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Plasma Fuelling by Pulsed Supersonic Gas Injection on Tore Supra

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I. INTRODUCTION: PARTICLE FUELLING OF TOKAMAK PLASMAS

Two techniques are commonly used to fuel the plasma with particles: gas puffing at the plasma edge, and frozen pellet injection into the core (particle fuelling by neutral beams is not considered here, as its main goal is the heating of the plasma rather than the particle fuelling). A comparative analysis of these two techniques shows that:

i) Gas puffing (GP) at room temperature, the most commonly used technique, requires very little hardware (piezoelectric valves), and can be operated with a high reliability. It is therefore the basic tool to control the density in all tokamaks. However, fuelling efficiency, defined as the ratio between the number of particles reaching the confined plasma to the number of particles flowing through the valve, is usually poor. Typical values are in the 5 to 20 percent range, as most of the injected particles are ionised in the scrape-off layer, and rapidly lost either in the wall or in the exhaust system.

ii) Injection of solid pellets exhibits a high fuelling efficiency. Protecting itself by a very dense cloud of gas, the pellet can penetrate deeply into the plasma resulting in large fraction of the matter ionised inside the last closed flux surface. However, producing and accelerating frozen hydrogen is far more difficult, and expensive, than gas handling, and to date pellet injectors are seldom used in plasmas due their troublesome use.

An increase of the efficiency of the gas injection might be an alternative to pellets: on Tore Supra, fuelling efficiency in the range of 40 to 60 percent have been obtained with the Supersonic Pulsed Injector (SPI) described in this paper.

II. SUPERSONIC JETS AND $\vec{E}\otimes\vec{B}$ DRIFT

As the mean free path of the particle λ_g is proportional to the particle speed ($\lambda_g = v_g/n_e\langle\sigma v\rangle_i$), a first way to improve the fuelling efficiency relies on the increase of the velocity v_g, and of the directivity, of the molecules injected in the plasma edge. This can be obtained, to some extend, by the expansion of the gas through a Laval nozzle. A Laval nozzle is basically a tube with a varying cross section along its length: the section first decreases to a minimum –called the nozzle throat- and re-increases toward the nozzle exit (see figure 1). If the pressure at the entrance is higher enough than the pressure at the exit, the flow of gas through the nozzle becomes supersonic: its velocity increases along the flow, while its temperature decreases. The Mach number reaches 1 at the throat. The evolution of the

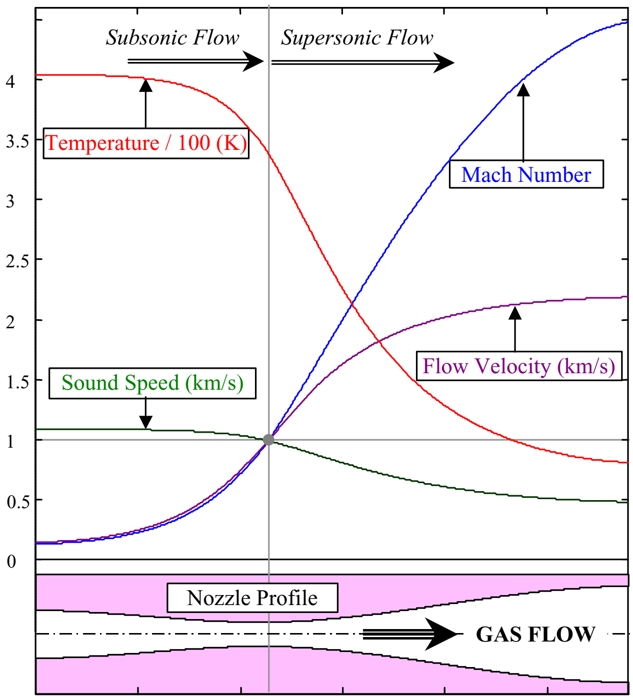

Fig. 1. Gas flow through a Laval nozzle in supersonic regime.

main parameters of the flow is plotted on figure 1, for the nozzle that has been used on Tore Supra. One must note that the outflow velocity (V_{INJ}) rapidly reaches a maximum value close to twice the initial sound speed, and that further increase of the Mach number is mainly due to the cooling down of the gas. The gain expected by such acceleration on the particles is quantified in chapter IV. Experimental increase in efficiency has been already observed on the Chinese Tokamak HT-7 [R1], where a high Mach number nozzle has allowed for an improved penetration of the molecular beam inside the plasma (15 cm depth, in a 22 cm plasma).

To ionise the molecules deeper in the plasma is not the only way to increase the fuelling efficiency. One can also benefit from the drift effect along the toroidal field gradient (also called $\vec{E}\otimes\vec{B}$ drift). When a high density bubble of plasma is formed, ions and electrons are vertically separated by the gradient and curvature drifts. The resulting ambipolar electric field pushes the plasma from the high field side toward the low field side of the tokamak. The main plasma is stabilised against the $\vec{E}\otimes\vec{B}$ drift by the rotational transform, but this stabilisation requires a poloidal uniformity of the plasma. $\vec{E}\otimes\vec{B}$ drift will then be obtained when the duration of the injection remains below the poloidal diffusion time $\tau \approx 2.\pi.R.q / V_{th}$ (with major radius R, safety factor q and ion thermal velocity V_{th}). Typical values at the edge are around 1 ms (R = 2.4 m; q = 5; T_I = 50 eV; V_{th} = 70 km/s), which is the duration of a pellet ablation by the plasma. This drift has indeed been observed with pellets, leading to an increase of the fuelling efficiency when ablation occurs on the high field side (drift toward the magnetic axis) compared to low field side (drift toward the edge) [R2].

A **S**upersonic **P**ulsed **I**njector (SPI) has been built for Tore Supra, with the aim of both improvement on the fuelling efficiency: on the first hand with a supersonic nozzle to accelerate the gas, and on a second hand a very short injection time, on the high field side, to benefit from the $\vec{E}\otimes\vec{B}$ drift. Its goal is basically to mimic as close as possible the effect of the ablation of a pellet, but with gas only. The main requirements are:

➔ Injection of 10^{20} molecules of D_2 within one millisecond;

➔ Repetition rate up to 10 pulses/second, with feed-back capability on the plasma central density;

➔ Operation on the high field side of the torus, i.e. in the vacuum, with temperature up to 200 °C, magnetic field of 6 Teslas, and within a few centimetres from the plasma (100 W/cm^2 during 100's of seconds).

III. SPI OPERATION ON PLASMA

SPI has been used on several plasmas during the 2001 Tore Supra campaign, to qualify the fuelling efficiency of the system. A typical example is plotted on figure 2 (TS shot #29128). Five pulses of gas are injected in an ohmic plasma (1 MA, 3.8 Teslas, 24 m^3), two standard gas puff and three SPI injection. The response of the plasma content is very different, even if the total amount of injected particles with both systems is roughly the same (1.6 10^{20} Deuterium atoms). It must be noted that the GP lasts 200 ms due to the limited conductance of the piezoelectric valve. In the opposite, the density rise caused by SPI is almost instantaneous.

The time evolution of five interferometer chords is plotted on figure 3, during a single SPI pulse (TS#28885). All five

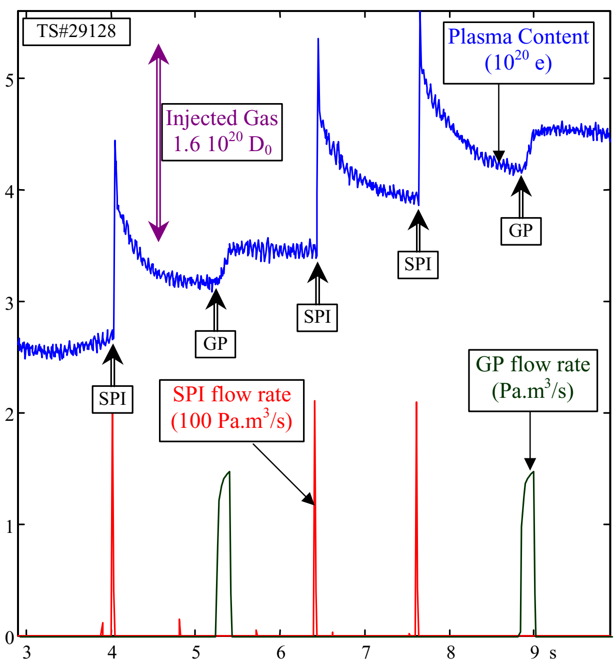

Fig. 2. Pulsed gas injection with GP and SPI

channels increase simultaneously within the time resolution of the diagnostic (2 ms). Five milliseconds after the injection, a MARFE is formed. MARFE (Multifaceted Asymmetric Radiation From the Edge) are produced when the temperature at the edge of the plasma is too low to sustain an equilibrium between radiation losses and convection heating from the core of the plasma. Usually, MARFE are precursors for density limit disruptions. The presence of the MARFE is diagnosed by the crossing of the central channels of the interferometer by the edge channels and by CCD camera imaging of the discharge. However, this marfe does not stay for more than a few milliseconds. It is followed by a diffusion period of 100-200 ms, while the profile, strongly perturbed by the injection, reorganize itself back to a profile with a peaking factor close to its initial value. On a longer time scale (1 second), the particles are pumped away from the plasma by the limiter.

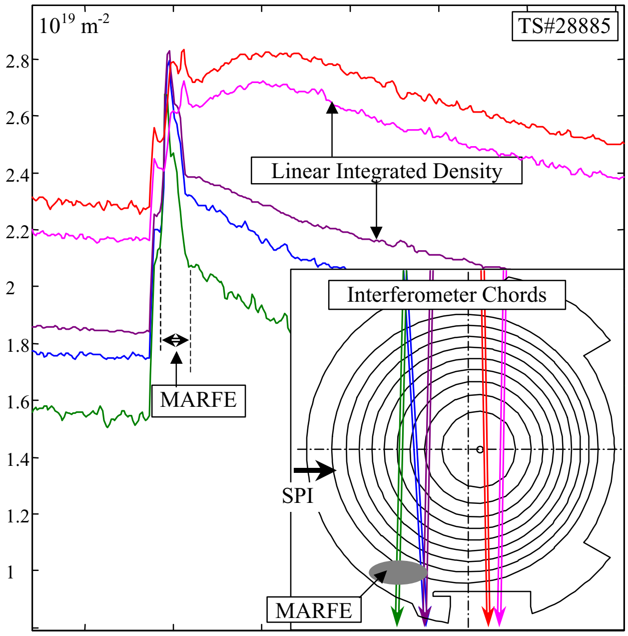

Fig. 3. Evolution of interferometer chords during SPI

A statistical analysis of the fuelling efficiency has been performed on 140 injections, in various plasma conditions. To suppress the effect of the MARFE from the analysis, the particle content increase is calculated 50 ms after injection, and compared to the value 10 millisecond before injection. Results are plotted on figure 4. Values range from 30 % up to 80 % (error bars are around ±5%). Best efficiencies are obtained when the plasma surface is closer to the nozzle exit. Additional heating of the plasma, either with lower hybrid waves or at ion cyclotron frequencies (up to 3 MW in both cases) does not diminish the efficiency (LH waves degrades pellet injection efficiency).

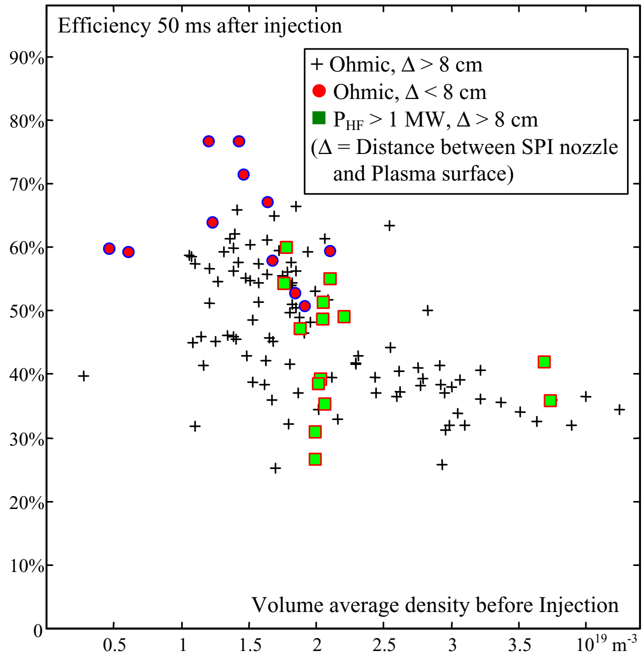

Fig. 4. Fuelling efficiency of SPI, as a function of the density.

IV. ANALYSIS OF THE FUELLING EFFICIENCY

The time evolution of the particle content in the plasma during both SPI injections and gas puffs injections has been simulated with a 1-D diffusion model. The diffusion coefficient D and the pinch velocity V are adjusted to fit the density profile prior to the injections, and kept constant afterward. The scrape-off layer density and temperature are calculated with the injected particle sources (GP or SPI), the recycling source, the power conducted from the core and a particle confinement time τ inversely proportional to the sound

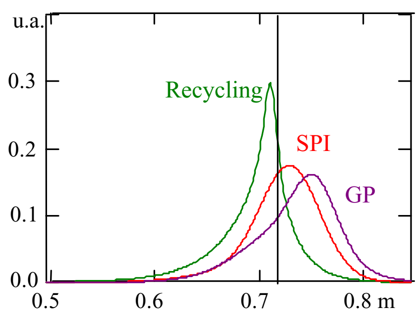

Fig. 5. Particles deposition profiles

speed (i.e. with a confinement dominated by the parallel diffusion). The particles deposition profiles are calculated with the neutral code EIRENE [R3], with the characteristic of the beams (sonic or supersonic) and of the plasma edge temperature and density. An example is plotted on figure 5, with the recycling flux deposition.

The two first injections from shot TS#29128 (figure 2) have been simulated, where a SPI injection is followed by a gas puff, 1.2 second after. The 5 interferometer chords (figure 3) are well reproduced by the code, excepted for the MARFE which is not included in the model. The increase in fuelling efficiency is found to be mainly due to the cooling of the plasma edge, which goes down as low as 5 eV on the last closed surface in the case of SPI, compared to 25 eV in the case of GP. This low temperature value is experimentally confirmed by Langmuir probe measurements. In addition to the increased penetration of the molecules (figure 5), the lower temperature also play a role through an increase of the confinement of the particles in the scrape-off layer. According to the 1-D model, no $\vec{E}\otimes\vec{B}$ effect is required to explain the better efficiency. A typical time evolution of the density profile is represented on figure 7 during the SPI injection.

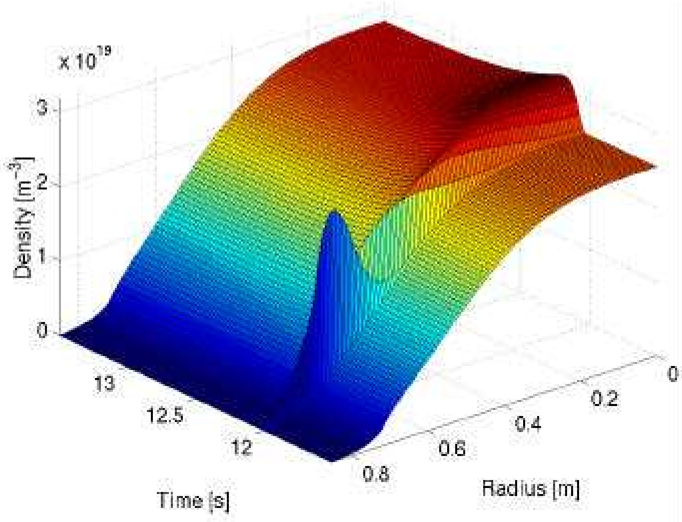

Fig. 7. Density profile evolution during SPI injection

V. Summary and References

The Supersonic Pulsed Injector has given its first result on Tore Supra in 2001. Intermediate between gas puff (low cost and low efficiency) and pellet injectors (high efficiency but high cost), it allows a good gas fuelling efficiency (up to 60 %), with a high reliability (continuous operation up to 12 Hz) and at a low cost (1/20th of a pellet injector).

The gas, injected with a high concentration, both spatially, with a supersonic nozzle, and temporally, with a fast mechanical valve, penetrates deeper into the discharge, probably due to the fast cooling of the plasma edge. The well known $\vec{E}\otimes\vec{B}$ drift, observed with pellet injected from the high field side, does not seems to play any role at this flow rate level (200 Pa.m^3/s).

Further operation of the SPI is planned in 2002 on Tore Supra, along several lines:

i) An improvement of the diagnostics related to SPI: a faster acquisition frequency for the interferometer, an edge reflectometer and fast spectroscopic analysis of the injected gas cloud. The additional information will allow a better understanding of the underlying physic of the observed increase of efficiency.

ii) An increase of the operating pressure of the SPI, allowing a shorter injection time, with the goal of further enhancement of the fuelling efficiency. Flow rates up to 1000 Pa.m^3/s (comparable to pellets) might trigger the $\vec{E}\otimes\vec{B}$ drift.

iii) Tests with a second SPI injector from the low field side, to validate the effect and fast cooling at the edge.

iv) Expansion of the data base of SPI injection to a broader range of plasma parameters.

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