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Fuel retention in impurity seeded long discharges in Tore Supra

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ABSTRACT

In next step machines, tritium retention in the carbon walls is a major concern. In Tore Supra, long pulses with impurity seeding were developed to study deuterium retention in stationary conditions at low edge temperatures. A double feedback was implemented, with deuterium injection set on plasma density and impurity injection set on the radiated fraction. Long discharges (~1 min) were obtained with radiated fractions in the range 60–80%. Neon and argon seeding were tested. In both cases, a small fraction of the injected impurity is transiently trapped in the wall, and released at the end of the shot. The deuterium retention rate decreases significantly with increasing radiated fraction, both for Ne and Ar seeding, in absolute and relative value (when related to D_2 injection rate, or Dα recycling on the limiter). Interpretation is still an open question, as different retention mechanisms could be affected (implantation, codeposition, bulk diffusion).

1. Introduction

In next step machines, tritium retention in the carbon walls is a major concern [1]. With its superconducting magnets and actively cooled plasma facing components, Tore Supra offers a unique opportunity to study this phenomenon in stationary conditions over long durations [2]. Previous experiments have shown that a constant fraction of the injected gas is retained in the wall during long pulses, indicating no sign of wall saturation [3]. However, these discharges, performed at low density/high edge temperature in order to reach record durations, are not representative of divertor scrape off layer (SOL) conditions in terms of Te, in particular for semi detached plasmas as contemplated for ITER scenarios. Moreover, Te is a key parameter in determining erosion/redeposition regimes on plasma facing components (PFCs), therefore influencing the fuel retention due to codeposition of deuterium (D) with eroded material. Long pulse scenarios with reduced pulse length (1 min) were then developed at higher density/higher power, showing that the retention rate depends mainly on the lower hybrid power in the parameter range explored [4]. However, the edge temperature reached in these experiments is still high (Te ~ 50 eV). In order to further extend the Tore Supra retention database towards lower Te, impurity injection was used to reach high radiated fractions and low edge temperatures.

This paper presents the long pulse scenarios with impurity seeding developed for this purpose and the results obtained in terms of particle balance for fuel as well as for the injected impurities.

2. Experimental scenario

Long pulses, as requested for particle balance studies (~1 min), were performed using lower hybrid current drive (LHCD) at low plasma current and medium density ($I_p = 0.6$ MA, $P_{LH} = 2.4$–2.7 MW, $\langle n_e \rangle = 2.1\ 10^{19}\ m^{-3}$, L mode). In order to control these discharges, a double feedback scheme was implemented, with deuterium injection set on plasma density and impurity injection set on the radiated fraction f_{rad}. Radiated fractions in the range 60–80% were obtained, to be compared with ~30% in equivalent discharges in pure deuterium (i.e. with the electron density n_e kept constant for comparison). Although possible to achieve in shorter ohmic plasmas, higher radiated fraction were difficult to control in LH heated discharges, due to the sensitivity of power coupling to SOL conditions. Tested impurities include neon (Ne) and argon (Ar). Nitrogen (N_2) was used for scenario development, but not for retention studies, as particle balance becomes difficult due to the complex chemistry of N_2 and D. At high radiated fraction (>60%), the electrons provided by the impurities reach more than

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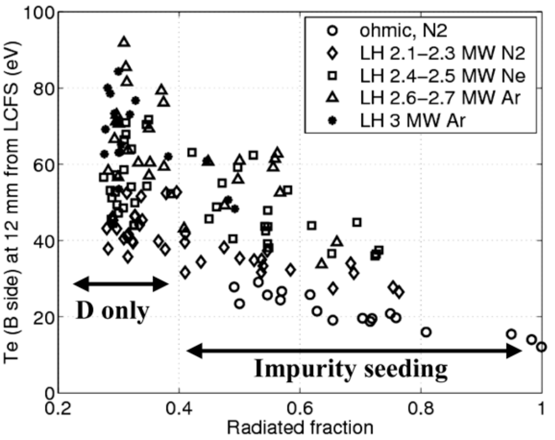

Fig. 1. Edge electron temperature (as measured at 12 mm from the LCFS by the mobile Langmuir probe) as a function of the radiated fraction for the impurity seeded discharges database. Radiated fraction around 30% corresponds to reference D only discharges, while higher radiated fractions correspond to impurity seeded discharges.

50% of the total electrons injected in the discharge, although the impurity fluxes injected are less than 10% of the D injected flux in terms of atoms (see Table 1, Section 3)[1]. The effective charge Z_{eff} goes from 2–2.5 for the pure D discharges to 3–4.2 for the equivalent discharges with impurity seeding.

Fig. 1 summarizes the edge temperature obtained (as measured at 12 mm from the LCFS by a reciprocating Langmuir probe) as a function of the radiated fraction for the whole impurity seeding database. In the range of f_{rad} used for retention studies (60–80%), the decrease of temperature is moderate (ΔTe = 10–20 eV between D only and impurity seeded discharges).

3. Particle balance

Tore Supra is equipped with diagnostics allowing to achieve reliable particle balance (accuracy ~ 10%) [5]. The D retention rate Φ_{wall} is calculated from

$$dN_p/dt = \Phi_{inj} - \Phi_{pump} - \Phi_{wall} \tag{1}$$

where N_p, Φ_{inj}, and Φ_{pump} are the measured plasma content, injected flux and exhausted flux, respectively (please note that neutrals in the vessel are not taken into account here, but they do not play any role in the stationary phase discussed in following sections). The main exhaust system during the shots is the toroidal pump limiter (TPL). The TPL pumping system can be switched off during discharges, in order to suppress uncertainties linked to Φ_{pump} in the particle balance (in this case, (1) simply becomes $\Phi_{wall} = \Phi_{inj}$ if the plasma is stationary).

3.1. Impurity balance

For Ne as well as for Ar seeding, impurities appear to be only transiently trapped in the wall for a small fraction, which is released at the end of the shot, as is seen from analysis of the exhaust gas with gas spectrometry. This result is confirmed by discharges with Ne seeding performed without active pumping, where after the first phase (~5 s) when Ne is injected to reach the radiated fraction set by the feedback system, no additional Ne injection is requested to maintain the radiated fraction throughout the discharge. Therefore, Ne and Ar trapping by the wall is not significant, and during shots with active pumping, the injected impurities are mainly exhausted by the TPL.

Table 1
Main discharge parameters for a scan of f_{rad} performed with Ne seeding (time dependent data taken at t = 30 s): radiated fraction f_{rad}, plasma effective charge Z_{eff}, Ne and D injected fluxes, the corresponding e-fraction from Ne in the injected gas, D retention rate taking into account corrections described in Section 3.2, Te at the LCFS from reciprocating probe measurements, Dα and CII spectroscopy from the VD3 line of sight (viewing the plasma loaded area of the limiter, see [6]), power load fraction falling on the TPL (f_{TPL}) and the vessel walls (f_{vessel}) from calorimetry.

Shot number	37724	37721	37725
f_{rad}	0.32	0.55	0.73
Z_{eff}	2	3.2	4.2
Ne injected flux (10^{20} Ne s^{-1})	0	0.1	0.15
D injected flux (10^{20} D s^{-1})	4.7	3.2	1.5
e-fraction from Ne in the injected gas	0	0.24	0.5
Corrected D retention rate (10^{20} D s^{-1})	3	1.85	0.45
Te at LCFS (eV)	70	60	50
Dα (VD3, au)	8	6	4.5
CII (VD3, au)	6.3	5	4
f_{TPL} (%)	55	39	28
f_{vessel} (%)	32	45	58

3.2. Deuterium balance

The D injected rate and the D retention rate obtained from particle balance are shown in Fig. 2 for a scan in f_{rad} performed with Ne seeding. Table 1 summarizes the main discharge parameters from the three shots compared. In the stationary phase of the discharge (t > 20 s), the plasma electron content and the exhaust gas (not shown here) are similar, but the D injection requested to maintain the electron density is strongly reduced while the Ne injection is raised. The calculated D retention rate is reduced accordingly.

However, the effect of impurities is not taken into account in the particle balance shown in Fig. 2. It affects first the D^+ fraction in the measured plasma electron content (here $n_e = n_{D+}$ is assumed, instead of $n_e = (1+Z_{imp}\chi_{imp})\, n_{D+}$ where Z_{imp} and χ_{imp} are the charge and the concentration of the impurity considered, $n_{imp} = \chi_{imp}\, n_{D+}$). However, in the stationary phase of the shot, it does not affect the particle balance as $dN_p/dt = 0$ (see Eq. (1)). The second effect is on the exhaust flux Φ_{pump}, where the measured pressure used to estimate Φ_{pump} includes both the deuterium and impurity contribution, while it is assumed to be D only in the calculation shown in Fig. 2. Fig. 3 illustrates the correction on the retention rate when taking impurities into account in the exhaust flux (data taken in the stationary phase at t = 30 s). The first set of data ($\Phi_{wall\ 1}$ w/o impurities) corresponds to assuming D only in the exhaust flux. The second set of data ($\Phi_{wall\ 2}$ with impurities) corresponds to assuming all the measured injected impurity flux Φ_{imp} is pumped by the TPL ($\Phi_{wall\ 2} = \Phi_{wall\ 1} + \Phi_{imp}$). Finally, the third (and most

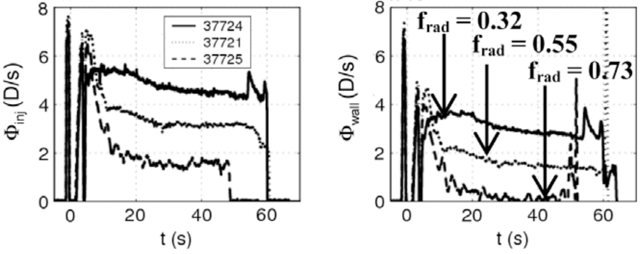

Fig. 2. D injected flux (left) and D retention rate (right) for three similar discharges with a scan in f_{rad} (see Table 1). Caution: impurities are not taken into account in the particle balance shown here, minimizing the retention rate calculated (see Fig. 3).

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[1] Please note that for fuel retention issues, what matters is the ion content of the discharge, in particular the D flux trapped in the wall as a function of the incident D flux on the vessel walls.

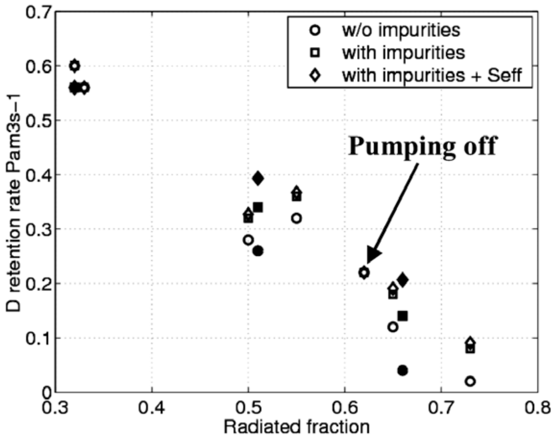

Fig. 3. D retention rate as a function of the radiated fraction (data at $t = 30$ s) following different assumptions, showing the effect of the impurities on the D particle balance. Circle: D retention rate without taking into account impurities in the exhausted flux. Square: D retention rate assuming impurities are pumped at the same rate as they are injected. Diamond: D retention rate taking into account impurity enrichment in the exhaust gas, due to a lower pumping speed. Open symbols correspond to Ne seeding, plain symbols to Ar seeding. Data for a shot with the TPL pumping off are also indicated.

accurate) set of data ($\Phi_{\mathrm{wall}\ 3}$ with impurities + S_{eff}) takes into account in addition that the effective pumping speed S_{eff} is lower for impurities, as seen from gas calibration measurements

$$\Phi_{\mathrm{wall}\,3} = \Phi_{\mathrm{wall}\,1} + \Phi_{\mathrm{imp}}/F_{\mathrm{imp}} \qquad (2)$$

where F_{imp} is the correction factor due to the pumping speeds ($F_{\mathrm{imp}} = 0.85$ and 0.6 for Ne and Ar, respectively). This correction is stronger for Ar (closed symbols) than Ne (open symbols) as the impurity enrichment in the exhaust gas is higher. It also becomes more pronounced as the radiated fraction increases, as seen in Fig. 3. Data for a shot performed with TPL pumping off, therefore not affected by impurity in the exhaust gas, are also shown, in good agreement with the corrected retention rates.

4. Discussion

Fig. 4 summarizes the results obtained for the impurity seeding database, with the injected D_2 and Ar/Ne fluxes, the D retention rate (corrected values), and the D retention fraction ($f_{\mathrm{wall}} = \Phi_{\mathrm{wall}}/\Phi_{\mathrm{inj}}$) as a function of the radiated fraction (data taken at $t = 30$ s). The experimental trend is the same for Ne and Ar seeded discharges, with a reduction of the retention rate both in absolute and relative value.

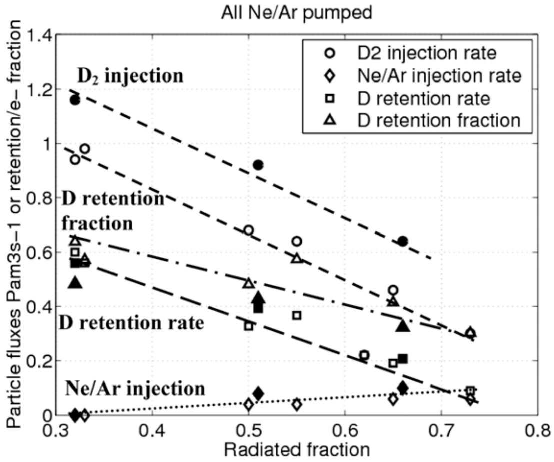

Fig. 4. D_2 injection rate (Pa m^{3}s^{-1}), Ne/Ar injection rate (Pa m^{3}s^{-1}), D retention rate (Pa m^{3}s^{-1}) and D retention fraction as a function of the radiated fraction for the impurity seeded discharges database (data at $t = 30$ s). Open symbols correspond to Ne seeding, plain symbols to Ar seeding. Dashed lines are only meant to guide the eye of the reader.

As the Te decrease obtained in these experiments is moderate, no major direct effect is expected on the retention rate (no significant impact on the carbon erosion yield, and therefore codeposition, for instance). However, the effect of increasing the radiated fraction on the ion temperature Ti is still to be assessed, and not taken into account here, although it could be significant.

In the following, we will compare a reference D only case (shot 37724, $f_{\mathrm{rad}} \sim 0.3$) and a highly radiating Ne seeded case (37725, $f_{\mathrm{rad}} \sim 0.7$), see data in Table 1. The retention rate decreases by a factor 6 between the D only discharge and the equivalent impurity seeded discharge at high f_{rad}, while the D injected rate only decreases by a factor 3.

To explain this result, the first effect to take into account is plasma dilution. Indeed, since the electron density n_e is kept constant for the comparison between discharges, the deuterium density n_{D^+} in the plasma varies. For instance, assuming the impurity concentration in the plasma edge is the same as in the injected fluxes, ($\chi_{\mathrm{imp}} \sim 10\%$, probably underestimated in the plasma edge) and $Z_{\mathrm{imp}} = 10$ for Ne (probably overestimated for the plasma edge), one obtains $n_{\mathrm{D+seeded}} = 0.5\ n_{\mathrm{D+\ only}}$ for the highly radiating Ne case compared to the D only equivalent case. Taking into account both plasma dilution (factor 2) and temperature decrease (additional factor 1.2, see Table 1) yields to a total reduction of ~2.4 on the incident D^+ flux on the TPL. This is in rough agreement with the measured Dα recycling on the limiter, as seen from visible spectroscopy (optical fibers with line of sight on the plasma loaded zones of the TPL [6]), with a decrease in the Dα raw signal by a factor ~1.8 (in the temperature range involved, a limited effect on the S/XB factors used to translate the Dα signal in particle flux is expected). Therefore the reduction in the incident D^+ flux on the TPL (factor ~2) does not seem enough to explain the observed decrease in the D retention rate (factor 6).

To go further, we will review how the different retention mechanisms could be affected by the impurity injection.

First, it has to be noted that increasing f_{rad} leads to a change in the power load distribution in the vessel, as measured by calorimetry. Indeed, the main power loaded plasma facing component, taking roughly 60% of the injected power, switches from the TPL to the vessel walls (i.e. inner carbon bumpers + stainless steel inner vessel protection panels) when increasing f_{rad} (see the fraction of power falling on the TPL f_{TPL} and the vessel walls f_{vessel} in Table 1). This could lead to a change of the particle flux distribution in the vessel as well, affecting the overall particle balance.

Carbon erosion, and therefore codeposition, is also affected. In the Te range obtained, no major change in the erosion yield of carbon by D is expected, so that the carbon source due to D impact should decrease as the incident D flux on the limiter (factor 2.4). However, an additional contribution to the carbon source will come from Ne sputtering. Indeed, the CII light on the limiter is seen to decrease with increasing radiated fraction, while the CII/Dα ratio increases, indicating that Ne participates to sputtering (see Table 1). However, the moderate CII decrease (factor 1.6) does not seem enough to explain the decrease in the experimental retention rate.

Finally, bulk diffusion could also be affected, as the transient wall trapping of the injected impurities could lead to porosity plugging for deuterium.

5. Conclusion

In order to extend the retention database of Tore Supra towards lower Te, long pulse scenario with impurity seeding have been developed. Long discharges (~1 mn) were obtained with radiated fractions in the range 60–80%. Neon and argon seeding were tested. In both cases, a small fraction of the injected impurity is transiently trapped in the wall, and released at the end of the shot. The deuterium retention rate decreases significantly with increasing radiated fraction, both for Ne and Ar seeding, in absolute and relative value (when related to D_2 injection rate, or Dα recycling on the limiter). The decrease in the incident D flux on the limiter due to plasma dilution when injecting impurities does not seem enough to explain this result. Interpretation is still an open question, as, from a first crude analysis, different retention mechanisms could be affected (implantation, codeposition, bulk diffusion). Further data analysis and associated modelling are needed in order to extrapolate those results to ITER, where the reference scenario relies on impurity seeding to obtain semi detached plasmas.

References

[1] J. Roth, E. Tsitrone, A. Loarte, et al., J. Nucl. Mater. 390–391 (2009) 1.
[2] E. Tsitrone, J. Nucl. Mater. 363–365 (2007) 12.
[3] E. Tsitrone, C. Brosset, J. Bucalossi, et al., in: Proceedings of 20th IAEA Fusion Energy Conference, Vilamoura, 2004.
[4] J. Bucalossi, C. Brosset, E. Dufour, et al., in: Proceedings of the 32nd EPS Conference on Plasma Phys., Tarragona, ECA vol. 29C, 2005, O-4.005.
[5] J. Bucalossi, C. Brosset, B. Pégourié, et al., J. Nucl. Mater. 363–365 (2007) 759.
[6] E. Delchambre et al., J. Nucl. Mater. 390–391 (2009) 65.