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The response of the Tore Supra edge plasma to supersonic pulsed gas injection

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Abstract

The response of the scrape-off layer (SOL) to supersonic pulsed gas injection (SPGI) in Tore Supra is measured by a reciprocating Mach probe. The edge density increases abruptly following injection and decays to its pre-injection value in about 10 ms. The edge temperature falls to 5–10 eV range. The perturbation appears to be toroidally symmetric. The density increase depends on the injected amount of deuterium gas, but the temperature decrease does not. The parallel Mach number changes during the density spike; the sign of the change depends on the poloidal location of the injection nozzle. We use a simple one-dimensional fluid model for the SOL to interpret the measurements. The Mach number change lasts about 10 ms as well, indicating the existence of a poloidally localized ionization source in the vicinity of the nozzle.

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Keywords: Edge plasma; Gas injection and fuelling; Probes; Plasma flow; Tore Supra

1. Introduction

Edge measurements are needed in order to understand the mechanisms of different gas fueling techniques in tokamaks [1]. In this paper, the influence of supersonic pulsed gas injection (SPGI) [2] on the scrape-off layer (SOL) is studied by a reciprocating Mach probe (RMP) in Tore Supra [3]. The study of SPGI is also important from the point of view of flow measurements which are a current topic of SOL research due to their role in impurity transport (cf. tritium rich carbon flakes on the inboard divertor louvers of JET [4]). SPGI can modify the recycling ionization source and the SOL flows. These experiments, therefore, provide a test for SOL modeling.

2. Experimental set-up

The SPGI is achieved by the gas expansion through a Laval nozzle, which is a tube with varying cross-section. Mach numbers up to 5 are reached. Supersonic gas injectors have been installed on the equatorial plane on the high- and low-field sides (Fig. 1) and are able to inject roughly 1 Pa m^3 of deuterium gas (D_2) within 2–4 ms. The large amount of gas immediately cools

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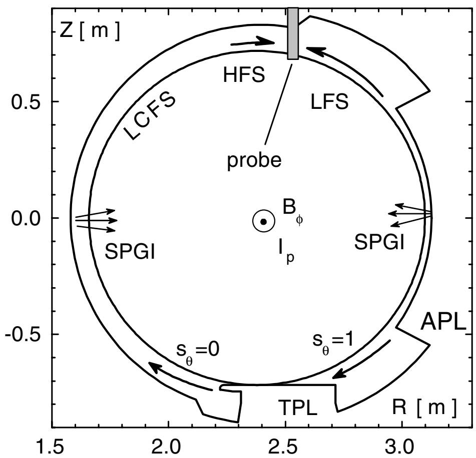

Fig. 1. Poloidal section of Tore Supra. The Mach probe is on top of the torus and collects particles from the HFS and LFS. The last closed flux surface (LCFS) is defined by the bottom toroidal pump limiter (TPL). One supersonic pulsed gas injection nozzle (SPGI) is located on the HFS wall, and the second nozzle is on the LFS antenna protection limiter (APL).

down the SOL, increases the edge particle confinement time, and increases the probability that an edge ion can diffuse radially inward and fuel the core [5].

A fast reciprocating Mach probe [6] is used to study the Tore Supra SOL plasma response to SPGI. It enters the plasma from the top of the torus several times during the discharge. It is oriented so that it can measure the parallel particle flow, plasma density, and electron temperature. It consists of a carbon-fiber composite (CFC) cylinder of 4 cm diameter and 5 mm thickness, which protects six graphite pins. The CFC cylinder is pierced with 4 mm diameter holes having their axes aligned with the magnetic field direction such that three pins collect charges from the high field side (HFS) and three from low field side (LFS) of the tokamak. It measures one I–V characteristic for each pin every 2 ms.

3. Experimental results

Interesting results were obtained from RMP measurements of the effect of SPGI on the SOL. Here, we focus on shot 30496 with major radius $R = 2.38$ m, minor radius $a = 0.72$ m, volume-averaged density $\langle n_e \rangle = 1 \times 10^{19}\,\mathrm{m}^{-3}$, plasma current $I_p = 0.8$ MA, and toroidal magnetic field $B = 3.86$ T. Four SPGIs were performed in this shot – two from the HFS and two from the LFS. All of these injections were synchronized with the RMP reciprocations. They occurred when the probe was leaving the plasma, so that the measurements obtained on the ingoing part of the plunge (before injection) could be used as reference profiles. We concentrate on the reciprocations/SPGI at times $t = 4$ and 7 s, which correspond to injection from HFS and LFS, respectively. The probe signals are very reproducible from discharge to discharge, for a given plasma configuration, injection characteristics, and probe radius. The injections occurred when the probe was moving with low speed near the turning point of its trajectory; it moved from 5–10 mm during the time of interest. We can, therefore, consider that we are measuring temporal variations at almost fixed distance from the LCFS of $r - a \approx 2$ cm. The measurements are shown in Fig. 2.

In Fig. 2(a) we plot the electron density normalized to its unperturbed, pre-injection value. The density increases faster than the temporal resolution of our measurement (2 ms), then decays to its unperturbed value with a time constant of roughly 10 ms. Deuterium atoms (3.1×10^{20}) were injected through the HFS nozzle, and 1.2×10^{20} through the LFS nozzle. The relative density increase is larger during HFS injection.

In Fig. 2(b) the average electron temperature of all six pins (thick full curve) is shown. The thin dotted curve corresponds to the unperturbed, pre-injection value. The temperature drops to the range of 5–10 eV as quickly as the density rises. The relative drop in Fig. 2(c) is independent of the point of injection and of the amount of injected gas. The temperature remains low while the density decays, and only returns to its original value after the density returns to its pre-injection value. Fig. 2(d) shows ion saturation current on the LFS (thin full curve) and HFS (thick full curve) of the probe. The unperturbed, pre-injection values are indicated by the thin

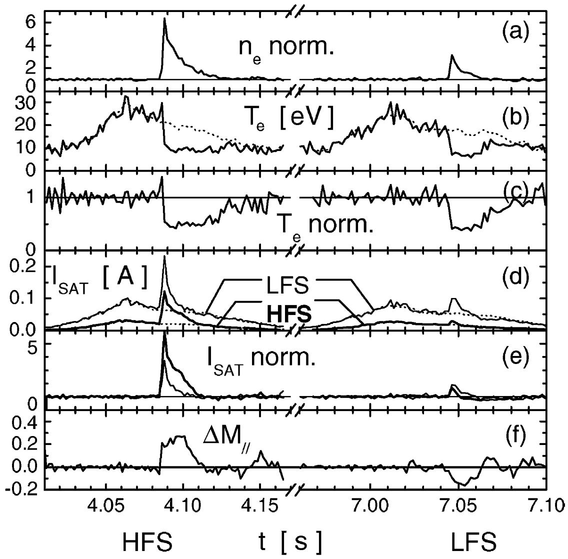

Fig. 2. Time dependence of (a) SOL density n_e, (b) and (c) electron temperature T_e, (d) and (e) ion saturation currents I_{sat}, and (f) change of Mach number M during SPGI from HFS and LFS.

dotted curves. The relative changes of the ion current with respect to the unperturbed pre-injection values are shown in Fig. 2(e). For HFS injection, we see that the HFS ion current is more strongly affected than the LFS. The opposite happens for LFS injection. In fact, for LFS injection, the HFS ion current is practically unaffected. It appears that the probe is sensitive to the poloidal location of the injection point. The relative ion current becomes less than 1 after the initial fast decay. This is due to the low temperature that persists for some time after the fast density decay. In Fig. 2(f) we plot a change of the parallel Mach number with respect to its unperturbed, pre-injection value. The sign of the change is positive for HFS injection, and negative for LFS injection. In Tore Supra we define positive flow to be directed from the HFS towards the LFS, i.e., in the clockwise direction in the poloidal section of Fig. 1.

4. Theoretical model

In order to gain some insight into the possible implications of these observations, we apply the simple, 1D, isothermal fluid model for the SOL [7] with an arbitrary source of ions $S(x_\parallel)$ in the convection-dominated, low recycling regime. The equations of conservation of mass and momentum on the domain $-L/2 \leqslant x_\parallel \leqslant L/2$, where $x_\parallel$ is the distance along the magnetic field line and L is its length, are

$$\frac{\mathrm{d}}{\mathrm{d}x_\parallel} nV_\parallel = S(x_\parallel) \quad \text{and} \quad \frac{\mathrm{d}}{\mathrm{d}x_\parallel} n\left(V_\parallel^2 + c_\mathrm{s}^2\right) = 0, \tag{1}$$

where n is the ion density, $V_\parallel$ is the parallel flow speed, and the sound speed is $c_\mathrm{s}^2 = k(T_\mathrm{e} + T_\mathrm{i})/m_\mathrm{i}$, with the electron temperature T_e and ion temperature T_i. The source term is a free function that is in general independent of n and $V_\parallel$. We define a dimensionless distance as

$$s_\parallel = \frac{1}{\langle S\rangle L}\int_{-L/2}^{x_\parallel} \mathrm{d}x_\parallel S(x_\parallel), \quad \text{with}$$
$$\langle S\rangle = \frac{1}{L}\int_{-L/2}^{L/2} \mathrm{d}x_\parallel S(x_\parallel) \tag{2}$$

being the average source rate in the SOL. We define the Mach number $M = V_\parallel/c_\mathrm{s}$, and enforcing the Bohm criterion at both boundaries

$$M(s_\parallel = 0) = -1, \quad M(s_\parallel = 1) = +1, \tag{3}$$

we obtain the solution for density

$$n = \frac{n_0}{M^2+1}, \quad n_0 = \frac{\langle S\rangle L}{c_\mathrm{s}} \tag{4}$$

and Mach number

$$\frac{M}{M^2+1} = s_\parallel - \frac{1}{2}. \tag{5}$$

A measurement of the Mach number provides an estimate of where the probe is situated with respect to the source distribution. In Tore Supra, on top of the tokamak, the ion flow is directed towards the HFS with $M \approx -0.5$, which indicates, if we ignore the $E \times B$ drift, that the source is concentrated on the low field side. The probe position would be approximately $s_\parallel \approx 0.1$ according to the solution displayed in Fig. 3. A change of the Mach number reflects a shift of the stagnation point,

$$\Delta M \approx \Delta s_\parallel. \tag{6}$$

This simple equation explains the sign of the observed Mach number variation in Fig. 2(f). When injection is from the HFS, we expect the source distribution (the center of which, $s_\parallel = 0.5$, defines the stagnation point of the flow) to shift in that direction. In other words, the probe moves towards the LFS (in our special normalized coordinate system) and the Mach number should increase. The opposite holds for injection from the LFS.

The measured change of Mach number implies that following the injection, the ionization of some fraction of the gas proceeds during the next 10 ms or so somewhere in the poloidal vicinity of the nozzle. The Mach number change only describes a modification of the spatial distribution of the source, and gives no information about its absolute value. The density measurement gives us the average source rate on a given flux surface via Eq. (4). Let us now attempt to quantify the magnitude of the local ionization rate with respect to the global recycling rate in the tokamak, and the quantity of injected gas. The principal recycling occurs within a few cm of the surface of the limiter, where the most intense fluxes are located. First we calculate the pre-injection source rate

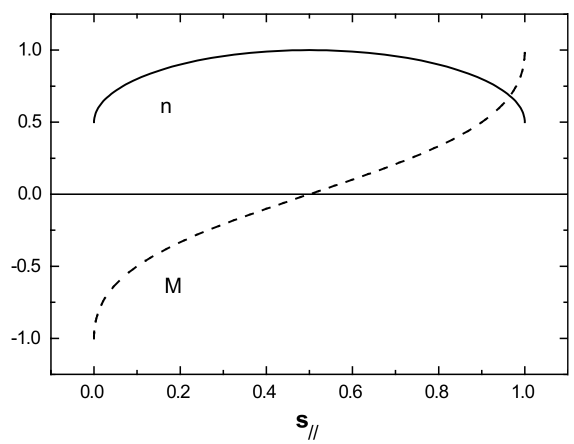

Fig. 3. Normalized density (full curve) and Mach number (broken curve) from simple fluid model as a function of the fraction of the source that lies between a given poloidal angle and the HFS of the limiter.

using the measured density, temperature, and Mach number profiles measured during the inward-going phase of the plunge

$$\langle S_1 \rangle = \frac{n(M^2+1)c_s}{L}. \tag{7}$$

Assuming toroidal symmetry, the total ionization rate is

$$\phi_1 \approx 4\pi^2 aR \int_{r-a}^{\infty} \mathrm{d}r \langle S_1 \rangle. \tag{8}$$

The integral of the profile (extrapolated to $r = a$) gives $4 \times 10^{21}\,\mathrm{s}^{-1}$ (Fig. 4). This rate includes direct ionization in the SOL plus the radial diffusion of ions from the confined plasma. An estimate of the core outflux is $\langle n_e \rangle V/\tau_p$. For a volume-averaged density of $10^{19}\,\mathrm{m}^{-3}$, plasma volume V of $25\,\mathrm{m}^3$, and a particle confinement time τ_p of the order of 0.1 s, this gives $2.5 \times 10^{21}\,\mathrm{s}^{-1}$. The core and SOL ionization rates are usually estimated to be comparable by neutral transport calculations, so these numbers are reasonable.

The total source rate on the surface $r - a = 2\,\mathrm{cm}$ is shown in Fig. 5(a). We would like to know how much of the additional source during each injection is due to local ionization near the nozzle, and how much is due to a change of the global recycling rate. We assume that the global recycling pattern does not change its poloidal distribution, even though its magnitude is modified. With this assumption, any change of $s_\parallel$ implies a change of the ratio σ of the total HFS to the total LFS source, with the imbalance due to the additional local ionization S_{SPGI} near the nozzle. Without the help of sophisticated SOL codes, we can only guess about this. It is conceivable, for example, that due to the cooling of the SOL and a decrease of the radial temperature gradient (the few measurements we have at other radii in ohmic discharges always give $T_e \sim 5$–$10\,\mathrm{eV}$ during injection), that the radial electric field and associated drifts might also decrease, and lead to a change in recycling asymmetries (if they exist to begin with). For HFS injection we have

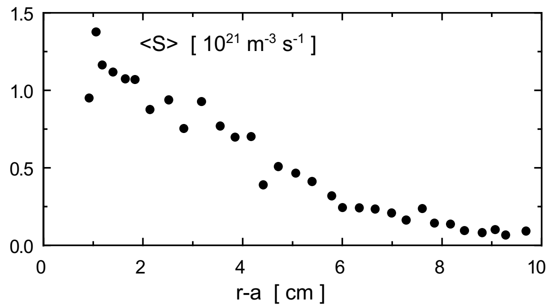

Fig. 4. Radial profile of field line averaged source rate for shot 30496 (before SPGI).

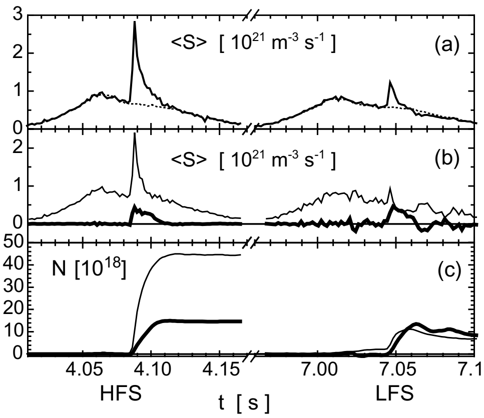

Fig. 5. (a) Total source rate (thick full curves) measured by fast-scanning probe for a HFS and a LFS SPGI. The unperturbed, pre-injection source rate is given by the thin dotted curves. (b) The two components of the total source rate: the global recycling source (thin full curves) and the local ionization source (thick full curves). (c) The source rate integrated over the SOL (thick full curves). The thin full curves are the integral of the extra source (difference between the curves in (a)).

$$\langle S_{\mathrm{SPGI}} \rangle_{\mathrm{HFS}} + \sigma \langle S_{\mathrm{LFS}} \rangle = s_\parallel \langle S \rangle \tag{9}$$

and for LFS injection,

$$\langle S_{\mathrm{SPGI}} \rangle_{\mathrm{LFS}} + \frac{\langle S_{\mathrm{HFS}} \rangle}{\sigma} = (1 - s_\parallel)\langle S \rangle, \tag{10}$$

where σ is calculated from the unperturbed profiles. The local source rate and the global recycling rate are shown in Fig. 5(b). The sum of the two gives the total source rate shown in Fig. 5(a). It is striking that the local source rates are roughly the same, independent of the quantity of injected gas. It seems that a small LFS injection has the same effect on the Mach number as a large HFS injection. In the former case, the density spike is entirely due to the local ionization near the LFS nozzle, whereas in the latter case the global recycling has also increased significantly.

In order to compare these local source rates with the total source rate we need measurements across the SOL. For now we do not have any other measurements. Despite this serious handicap, we assume that the radial profile of the additional sources has the same characteristic decay length as the density, $\lambda = 4\,\mathrm{cm}$ typically. In Fig. 5(c) we compare the integrated local ionization source due to the injection with the integrated extra source (i.e., the total source rate minus the unperturbed source rate). The local source is in the range of 5–10% of the number of injected deuterium atoms. This number is encouraging because we expect less than 100% of the injected atoms to ionize in the SOL.

5. Conclusion

We study the effects of a new kind of plasma fueling (SPGI) on the SOL. The first results show the following features. The SOL plasma density, temperature, and Mach number, significantly perturbed by the injection of a big amount of gas, relax in about 10 ms back to their values before injection. The maximum relative change of SOL density is proportional to the amount of injected gas, while the relative drop of temperature is not. The sign of the change of Mach number depends whether the gas is injected from LFS or HFS.

The asymmetric response of the Mach number to the poloidal location of the nozzle suggests that local ionization occurs, in addition to a change of the global recycling rate. Changes of Mach number could also be induced by a change of the radial electric field due to drop of temperature, but this effect should not depend on nozzle location. Rough estimates of the local ionization rate suggest that we are observing a source rate due to local ionization of the injected gas on a time scale of 10 ms. This time scale is slow compared to what we expect for the first, direct ionization of the gas pulse. This question will be the subject of future investigations.

The difference between LFS and HFS may simply be a result of the lack of measurements at other radii. Perhaps the recycling profile lies at a different radius than the local ionization. A simple fluid model gives highly intuitive results. It is essential to perform systematic studies of SPGI, which can make a significant contribution to the understanding of edge flows and the mechanisms of plasma fueling. In particular, experiments are planned to obtain measurements at several radii in the SOL during SPGI and pellet injection.

Acknowledgments

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