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Pellet fuelling experiments above the Greenwald density in Tore Supra

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1. Introduction

Next step tokamaks will need to operate at high densities to maximise the fusion power. Reaching high densities without degrading the confinement remains today a challenge, in particular when using gas puffing. Pellet injection has already demonstrated its capacity to reach, at least transiently, densities above the Greenwald density (n_G).

To study the behaviour of high density discharges during longer durations, high density pellet fuelled discharges have been achieved on Tore Supra using the pellet injector designed for steady state fuelling installed on Tore Supra in 2003[1].

2. High density discharges

High densities have been obtained in moderately ICR heated discharges (toroidal field 3.8T, Plasma current 0.6MA, ICRH power up to 3MW). The pellet injection parameters were 2.5 - 3.5 10^{20} atoms per pellet injected at 150 –200 m/s. They have been launched from the Low Field Side (LFS), Vertically (VHFS), and from the High Field Side (HFS) of the torus for a comparison of the different configurations. In order to investigate the behaviour of the plasma close to the Greenwald density, the density was slowly ramped-up from 70% to 150% of the n_G limit using only pellets to fuel the discharge during the whole density ramp (the pellet injection was controlled by a feedback loop on the density). A typical discharge achieved in the LFS injection configuration is illustrated on Fig.1 showing that densities significantly above n_G have been achieved: more than 145% of n_G transiently just after the last pellet injection and 120% of n_G after relaxation. An important feature of these shots is that during 1.8 s (corresponding to 24 confinement times in these conditions), the density was above the n_G limit without any

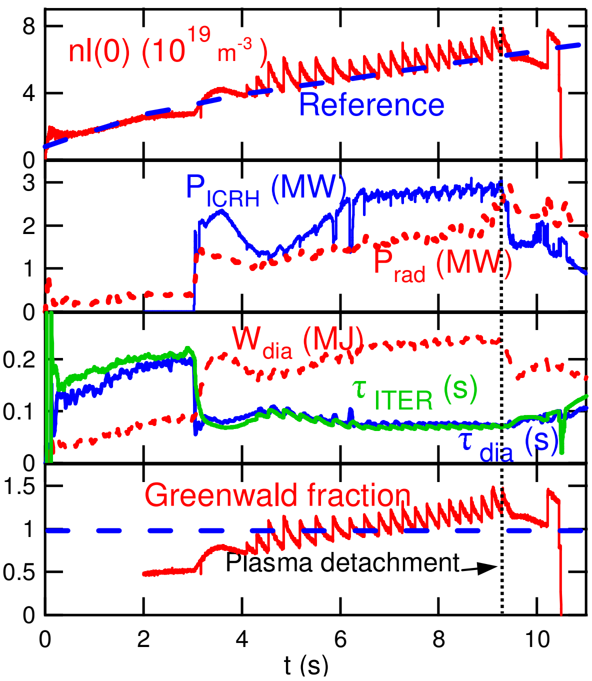

Fig.1: plasma and pellet parameters for #TS34899 (LFS) pulse. From top to bottom: plasma central line density and reference – ICRH and radiative powers – diamagnetic energy content, confinement time and ITER L-mode scaling law – Greenwald fraction

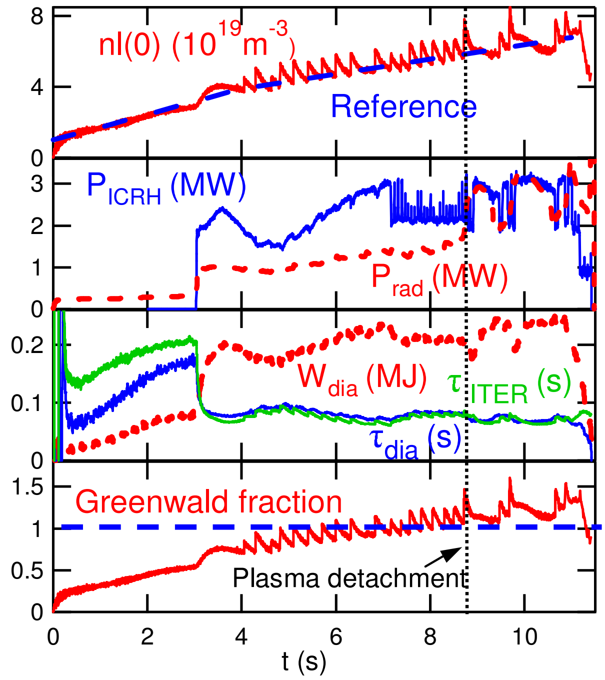

Fig.2: plasma and pellet parameters for #TS34902 (VHFS) pulse. From top to bottom: plasma central line density and reference – ICRH and radiative powers – diamagnetic energy content, confinement time and ITER L-mode scaling law – Greenwald fraction

significant MHD activity in the plasma. This shot ended with a disruption at 11.2 s following a plasma detachment at 9.3 s. The reason is a slow increase of the radiative losses during the density ramp, which could not be compensated by the limited ICRH power available.

No confinement loss is observed during high density operation with respect to the ITER L-mode confinement law [2], which is usually followed by the experimental confinement time in Tore Supra ($\tau_{ITER\ L\text{-}mode}\ \alpha\ \bar{n}_e^{0.4}\ P_{tot}^{-0.73}$), even above n_G. The confinement time remains constant despite the increase of the average line density ($\tau\ \alpha\ \bar{n}_e^{0.4}$) because of increasing ICRH power ($\tau\ \alpha\ P_{tot}^{-0.73}$). A similar discharge was achieved using VHFS injection (Fig.2) with similar results: 106% of n_G after relaxation and more than 135% transiently just after the last pellet injection. The phase above n_G lasted 0.65 s due to a smaller available ICRH power leading to a earlier plasma detachment (at 8.71 s). During the high density phase, the confinement time behaviour follows the ITER L-mode scaling law as well. HFS injection was also tested on this scenario but, due to the higher pellet erosion, it appeared that small pellets were not adequate to reach such high densities (cf 4.1).

3. Profiles evolution

When the density is increased by gas puffing, the profile flattens at high densities as shown on Fig.3 on which the scaling law giving the edge density as a function of volume average density $<n_e>$ is plotted ($n_{e\ LCFS}\ \alpha <n_e>^2$) [3]. Fig.3 shows that this trend is no more valid for pellet fuelled discharges (the edge density has been measured after the density profile relaxation following each pellet injection).

By analysing the data from a X-mode reflectometer, a linear dependence between edge density and $<n_e>$ after density profile relaxation can be observed.

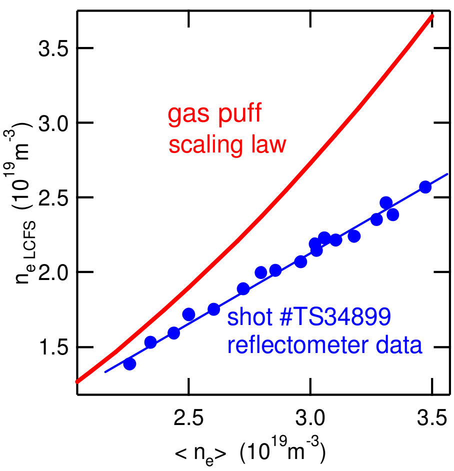

Fig.3: edge density as a function of volume average density during shot #TS34899 and for the experimental Tore Supra scaling law [3]

This proportionality combined with the evolution of the line integrated densities given by a 5 chords IR interferometer are consistent with a homogeneous

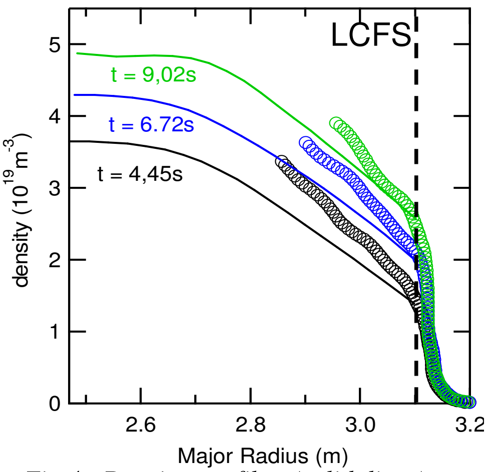

Fig.4: Density profiles (solid lines) at different shot times after pellet relaxation extrapolated from interferometer and reflectometer data (circles)

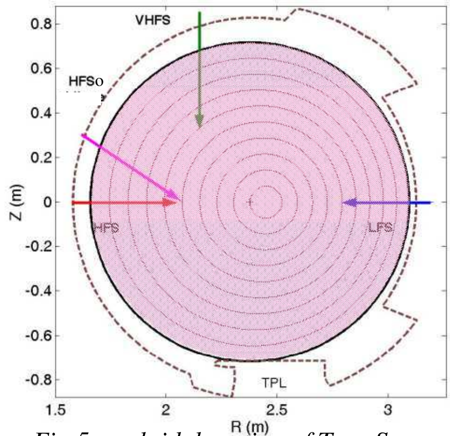

Fig.5 : poloidal section of Tore Supra showing the different pellet injection configurations

density increase of the whole profile: the shape of the density profile during high density pellet fuelled discharges appears to remain constant during the whole density ramp as shown on Fig.4 for different times of shot #TS34899 (LFS). These profiles were determined by reconstruction of the line integrated densities given by interferometry using the edge density measured by reflectometry.

The difference between gas puff and pellet injection at high densities could be explained by the fact that, at such densities, the core fuelling from the pellet ablation becomes significant compared to the edge fuelling (from the first wall in these expriments) which is dominant at low densities and for gas puff experiments.

4. Comparison between the different pellet injection configurations

4.1 Experimental results

The high density scenario described in section 2 was applied using 3 injection configurations shown on Fig.5: LFS, VHFS and the oblique High Field Side injection (HFSo). Same pellet parameters (at the exit of the injector) were used for all the configurations: 2.5 - 3.5 10^{20} atoms per pellet injected at 150 – 200 m/s. The deepest pellet penetrations are obtained using LFS injection thanks to the larger mass of the injected pellets. Indeed the LFS injection is the only one allowing a free flight trajectory without any pellet erosion (20% for VHFS and about 40% for HFSo at this speed). NGS scaling law taking into account this erosion allowed to extrapolate a good evaluation of experimental penetrations observed for VHFS and HFSo from LFS experimental penetration. No "pre-cooling" effect of the ablated material drifting in front of the pellet for HFS injection is observed. It is in agreement with the mean effective deposition profile which shows that there is a very moderate **∇B**-drift toward LFS in front of the pellet for HFSo injection (it is more favourable than LFS because the drift is important for the LFS injections). The results are summarised in table 1.

injection configuration	LFS	VHFS	HFSo
mean penetration normalized radius	0.44 *±0.01*	0.47 *±0.02*	0.56 *±0.03*
calculated penetration normalized radius		0.48 *±0.01*	0.53 *±0.01*
mean deposition normalized radius	0.55	0.51	0.54

Table 1: mean experimental penetration normalised radius, calculated penetration normalised radius, experimental deposition radius as a function of injection configuration for high density discharges

4.2 Simulation

The relatively low **∇B**-drift observed when injecting pellets from the HFS (VHFS and HFSo configurations) is in agreement with simulations using the pellet ablation code HPI (fig.6) [4]. The results show that a typical pellet injected from HFS in a high density discharge at relatively low T_e experiences a very low **∇B**-drift compared to the LFS case (Fig.6).

The matter in mainly deposited around the maximum ablation radius for the HFS case. The difference between LFS and HFS drift could be explained by the electron pressure gradient. It is favourable to the **∇B**-drift when pellets are injected from the LFS and opposed to it when pellets are injected from the HFS.

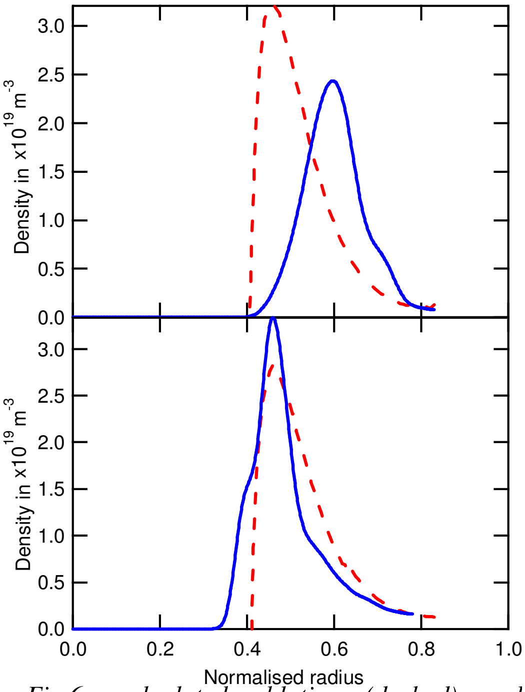

Fig.6: calculated ablation (dashed) and deposition (solid) profiles for a typical pellet injected at 220 m/s in high density discharge from LFS (top) and HFS (bottom)

This behaviour is different from the one observed on different experiments carried out on ASDEX Upgrade which show an important drift for HFS injection [5]. A hypothesis would be that the important additional power injected during these experiments would have increased the drift.

5. Conclusion

Recent high density experiments carried out on Tore Supra showed that operations with densities above the Greenwald density are possible without any MHD instability and without degradation of the confinement time (with respect to the ITER L-mod scaling law) for a duration well above the energy confinement time. The pellet fuelling at high densities allows lower edge densities and a constant density profile shape when density is the increased.

They showed also that in such cold plasma conditions, the **∇B**-drift is much smaller for the pellets injected from the HFS than for the LFS ones. No penetration improvement is observed for pellets injected from the HFS compared to LFS.

For future experiments, it will be possible to investigate higher ICR power allowing :

i. To maintain the density constant above n_G for several seconds in order to investigate if the edge density and the confinement remains constant for steady state discharges.
ii. To investigate if the **∇B**-drift increases with the injected power.

References:

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