rate) is observed in the first discharge while a net wall retention is observed in the second one, the gas injection rate having increased due to the conditioning of the components.

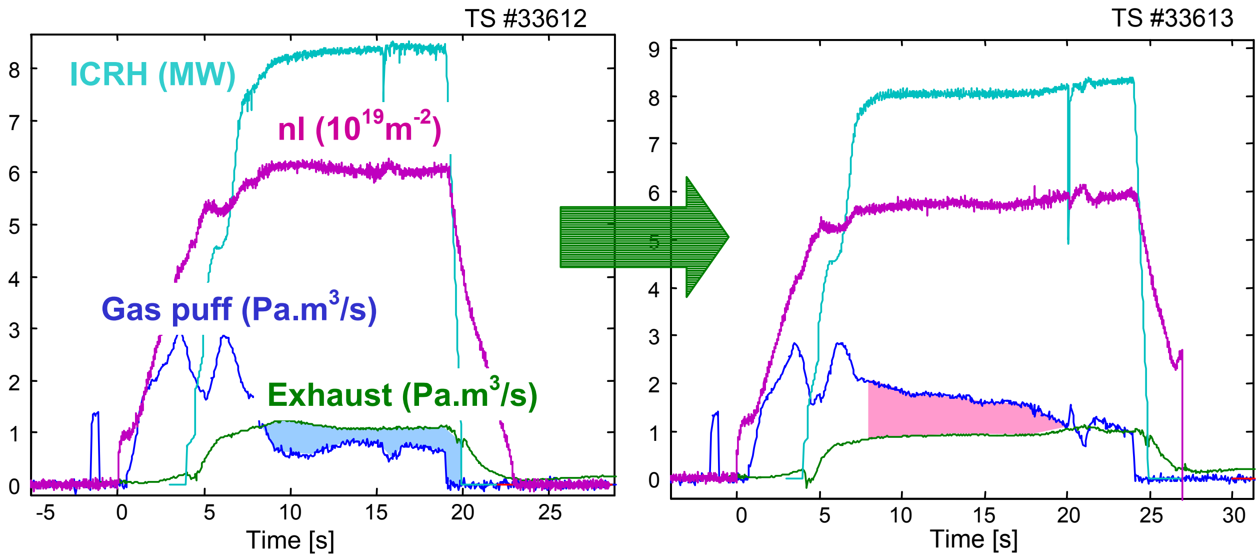

Figure 4: particle balance for two consecutive high power, high density discharges. In the left panel discharge (TS#33612), there is a net wall outgassing between 10 and 20s while in the right panel one (TS#33613), there is a net wall retention.

Particle balance

In comparison with the low power low density long duration discharges (GJ LHCD only scenario), the gas injection rate necessary to maintain the plasma density in the high power high density scenarios (LHCD+ICRH) is substantially increased (up to a factor 3). Visible spectroscopy of D_α and CII line brightness indicates a deuterium flux of ~2 10^{22} D/s and carbon flux of ~3.5 10^{20} C/s to be compared to respectively 1 10^{22} D/s and 1.5 10^{20} C/s [5]. The edge electron temperature and density measured by a reciprocating probes are also different (as shown in figure 5), confirming as expected a higher recycling regime. On the other hand, particle balance analysis based on pressure measurements shows that the absolute

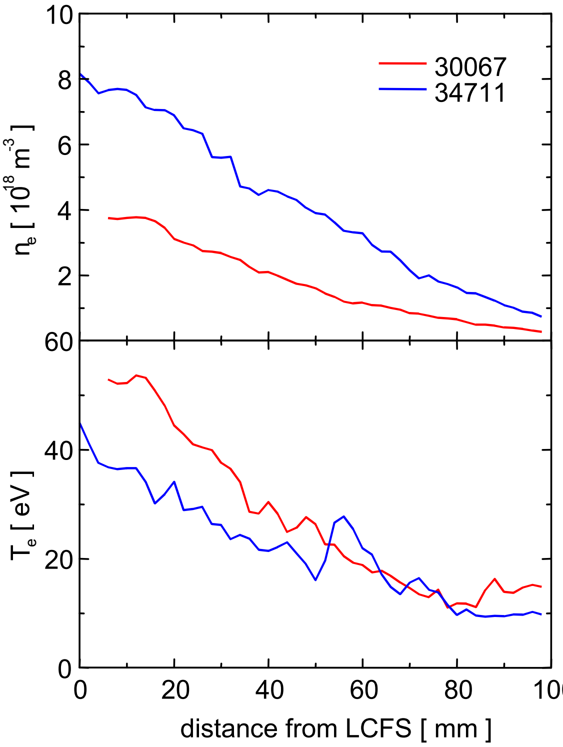

Figure 5: SOL electron density (top panel) and temperature (bottom panel) measured by fast scan reciprocating probe for TS#30067: nl=2.6 $10^{19}m^{-2}$, LHCD=3MW and TS#34711: nl=4 $10^{19}m^{-2}$, LHCD/ICRH=3/2MW.

LHCD power (<3 MW) indicates a lower retention rate. Therefore, long pulse discharges with different LHCD power have been analysed in terms of deuterium retention. Thus, the curve showed in figure 6 has been obtained indicating an important dependence of the retention rate on the LHCD power. A possible explanation could be an enhancement of the retention rate due to the modification of the SOL (higher T_i?) induced by the supra-thermal electrons generated in front of the LH grill.

in vessel retention rate, computed after >30 s of plasma, is roughly equivalent in both scenarios (~3 10^{20}D/s), whatever the ICRH power (from 0 to 4 MW) and whatever the plasma density (nl from 2.5 to 4 10^{19} m^{-2}).

Discussion

This result could indicate that the retention mechanisms could be dominated by wall processes such as diffusion in carbon porosities rather than plasma processes such as co-deposition, dependent on edge conditions. Besides, analysis of carbon deposits originating from different locations inside the vessel reveals relatively low deuterium content, unable to account for the large deuterium in-vessel retention worked out from particle balance analysis [2].

However, discharges performed with lower

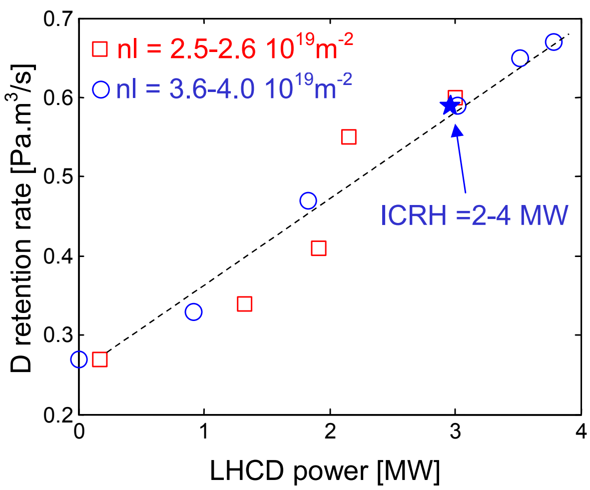

Figure 6: D retention rate vs LHCD power.

[1] D. van Houtte et al., Nuclear Fusion 44 (2004), L11-L15
[2] E. Tsitrone et al., 20th IAEA FEC, Vilamoura, Portugal (2004)
[3] G.T. Hoang , 16th RF Conf., Park City, Utah, USA (2005)
[4] L. Colas et al., 16th RF Conf., Park City, Utah, USA (2005)
[5] E. Dufour et al., this conference.