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Pellet fuelling in Tore Supra long discharges

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Abstract

A new pellet injector, able to inject continuously hydrogen or deuterium pellets, was installed on Tore Supra in 2003 and preliminary experiments aiming to fuel long discharges were performed. In combination with Lower Hybrid (LH) Current Drive, pure pellet fuelled discharges lasting up to 2 min were achieved. The LH power was switched off just before each pellet injection (LH notching) to maintain a relatively deep pellet penetration by reducing the energy of the super-thermal electrons driven by the LH wave. A comparison, based on a particle balance study, between two comparable pellet fuelled and gas fuelled discharges has been done. In the two cases, the volume average density is the same and the analysis shows that the particle source, the pumped flux and the wall retention are similar and appear to be independent of the fuelling method for the low plasma current and density conditions considered ($I_p = 0.6$ MA, $\langle n_e \rangle = 1.5 \times 10^{19}$ m^{-3}).

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1. Introduction

The control of particles is an essential issue in the route toward the deuterium–tritium long discharges planned in future machines like ITER. In order to minimize the radioactive tritium inventory, efficient continuous fuelling methods as well as low particle in-vessel retention are necessary. With its capacity to perform long discharges, thanks to its actively cooled plasma facing components and permanent magnetic field, Tore Supra offers a unique opportunity to address this issue over timescales relevant to plasma-wall interactions. Recently, gas fuelled discharges lasting up to 6 min (I_p = 0.5 MA, $\langle n_e \rangle = 1.5 \times 10^{19}$ m^{-3}, injected/extracted energy of 1 GJ [1]) were performed with the density controlled by a continuous gas injection (~0.8 Pa m^3/s or 3.9×10^{20} D/s) and the active pumping of the Toroidal Pump Limiter (10 neutralisers connected to 10 × 2200 L/s turbo-molecular pumps). However, the particle balance of such a discharge shows that about 60% of the injected matter is not extracted and remains trapped in the vessel (total of ~7×10^{22} D atoms at the end of the discharge). The co-deposition of a: C-D layers is suspected to play a dominant role in this retention, as supported by the presence of carbon flakes in shadowed areas [2]. In an attempt to minimize the retention, a similar experiment was undertaken with the plasma fed by injection of frozen deuterium pellets, the better fuelling efficiency of this method being widely demonstrated, particularly for High Field Side injection [3,4]. Therefore, a pellet injector able to fuel the plasma

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continuously was recently installed on Tore Supra. The necessity to use the Lower Hybrid Current Drive (LHCD) system to maintain the plasma current complicates pellet fuelling of such discharges. Indeed, the super-thermal electrons driven by the LH wave cause a volume heating of the pellets that leads to a dramatically enhanced ablation rate and strongly reduce their penetration and fuelling efficiency. To mitigate this deleterious effect, a notched scenario was used [5], in which the LH power is switched-off during a short time interval to allow the injection of each pellet. With this method, pellet fuelled discharges lasting up to 2 min were obtained for the first time in a tokamak. This paper presents the first results of steady-state pellet fuelling and discuss the particle balance of similar pellet and gas fuelled discharges.

2. Pellet injector and diagnostics

The new pellet injector installed on Tore Supra in 2003 [6] was built by PELIN Laboratory in St Petersburg (Russia). It is based on a screw extruder, cooled by liquid helium, producing a continuous hydrogen or deuterium rod of ice of rectangular cross section. An electromagnetic cutter punches cylindrical pellets (diameter 1.7 or 2 mm) from the rod, which are accelerated by a small gas puff from a fast valve (less than 1.5 Pa m^3 per pellet, totally pumped by the injector pumping line). The length of the pellets can be varied between 1.5 and 3.5 mm by moving one side of the rectangular nozzle, so that the pellet content can be adjusted between 1.5 and 6×10^{20} D atoms. This injector can inject pellets continuously at a frequency up to 10 Hz and a velocity between 100 and 600 m/s, with a very high reliability (~99%). Usually, a feedback loop is used to control the plasma density by adjusting the injection frequency. Pellets can be injected from four different poloidal locations: the first on the Low Field Side, the three others on the High Field Side, regularly distributed from the top of the vacuum chamber to the equatorial plane. A fast selector and a set of guide tubes is used to convey the pellets to the High Field Side. The whole system is designed to determine the optimised configuration in the (v, α) domain, where v is the pellet velocity (limited by the small radii of curvature of the guide tubes for the HFS configurations) and α the poloidal angle of injection. So far, most of the experiments were carried out in the LFS configuration that do not require adjustments or optimisation of the guiding system, and the results presented in this paper focus on this configuration.

Specific diagnostics, as CCD cameras and fast $H\alpha$ measurements, are available to characterize pellet ablation and the instantaneous matter deposition profile for the different configurations. Also, particular attention was paid to the measurement of the pellet mass, the knowledge of the latter being essential to the particle balance analysis. Consequently, two different diagnostics were installed to measure the pellet particle content at the injector exit. The first is based on volume reconstruction, from a double snapshot of the pellet in flight along two perpendicular directions, taken by a CCD camera. The second is a microwave cavity, calibrated with a baratron gauge that measures the pressure jump occurring when the pellets are sublimated in a known volume. The accuracy of both measurements is estimated to be ±20%. In the LFS configuration, and since there is no guide tube in which erosion could occur in this case, these measurements yield directly the plasma fuelling source.

3. Experimental results

3.1. Pellet fuelling of Ohmic and LH discharges

Standard Ohmic and LH driven discharges, with no feedback control of the density, were performed using LFS launched pellets as fuelling system. In both cases, the plasma current was $I_p = 1.2$ MA, driven – in the latter case – by the LH power in the 2–3 MW range, 0° phasing. Pellets were injected at a velocity of 500 m/s (±10%) with an average size of 1.5×10^{20} atoms per pellet. For both scenarios, the traces of the volume averaged density are displayed in Fig. 1(a). In the LH

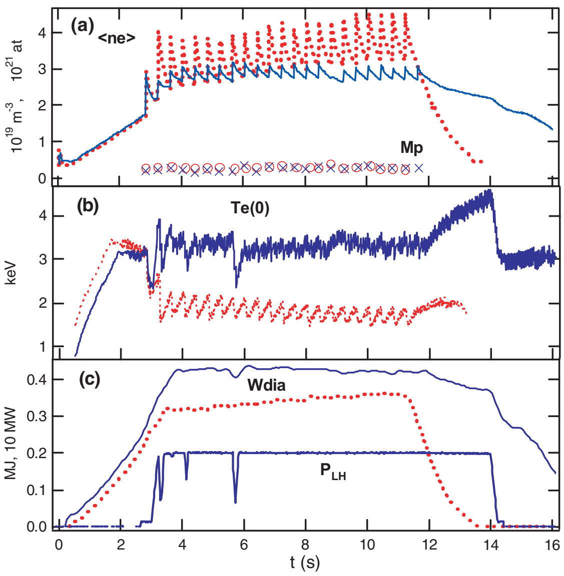

Fig. 1. Comparison of two pellet fuelled discharges without (*TS*31889, dashed curves) and with LH power (*TS*31890, solid curves): (a) average density and pellet content (○, without LH; ×, with LH); (b) central temperature; (c) diamagnetic energy and LH power (10 MW).

driven discharge, the suprathermal electrons driven by the wave (of typical energy ~100–300 keV in the ablation zone) strongly increase the ablation rate and reduce dramatically the pellet penetration. The resulting instantaneous fuelling efficiency ($\eta_i = \Delta N_e/M_p$, where ΔN_e is the increase of the plasma electron content and M_p the pellet particle content) drops by a factor of 2 to 3 relative to the Ohmic case. A comparison of the central electron temperature and stored energy in both cases is displayed in Fig. 1(b) and (c). To increase the penetration and fuelling efficiency in LH driven discharge, it is necessary to notch the LH power and to inject the pellet in the short time interval during which the power is switched-off [5].

3.2. Long discharges fuelling

The same long discharge scenario ($I_p = 0.6$–0.8 MA, $\langle n_e \rangle = 1.5 \times 10^{19}\,\text{m}^{-3}$, $B_t = 3.4$–3.8 T, 2.6 MW of LH power) was investigated with the plasma fuelled by gas puff or pellet injection. Since the LH discharge was performed at $V_{loop} \sim 0.07$ V with a feedback loop on the plasma current, the time interval during which the power was switched-off had to be as short as possible to limit the flux consumption. For these first experiments, a LH-free period of 50 ms was applied, with a delay $\tau_D \approx 30$ ms between the injection time of each pellet and the power switch-off, this value of τ_D being – owing to the available LH power – the best compromise between discharge duration and fast electron tail relaxation [5]. In such conditions, the energy of the fast electrons is significantly reduced at the pellet injection time and the ablation is intermediate between that resulting from volume heating by fast electrons and the usual thermal ablation process. This is demonstrated in Fig. 2 by the display of CCD pictures of the ablation cloud in the three conditions discussed above: full LH (Fig. 2(a)), notched LH (Fig. 2(b)) and Ohmic (Fig. 2(c)). An overall recording of the main pellet and plasma parameters for a 2 min long, notched LH, pellet fuelled discharge is shown in Fig. 3. In this case, 155 pellets were injected at a frequency close to 1.3 Hz to maintain the average plasma density near the target value of $1.5 \times 10^{19}\,\text{m}^{-3}$. A well controlled steady-state plasma was obtained, as demonstrated by the different plasma parameters presented on Fig. 3 (I_p, V_{loop}, $\langle n_e \rangle$ and Wdia). The discharge ended when all the available flux was consumed. The sensitivity of the pellet penetration L_p to the delay τ_D is clearly illustrated since, when τ_D is reduced in the 0–10 ms range due to fluctuations in the pellet mass and velocity, L_p is similar to the case without notching. The last pellet was fired about 600 ms after the switch off of the LH power, thus in an Ohmic plasma, giving a reference for the penetration depth. The total number of atoms brought to the plasma by the 155 pellets was estimated to be 4×10^{22} from the

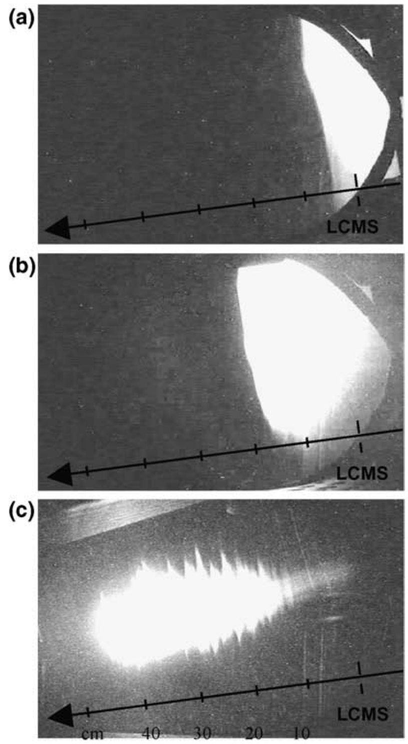

Fig. 2. CCD images of the ablation cloud of pellets injected during the discharge displayed in Fig. 3(a). From top to bottom: with LH (delay ~ 0), with LH notched (standard case) and in Ohmic plasma (last pellet).

pellet mass diagnostics, leading to an average instantaneous fuelling efficiency η_i of 65%. A detailed particle balance is discussed for this discharge in the following section.

3.3. Particle balance and discussion

A particle balance was performed on two similar discharges, the first fuelled by pellet injection (*TS*33009), the second by gas puff (*TS*33001). As seen in Figs. 4 and 5, the volume average densities and edge parameters were equal in both cases. A comparison in terms of particle balance is displayed in Fig. 4, where the time integrated injected and exhausted fluxes and the corresponding retention are plotted for the time interval during which the two discharges are identical ($t > 20$ s). No change with the fuelling method can be seen: the injected and exhausted fluxes are equal (within 7%) and thus the resulting retention. The main cause of this insensitivity is the relatively high electron temperature in the Scrape-off Layer, that have for consequence that about 85% of the recycling flux is ionized out of the Last Closed Flux Surface. It results that the effective source is completely dominated by the recycling (~2.2×10^{22} particles/s,

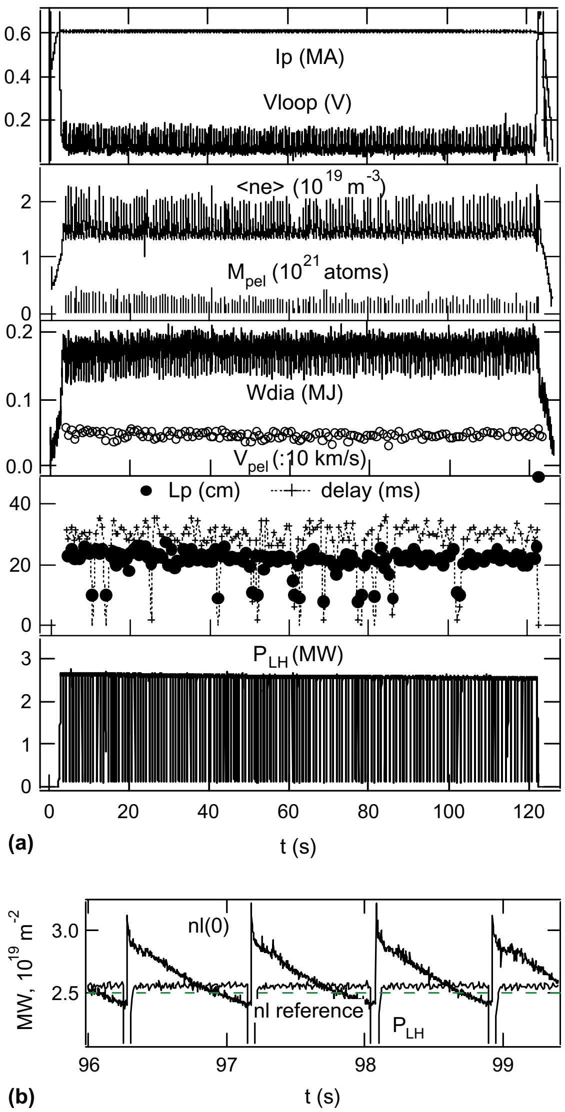

Fig. 3. (a) Time evolution of the plasma and pellet parameters for the 2 min discharge (*TS33009*). From top to bottom: plasma current and loop voltage, volume average density and pellet content, plasma diamagnetic energy and pellet velocity, delay between P_{LH} cut off time and pellet entering the plasma and pellet penetration depth, LH power. (b) Close-up of P_{LH} notching and central line density compared to the reference.

i.e. more than 60 times the injected flux) and that the fuelling efficiency of each particular method does no longer play a significant role in the global balance. Moreover, in the case of the LH notched scenario, the pellet penetration remains significantly reduced (see Fig. 2) for the configuration tested. This effect, cumulated with the outward ∇B-induced drift (unfavorable for LFS launched pellets), leads to a still shallow pellet particle source. In the present case, the pumped and trapped fluxes represent respectively $\varepsilon = 0.5\%$ and $\pi = 0.8\%$ of the total flux circulating in the SOL. In such long duration, low

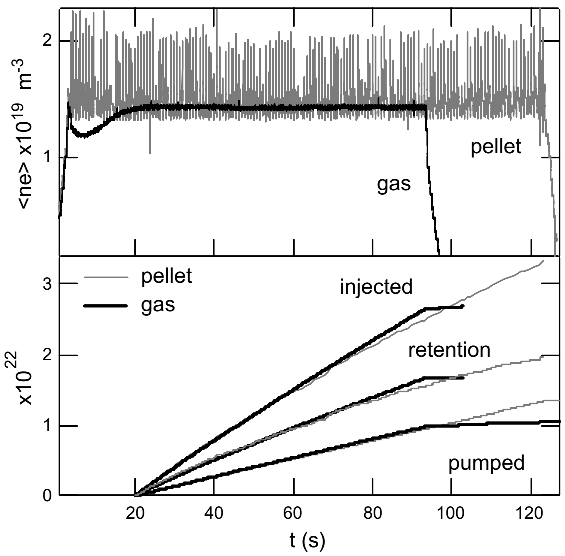

Fig. 4. Comparison of the volume average density, injected and pumped particle fluxes and resulting retention for two 2 min discharges fuelled by pellet injection (*TS33009*) or gas puff (*TS33001*).

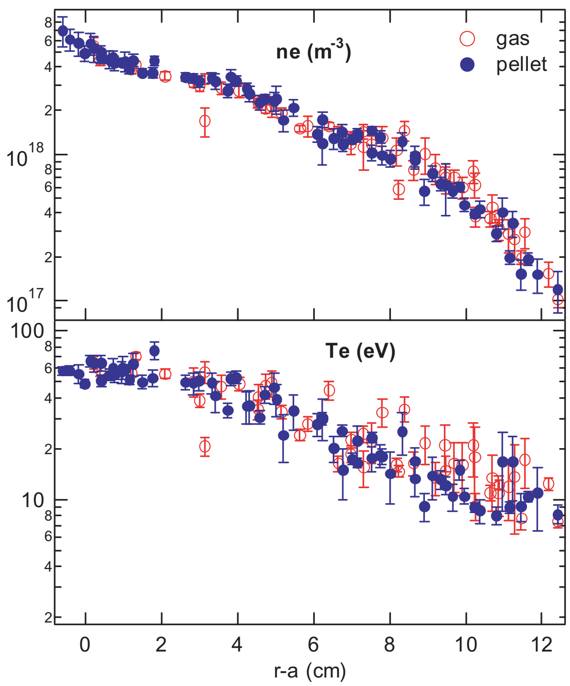

Fig. 5. Comparison of the density and temperature profiles in the SOL for discharges *TS33001* ($t = 20.2$ s) and *TS*33009 ($t = 12.3$ s, 180 ms after pellet ablation) from a reciprocating Langmuir probe.

density, low current discharges where the effective particle source is essentially due to the recycling, one cannot expect a significant reduction of the retention by changing the direct source penetration or fuelling efficiency.

4. Conclusion

The continuous pellet injector installed recently on Tore Supra allowed the comparison of gas and pellet fuelling during long discharges in the low current/low density regime imposed by the presently limited LH power available. In such conditions, the recycling dominates widely the circulating flux in the SOL (more than 60 times the injected flux), that is the main cause of the important retention observed. New experiments are planned during the next Tore Supra campaign. They will be performed at higher density, higher current and in optimised scenarios in what concerns the LH notching and pellet injection geometry.

References

[1] D. van Houtte, G. Martin, A. Becoulet, et al., Nucl. Fusion 44 (2004) L11.
[2] Ch. Brosset et al., these Proceedings. doi:10.1016/j.jnucmat.2004.10.045.
[3] P.T. Lang et al., Phys. Rev. Lett. 79 (8) (1997) 1487.
[4] L.R. Baylor, T.C. Jernigan, C. Hsieh, Fus. Technol. 425 (1998).
[5] A. Géraud, C.A. Foster, B. Pégourié, et al., ECA Vol. 16C (Part I) EPS, 1992, p. 159.
[6] A. Géraud, I. Viniar, S. Skoblikov, et al., Fusion Eng. Des. 69 (2003) 5.