# Fuelling methods comparison above Greenwald density in Tore Supra

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## 1. Introduction

The choice of a fuelling scheme for reactor class plasmas is one of the issues that ITER must deal with. Former and current tokamaks usually operate with gas puff fuelling because of its reliability. But it has been proven that the central line average electron density is limited to values around the Greenwald density ($n_eGr$) using this technique.

Pellet injection fuelling is able to fuel plasmas at higher densities without energy confinement losses [1-2]. In order to understand the plasma behaviour at high $n_eGr$ fractions, similar discharges using different fuelling methods have been performed on Tore Supra.

## 2. Comparison discharges

The comparison discharges have the same scenario: circular plasma (R = 2.38 m and a=0.72 m), moderate ICRH power (2 to 4 MW), low plasma current (0.6 MA) and a density ramp-up from 0.7 to 1.2 $n_eGr$ or a density plateau at 1.2$n_G$. This scenario was applied using gas puffing and pellet injection (figure 1). Pellet injection allowed reaching the highest $n_eGr$ fraction (up to 1.2 $n_eGr$) without any confinement loss with respect to the ITER L-mode scaling law $\tau_{ITER}$ (figure 2). It allowed operating above $n_eGr$ during more than 6 s (100 confinement times) at a stable density value thanks to a feedback control of the density.

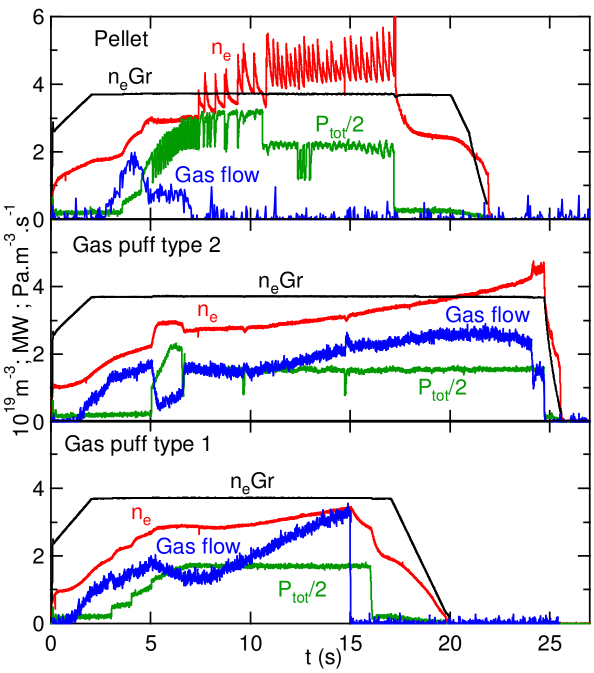


*Fig.1: plasma parameters for #TS37133 (pellet), #TS37307 (Gas puff type 2), and #TS38848 (gas puff type 1): central line average density ($n_e$), Greenwald density ($n_eGr$), ICRH power ($P_{tot}$) and injected gas flow*

The gas puff discharges showed 2 different behaviours.

<u>Type 1</u>: during the shot #TS38848 (representative of the general case), it was not possible to reach $n_eGr$ before the programmed end of the shot despite a high fuelling rate (3.4 Pa.m$^3$.s$^{-1}$). As shown on figure 2, the confinement followed $\tau_{ITER}$ dependencies until the density reached 0.85

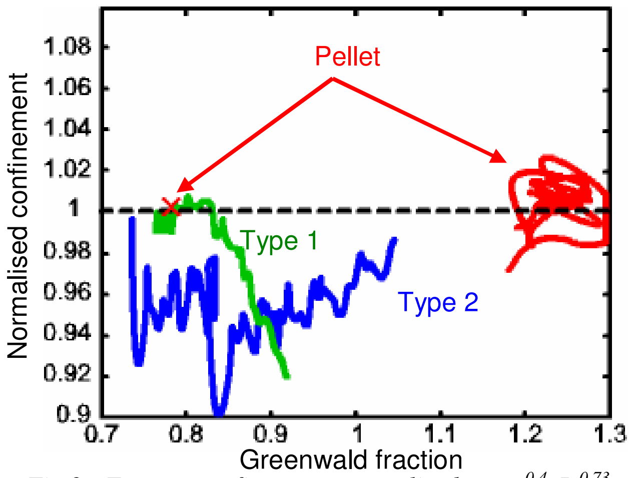


*Fig.2: Energy confinement normalised to $n_e^{0.4}$ $P^{-0.73}$ (changing parameters of the ITER L scaling in these shots) as a function of the Greenwald fraction for pellet, type 1 and type 2 shots*
*NB : for the pellet shot, only the plateau is shown, the first part being too noisy due to ICRH fluctuations*

$n_e$Gr. At higher densities, the confinement started to degrade.

Type 2: during the shot #TS37307, the gas injection enabled to reach 1.1 $n_e$Gr with a lower fuelling rate (2.5 $Pa.m^3.s^{-1}$) than for #TS38848. During this ramp-up, despite a slight degradation at the beginning of the density increase, the confinement was following the ITER scaling law.

At high densities, the confinement appears to strongly depend on the fuelling method. This behaviour can be related to the evolution of the density profile shape during the density evolution as discussed in the following section.

## 3. Density profile evolution

The density profile evolution is very different for the gas and pellet fuelled shots. The behaviour is the same at low $n_e$Gr fractions but starts to change at higher densities: the evolution of the density profile for the pellet fuelled shot (after relaxation, just before a new injection) and the type 2 gas puff fuelled shot is quite similar: the local densities on the whole profile increase linearly with the volume average density as shown on figure 3 for the edge density. The type 1 gas case mentioned above must be distinguished: the density profile dramatically broadens when the average density increases as shown on figure 3 (the edge density is much higher than for the pellet case for the same volume average density). At high $n_e$Gr fraction (>80%), the density profile seems to lose its poloidal symmetry. Indeed the reflectometer data (measured in the torus mid-plane) detect a hollow density profile. But the IR interferometry data (which were compatible with reflectometry data at lower densities) detect a much lower edge density compatible with a monotonic profile (figure 4). The difference is that the edge interferometer chord does not "see" the mid-plane of the plasma. This incoherence can then be explained by the loss of the poloidal

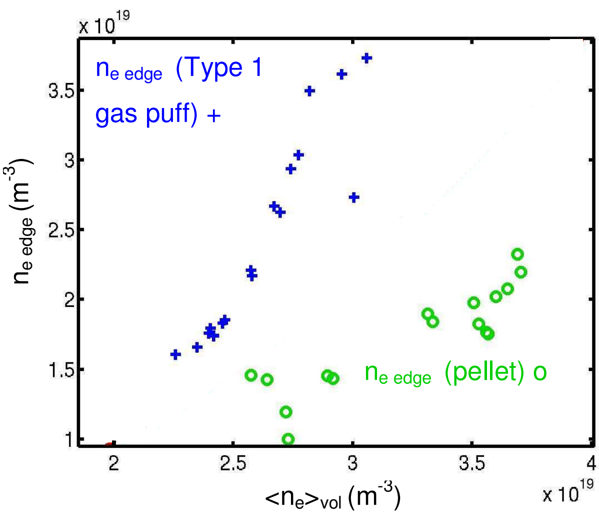


*Fig.3: edge density (reflectometry data) as a function of the volume average density*

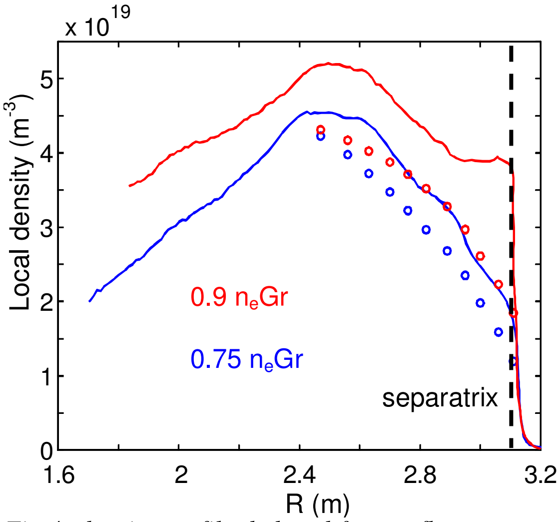


*Fig.4: density profile deduced from reflectometry (curve) and interferometry (circles) data for 0.75 and 0.9 $n_e$Gr during the type 1 shot*
*NB : difficulties to deduce the real shape of the density "hole" using reflectometry but its existence is detected*

symmetry with the appearance of a dense plasma bubble close to the edge in the horizontal plane. This hypothesis is consistent with the local radiation power deduced from the bolometric tomography evolution (figure 5). The location of the emission areas is close to the 2 gas puff valves used during this shot. At high $n_e$Gr fractions, gas fuelling seems to lead to an accumulation of matter at the edge, developing a non homogeneous edge over-density.

An analysis of the effective diffusion coefficient (D) and pinch velocity (v) has been performed (before the poloidal symmetry was lost) in order to discuss the density profile relative evolutions in term of matter transport modification.

## 4. Transport analysis

In order to determine the effective transport coefficients, different codes were used: the 1D source code JONAS [4] in order to evaluate the recycling (and gas injection) source at the edge then the transport code CRONOS [3] to estimate D and v. JONAS computes the probability for a particle to reach a certain area of the plasma. To determine the effective source, the results of the simulation have to be multiplied by the total number of particles going through the separatrix per second. This number was determined using the reciprocating Langmuir probes data: the saturation current was measured during movements of the Langmuir probe from the vacuum vessel wall to the separatrix. Taking into account the effective collection area of the probe, it enabled to deduce the particle flux along the trajectory of the probe. By integrating these values on the whole torus, it was possible to determine the total ion flux flowing from the Scrape-Off Layer to the limiter. This flux was then assumed equal to the neutral flux from the limiter into the plasma. Using the computed edge source and the measured density profiles, the CRONOS code allows estimating an effective v/D (figure 6) for each studied shot

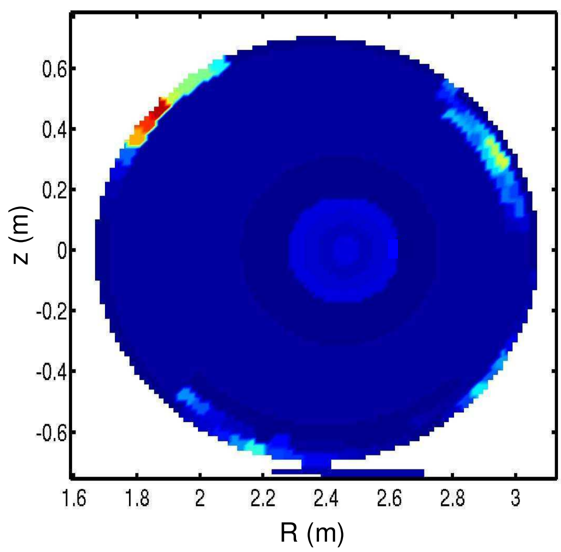


*Fig.5: Bolometric tomography (poloidal section) time evolution during the density ramp-up (from 75% to 95% of $n_G$) of shot #TS38848*

(Gas puff type 1, Gas puff type 2 and pellet case). For the pellet and type 1 shots, v/D do not evolve significantly with the density and remains at relatively low values. This is compatible with the broadening of the density profile observed in the type 1 case (figure 3): the matter injected at the edge (gas puff and recycling flux) is expelled by the diffusion. The much higher density peaking for the pellet case, despite a similar v/D value, is compatible with the core fuelling of the pellets. The results for Gas puff type 2 shot are different: v/D is much higher at the plasma edge. It implies that the matter injected at the edge can penetrate much deeper. It is consistent with the density peaking similar to the pellet case despite an edge fuelling.

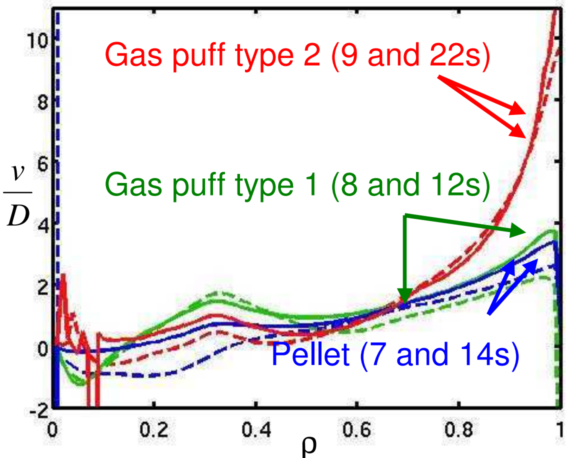


*Fig.6: ratio between v and D as a function of the normalised radius for gas puff type 1, gas puff type 2 and pellet shots*

The differences observed between type 1 and type 2 gas fuelled shots could be due to a different ICRH power deposition (a lower hydrogen minority fraction observed for the type 1 inducing a change in the $T_e/T_i$ ratio) and/or a slightly higher Zeff. A first comparison of the ITG and TEM growth rates for these two shots shows that these small differences could explain the different transport behaviour between type 1 and type 2 cases.

**5. Conclusion**

The effect of the fuelling method on plasma confinement and transport is significant at high $n_e$Gr fractions. Pellet fuelling appears to be the less disturbing fuelling method allowing the plasma to behave at high $n_e$Gr fractions as at low (similar transport, validity of the scaling laws…). It would be interesting to perform other experiments even higher densities (>1.2 $n_e$Gr) since no density limit were found so far.

Gas puff fuelling generates significant confinement degradation and poor density peaking with a poor plasma fuelling efficiency (type 1). Nevertheless it was observed that slightly different plasma parameters (H fraction, Zeff…) enable gas puff discharges (type 2) to behave similarly to pellet fuelled ones but the way to achieve such plasma conditions still need further studies. Other experiments will be required to get a better understanding of the phenomena allowing reaching high $n_e$Gr fractions using gas puffing.

**References**

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