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Interaction of plasma transport and turbulence on particle fuelling

P. Tamain [a,*,1], G. Bonhomme [b], F. Brochard [b], F. Clairet [a], C. Gil [a], J. Gunn [a], P. Hennequin [c], G. Hornung [a], J.L. Segui [a], L. Vermare [c], Ph. Ghendrih [a], Tore Supra Team [a]

[a] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[b] Institut Jean Lamour, Université de Lorraine, Boulevard des Aiguillettes, BP 239, F-54506 Vandoeuvre-lès-Nancy Cedex, France
[c] Ecole Polytechnique, LPP, CNRS UMR 7648, 91128 Palaiseau, France

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ABSTRACT

We report the results of an experimental investigation of the impact of Supersonic Molecular Beam Injection in the Tore Supra tokamak. Several diagnostics were synchronised with the injection to extract a global picture of the physics at play from the time scale of turbulence ($\sim$10 μs) to the full-recovery time ($\sim$1 s). As previously reported, a strong impact of the injection on density and temperature profiles is observed. Both fields exhibit a complex dynamic response involving different phases and time scales. In particular, we show that the effective particle fuelling efficiency is determined by a period of degraded confinement that follows the injection, during which the edge density collapses, in some cases, lower than the initial one. This phase is characterised by a dramatic change in the turbulent transport, with a drop of the frequency spectrum and the observation of large coherent structures as opposed to small intermittent fluctuations before the injection.

1. Introduction

Particle fuelling is essential to control the density in tokamak plasmas. In ITER, a fuel ion flux to the core of up to 100 Pa m^3 s^{-1} will be required in steady state [1]. These particles will have to penetrate through the pedestal (T_e = 3–5 keV at the top) without affecting the H-mode confinement.

Three main methods of particle fuelling are routinely used in current machines: gas puffing, supersonic molecular beam injection (SMBI) and pellet injection (neutral beam injection can also contribute in a non negligible way to particle fuelling). The associated fuelling efficiencies, as found on Tore Supra, range from 5% to 10% for gas puffing up to 90% for pellet injection, through 40–50% for SMBI. In ITER, due to the expected pedestal conditions, these figures should be lower, so that only high-field side pellet injection is considered as being able to fulfil the required particle fuelling rate. The choice of high-field side with respect to low-field side injection is motivated by the experimental observation of a better fuelling efficiency, usually explained as resulting from drift effects on the ablation cloud surrounding the pellet [2]. Thus, the interaction between the injected particles and the local plasma transport appears as a major player in the physics at play during particle fuelling [3]. However, in the absence of reliable models for the particle transport and redistribution after an injection, extrapolations to ITER remain speculative and can exhibit very different results depending on the chosen transport parameters [4].

We present here the results of an experimental investigation of the interaction between particle fuelling and plasma transport during SMBI in the Tore Supra tokamak. Particular effort was put into providing exhaustive diagnostic coverage to observe the interaction between the plasma and the injection. The experimental setup is described in Section 2. We then focus on the response of the plasma temperature and density to demonstrate the existence of a degraded confinement phase that determines the fuelling efficiency (Section 3). Turbulent-resolved measurements detailed in Section 4 back up this explanation by showing a dramatic change of the fluctuations characteristics during this period. These results are finally discussed and summarised in Section 5.

2. Experimental setup

Tore Supra is equipped with three supersonic gas injectors, one located in the low-field side (LFS) mid-plane and the two others in the high-field side (HFS) one (see Fig. 1). They are able to inject gas at a Mach number of the order of 4 with a flow rate of 200 Pa m^3 s^{-1} for a duration of 2 ms, which represents an influx 5 $\times$ 10^{20} particles per pulse [5,6]. In this paper, we focus on results obtained with the LFS injector. The injections were performed in limited ohmic plasmas with HFS contact point on the inner bumpers. The toroidal floor limiter was 2 cm away from the Last Closed Flux Surface (LCFS) and the outboard poloidal limiter located in sector 3 was advanced 2–4 cm away from the LCFS in order to allow for pecker

* Corresponding author.
E-mail address: patrick.tamain@cea.fr (P. Tamain).
1 Presenting author.

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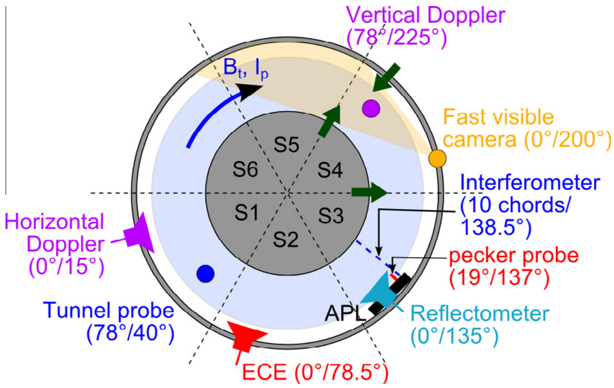

Fig. 1. Top view of the tore supra tokamak showing the distribution of the diagnostics used. The angles refer to the poloidal/toroidal positions (poloidal: 0° = LFS mid-plane, increasing in electron diamagnetic direction; toroidal: 0° = plane S1/S6, increasing counter I_p). The three thick arrows are the 3 supersonic injectors, poloidally located in the mid-plane. APL is the outboard antenna protection limiter.

probes measurements up to the LCFS (see below). The plasma current I_p was varied from shot to shot from 0.8 MA to 1.5 MA while keeping the volume-averaged density around 2.4×10^{19} m^{-3}. Depending on I_p, two to three injections were performed per shot, separated by enough time to let the plasma density and temperature fully recover from one to the following.

The diagnostic coverage used in this study is shown in Fig. 1. These diagnostics are the following:

- *ECE system:* electron temperature measurements were acquired with the Tore Supra 32-channel heterodyne electron cyclotron emission radiometer [7,8]. Fast acquisitions at 1 GHz were synchronised with the SMBIs.
- *Far infrared interferometer:* the interferometer is located in sector 3. It comprises 10 chords distributed in the poloidal plane, as represented in Fig. 5. The standard time resolution is 1 ms but fast acquisition windows with a time resolution of 10 µs were synchronised with the injection to capture the fast dynamics [8].
- *Ultrafast sweeping reflectometer:* this profile reflectometer is located in sector 3 just beside the outboard limiter housing the pecker probes. It can measure density profiles in the edge of the plasma with a time resolution up to 3 µs per profile for a time window of 10,000 profiles [9].
- *Fast visible imaging:* the Tore Supra fast visible camera [10,11] was used to monitor edge plasma fluctuations. In order to get sufficiently time-resolved movies, a resolution of 128 × 160 was chosen, allowing for a frame rate of 57 kHz with 10 µs exposure time.
- *Pecker probes:* Tore Supra has recently been equipped with reciprocating probes located in the outboard poloidal limiter in the vicinity of the LFS mid-plane [12], where the radial turbulent flux was shown to be ballooning in character [11]. The system is composed of two magnetically driven manipulators, each of which can insert up to 3 cm in front of the limiter two tunnel probes [13] positioned back to back in a Mach probe configuration. These allow the measurement of the ion saturation current j_{sat} at a sampling rate of 1 MHz, as well as an insight on the electron temperature T_e and on the parallel velocity of the plasma. The total duration of a plunge is of the order of 100 ms. For technical reasons, only the top probe, located 19° above the equatorial plane, could be used in the considered discharges.

Particular effort was put in synchronising the data acquisition windows with the injections. The exact synchronisation was varied from one injection to the other in order to get highly-resolved measurements on longer time scales. In the remainder of this paper, the $t = 0$ time reference is, unless explicitly stated, the time t_{SMBI} of the electric trigger to the supersonic injector valve. For LFS injection, a repeatable time delay of 23 ms is observed between the trigger and the first observable perturbation of the plasma. This is most likely due to the inertia of the injector and the flight time of neutrals from the nozzle to the plasma.

3. Impact of SMBI on the plasma confinement and consequences on the fuelling efficiency

Let us first focus on the global response of the plasma. One of the most widely reported impacts of a supersonic injection is a drop in the temperature of the plasma. This effect is believed to be fundamental in explaining the increased efficiency of SMBI with respect to gas puffing, since a cold edge plasma both increases the parallel loss time of particles to the wall and favours the neutrals penetration [4]. Such behaviour is found also in Tore Supra, as shown in Fig. 2 which gives the time traces of the electron temperature measured by ECE at radii varying from the LCFS to the centre of the plasma in a shot at I_p = 1.2 MA. A sudden cooling of the edge plasma from 200 eV to 120 eV on a time scale of 4 ms is observed, propagating up to the centre where the temperature decreases from 2.1 keV down to 1.7 keV on a longer time scale (of the order of 100 ms). These cold conditions remain for a period of 40–60 ms on the outermost ECE channels ($R_{LCFS}-R$ < 20 cm) before the temperature starts relaxing back to the initial one. For the central channels as well as the outermost one, this relaxation occurs on a slow and unique time scale of the order of 0.8 s (about 3 times the pre-SMBI energy confinement time). For intermediate channels (2.5 cm < $R_{LCFS}-R$ < 20 cm), this slow relaxation is preceded by a faster temporary rise. The corresponding characteristic time depends on the considered radius, ranging from 55 ms 2.7 cm inside the LCFS to more than 200 ms 20 cm inside the plasma. The current scan showed that the plasma current I_p has a strong influence on these dynamics, the duration of the intermediate cold phase as well as the penetration depth of the cold front increasing with decreasing I_p.

The density also exhibits distinct phases in its response to the injection. Fig. 3 shows the time traces of the volume-averaged density measured by the interferometer after each LFS SMBI pulse in our database. The volume-averaged density is calculated from the density profile which is itself reconstructed from the 10 chords of the interferometer using a least-mean square method and

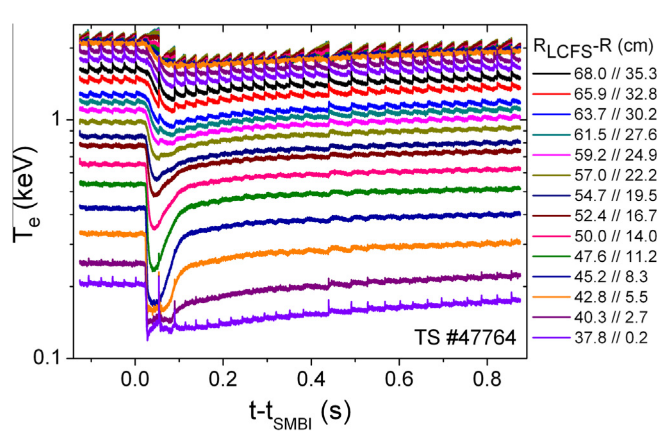

Fig. 2. Electron temperature time traces measured by 28 channels (28 radial positions; two lines of each colour corresponding to the 2 different radial positions indicated in the right-hand side legend) of the ECE radiometer during a supersonic injection in a discharge with I_p = 1.2 MA plasma current.