Particle fuelling for long pulse with standard gas puff and supersonic pulsed gas injection

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Abstract: In addition to the standard gas puff and to the technically complex pellet injection, a novel intermediate method, based on the injection of a supersonic high density cloud of neutrals, has been recently implemented on the Tore Supra tokamak. Fuelling efficiency, in the 30-50% range are found while it lies in the 10-20 % range for the gas puff. It is not sensitive to the plasma density and to the additional heating. According to modelling, the increased efficiency is attributed to the very short injection duration compared to the particle confinement time and to the strong cooling of the plasma edge resulting from the massive injection of matter. A feedback loop on the frequency of the injector has been successfully implemented to control the plasma density. In long pulse experiments (>200s), wall saturation has not been reached. Gas puffing rate was typically around 1 Pa.m^{3}s^{-1} while dynamic wall retention around 0.6 Pa.m^{3}s^{-1}. Co-deposited carbon layer could trap such large amounts of gas. A discharge fuelled by supersonic pulsed gas injections exhibits lower wall retention than a gas puff fuelled discharge.

1. Introduction

Particle fuelling in ITER is found to be a difficult issue. To date only high field side pellet injection appears to meet the requirements for fuel penetration. Steady state operation of this scheme is still to be assessed. On Tore Supra, three different ways of particle fuelling are currently under investigation in the frame of steady state and long pulse operation (>200s). In addition to the standard gas puff (GP) and to the technically complex pellet injection, a novel intermediate method, the supersonic pulsed gas injection (SPGI), based on the injection of a supersonic high density cloud of neutrals, has been recently implemented. This is illustrated on Figure 1, where the same total quantity of particles is injected for the three different methods.

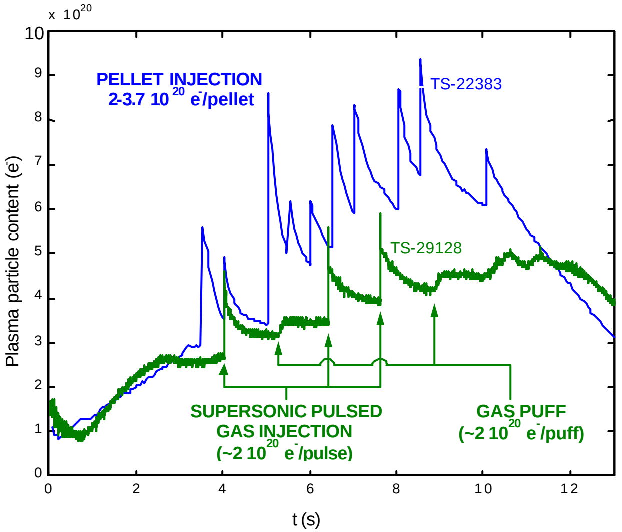

Figure 1. Comparison between the three different particle fuelling methods of Tore Supra. TS-22383: pellets (vertical injection, 456m/s); TS-29128: pulsed supersonic gas (M~5, ~10^{23}e/s) and gas puff (~10^{21}e/s).

The standard GP penetration is given by the dissociation and ionisation mean free path of the injected molecules ($\lambda_{mfp} << a$), somewhat increased by charge exchange between the incoming flux of cold neutrals and hot plasma ions. The resulting fuelling efficiency (defined as the increase in plasma particle content divided by the number of injected particles) is poor, typically around 10-20% for limiter plasma and less than 5% for divertor plasma in H-mode. Therefore, large amounts of gas are necessary to reach and maintain a high plasma density, which could be of concern for tritium inventory, due to the large wall pumping capacity. There is also concern that uncontrolled recycling in the main chamber might degrade global confinement. Pellet injection leads to very high fuelling efficiency (up to 100% on small machines) as the pellet particle deposition occurs deeper into the discharge. A beneficial ***E*⊗*B*** drift effect has also been evidenced for HFS pellet injection [1]. In addition, pellets injection peaks the density profile rising the central density above the Greenwald density potentially improving plasma performance. However this beneficial feature of core fuelling cannot be achieved in a large device like ITER. Another drawback of the method lies in the technical complexity of the system particularly for steady-state operation that requires a highly reliable repetitive pellet launcher [2].

The SPGI stands between gas puff and pellet injection. A small volume of gas at high pressure, containing about half a plasma content in particles (0.4 Pam^3), is expanded through a Laval nozzle into the plasma chamber within 1-2 ms. Compared to GP, the generated molecular supersonic beam has a higher speed and a lower divergence. First experiments on Tore Supra, with an injector located on the high field side (HFS) to benefit from a potential drift effect, as already observed with the pellet ablatant clouds, exhibits an improved fuelling efficiency compared with GP in the range of 40-50% (measured 50 ms after the injection pulse) [3]. However, according to 1D modelling, no drifts were necessary to explain the experimental data: the strong edge plasma cooling, due to the massive injection of matter, and the short injection time were identified as the main factors leading to the improved fuelling efficiency [4]. Since then, a low field side (LFS) injector has been installed on Tore Supra for comparison.

2. Analysis of the particle fuelling with supersonic pulsed gas injection

2.1 Plasma response

Observations with a CCD camera show that the injection is followed by a brief detachment phase, which lasts less than a video frame (20ms). The time evolution of the five interferometer chords is plotted on figure 2 with D_α line intensity measured on the main plasma-facing component, the toroidal pumped limiter (TPL), as well as reciprocating Langmuir probe (RLP) data. The injection phase lasting about 2 ms for the HFS injection corresponds to the first step of the interferometers chords. The second step can be attributed to a MARFE-like structure which crosses the interferometer chords from the HFS to the LFS

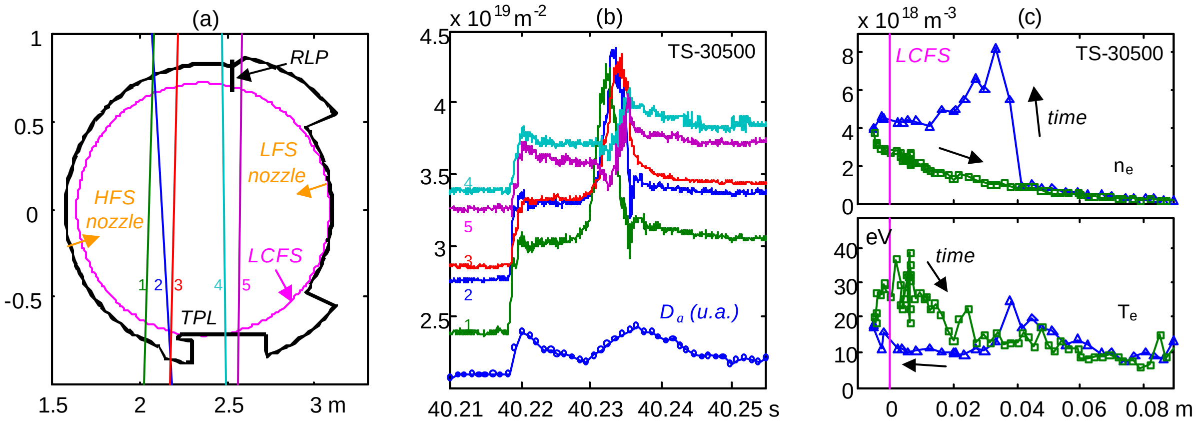

Figure 2: (a) Experimental set up showing the HFS and LFS nozzle locations, the five chords for the line integrated density measurements and the reciprocating probe trajectory; (b) Time evolution of the line integrated density and D_a line during HFS injection; (c) Reciprocating probe measurement. Triangles stands for the way of the probe into the plasma and corresponds to the SPGI time, squares show the way back of the probe after the injection.

~10-15 ms after the gas pulse. Similar measurements performed with LFS injection, but with a reduced injection rate, show less pronounced steps and a delay of only 2 ms between the two steps. In this case, the smaller edge perturbation could lead to a faster resorption of the MARFE.

The detachment phase is also clearly seen on the Langmuir probe path. As the probe dives into the plasma, the edge density suddenly rises up while the edge temperature drops below 10eV. This phase lasts ~20 ms (2 ms separates two consecutive data points).

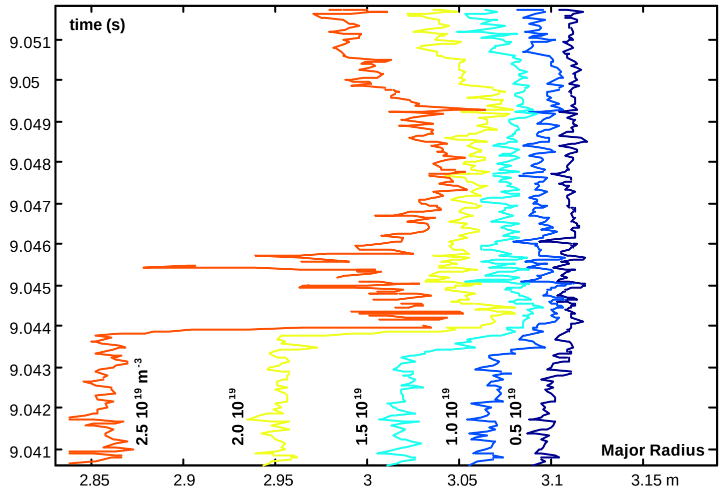

Figure 3. typical time evolution of the edge density profile during a pulsed supersonic gas injection (LFS) measured by reflectometry (TS-30510).

Fast edge density profile measurements worked out with a reflectometer located in the outer equatorial plane with an acquisition rate of 70µs are reported on Figure 3. The data are taken from a LFS injection where the LCFS was located at R~3.09 m. The density profile stiffens up in a fraction of ms as the cloud of neutrals is ionised inside the plasma.

The density profile peaks during 100-200 ms as the strong density gradient at the edge diffuses into the core. Afterwards, the density profile recovers its peaking factor from before the injection.

2.2 Fuelling efficiency

The supersonic pulsed gas injection has been tested over a wide range of scenario. Results either for HFS and LFS are displayed on Figure 4. The fuelling efficiency has been derived from interferometer measurements: the particle content 10 ms before injection is compared to the particle content 50 ms after injection, in order to suppress from the analysis the peaks showed on figure 2.b.

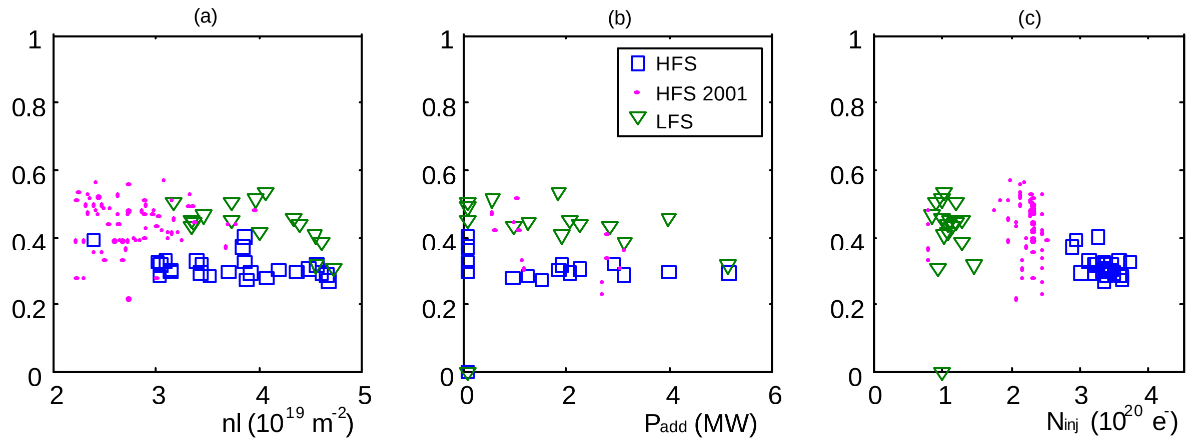

Figure 4. Fuelling efficiency of SPGI measured 50 ms after the injection vs (a) the plasma line integrated density before the pulse, (b) the additional heating power (ICRH+LHCD), (c) the number of injected particles.

The fuelling efficiency from the LFS tends to be better than from the HFS. Therefore, the drift effect, previously mentioned, does not take a significant part in the fuelling process as identified in the modelling. Besides, the variation of the distance between the HFS nozzle and the plasma surface from 0 to 0.12 m did not show any effect. The reduced number of particles in the LFS injection (and the reduced injection duration) could explain the better efficiency as suggested in the Figure 4. Furthermore, the MARFE, observed during HFS injection, is less prone to develop in LFS injection.

According to the experimental data shown on Figure 4, plasma density and additional heating scenario up to 6 MW (ICRH and LHCD) are not critical for that fuelling system. In particular, unlike pellets, gas impulsions are insensitive to suprathermal electrons generated by LHCD.

3. Particle fuelling in long pulse discharges

3.1 Gas puff

The density control has proven to be satisfactory during the 2002 long discharge campaign [5]. The pumping system of the TPL [6] was fully operational with 10 neutralisers connected to turbo-molecular pumps (pumping speed 2.2 m^3s^{-1}). A typical long pulse discharge is represented on Figure 5 (I_p = 0.5 MA, B_t = 3.87 T). The plasma density, LHCD power, gas puffing flux and the TPL extracted flux are plotted as a function of time.

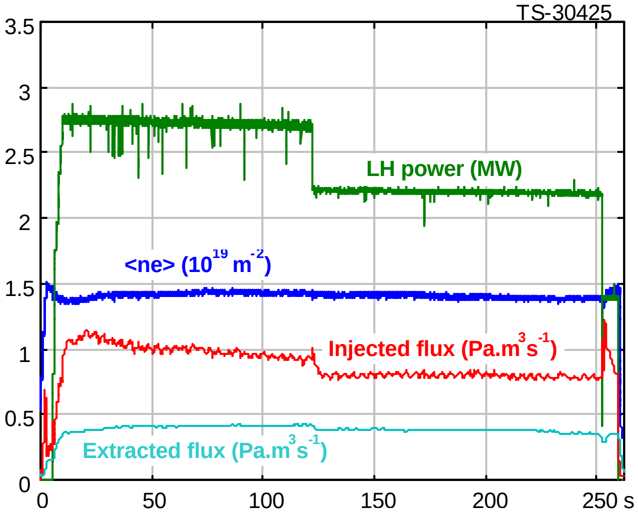

Figure 5. Time evolution of the plasma voume averaged density during a long pulse discharge (TS-30425). Also shown is the lower hybrid power and the fluxes injected by gas puff and extracted by the TPL.

The first thing to note is that density is perfectly controlled over the whole pulse duration (currently limited by the heating system). On the other hand, even after 4 minutes of discharge with significant additional power, the gas flow rate is still much higher than the extracted rate. It indicates that the wall does not come to saturation. The particle balance deduced from pressure measurements [7] indicates that roughly 60% of the injected particles are trapped in the wall at the end of the discharge (~130 $Pa.m^3$). During long pulse operation, it has also been observed that for identical plasma condition, the dynamic wall retention is the same whether the pumping system is operated or not, the feeding gas flow rate adjusting accordingly to match the required density. Taking into account the 15 m^2 of carbon surface inside the vessel, and a saturation ratio of 0.4 deuterium per carbon atom for a 100 eV edge plasma, one finds a sink of 20 to 30 $Pa.m^3$, far below the experimental dynamic retention. The metallic surfaces are estimated to be a negligible deuterium sink. Thus, co-deposition seems to play a role in the continuous trapping of the gas during the discharge. Indeed, flaky deposited carbon layer have been observed on the neutraliser plates beneath the TPL during a Tore Supra shutdown (~150µm after 2h20 of plasma). These layers are currently under analysis. The rate of deuterium trapping for Tore Supra for this type of scenario (GP fuelling, Ip=0.5-0.6 MA, <ne>=1.5-2 $10^{19}m^{-3}$, ~3MW of LHCD) is found to be about 0.6 $Pa.m^3s^{-1}$ or ~3.8 g/h.

3.1 Supersonic pulsed gas injection

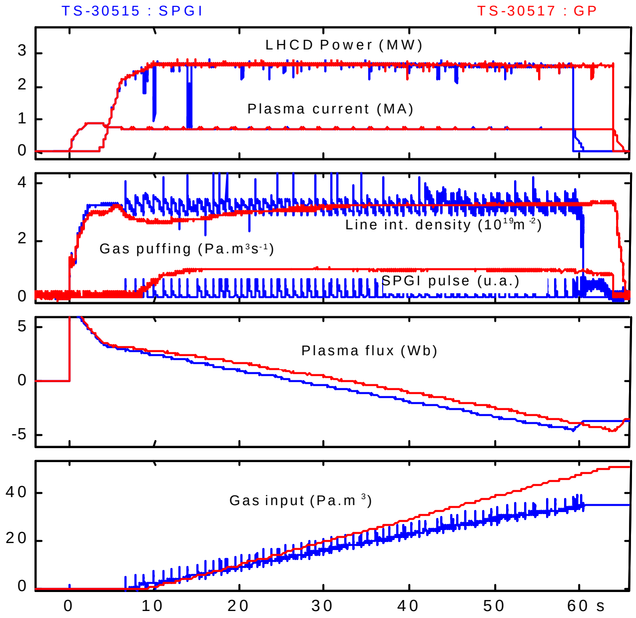

Figure 6. Comparison between a discharge fuelled by gas puffing (TS-30517) and a discharge fuelled by SPGI (TS-30515).

The SPGI system has been successfully implemented to control plasma density with a feedback loop on the frequency of the injector (up to 10 Hz). It has been tested in a long pulse discharge. Figure 6 shows the time trace of the two similar discharges except for the particle fuelling method. As can be seen on the density trace, the SPGI system exhibits a very good time response in comparison to GP (same reference density waveform) and is very efficient: ~1.2 Hz has been necessary to maintain the density at the requested level (66 pulses). Flux consumption is just about the same that with GP and the density perturbation do not hinder the LH coupling.

Particle balance shows that TPL extraction is the same for both discharges (function of the plasma density) while the amount of gas necessary to feed the discharge is reduced by ~20-30% in the SPGI case (consistent with fuelling efficiencies reported in section 2). In the end, wall inventory is reduced by almost 50%.

4. Discussion and summary

SPGI is found to be a promising alternative to GP and pellet injection on Tore Supra. Fuelling efficiency in the 30-50% range has been measured in different operating scenario both from HFS and LFS injection. The increased efficiency is attributed to the very short injection duration compared to the particle confinement time and to the strong cooling of the plasma edge resulting from the massive injection of matter. Tested on one long pulse discharge, first results tend to show a reduced wall inventory compared to a similar gas puffed discharge. To explain the large wall inventories obtained during long pulse operation, trapped deuterium in co-deposited carbon layer has been invoked.

References

[1] LANG, P.T., et al., Phys. Rev. Lett. **79** (1997)1487
[2] GERAUD, A., et al., “A new pellet injector for steady state fuelling in Tore Supra” Proc. 22th SOFT, Helsinki (2002)
[3] BUCALOSSI, J., MARTIN, G., et al., “Plasma fuelling by Supersonic gas injection on Tore Supra” Proc. 29th EPS, Montreux (2002).
[4] PEGOURIE, B., TSITRONE, E., et al., “Supersonic gas injection on Tore Supra” 15th Int. Conf. on Plasma Surface Interactions in Controlled Devices, Gifu (2002), accepted for publications in J. Nucl. Mater.
[5] JACQUINOT J., et al., this conference
[6] TSITRONE, E., et al., J. Nucl. Mater. Vol.266-269 (1999) p.963-968.
[7] BUCALOSSI, J., LOARER, T., et al., “Particle balance studies in JET” Proc. 28th EPS, Funchal (2001).