ELSEVIER

Journal of Nuclear Materials 241–243 (1997) 760–764

journal of nuclear materials

Retention of Ne and N_2 in the closed and pumped TdeV divertor with attached and detached plasmas

N. Richard *[,1], B. Terreault [2], E. Haddad [1], J. Gunn [2], G. Abel [2], S. Chiu [2], J.-L. Gauvreau [3], H.H. Mai [2], W.W. Zuzak [2]

Centre Canadien de Fusion Magnétique, 1804 Boulevard Lionel-Boulet, Varennes, Qué., Canada J3X 1S1

Abstract

We have studied the retention of a recycling impurity, neon, and a wall-pumped impurity, nitrogen, in the closed and cryopumped divertor of the TdeV tokamak, under a variety of heating, puffing, pumping and biasing conditions. Retention times were deduced from either the decay time or the rise time of the plasma impurity content, measured spectroscopically, following either a short puff or a steady injection. For both neon and nitrogen, the compression ratio increases rapidly with the main plasma density. Retention is not degraded by plasma detachment. In density scans, other conditions being kept constant, the compression ratio for neon is found to grow with the divertor neutral pressure as $\sim P_D^{1.5}$. However, by puffing, pumping or biasing, retention and P_D can be varied quite independently of each other.

Keywords: TdeV; Particle fuelling; Particle confinement; Detached plasma; Biasing

1. Introduction

High radiation levels will be necessary for power removal in long-pulse ignited tokamaks. The bulk of this power must be radiated near the plasma boundary or in the divertor region in order to retain high central temperatures. Encouraging results, using neon seeding, were obtained in TEXTOR [1]. The crucial point is to demonstrate high radiation levels (> 80% of input power) together with high confinement and low Z_{eff} [2]. Calculations indicate that it may be possible to radiate sufficient power close to the separatrix in ITER, using argon injection [3], but this requires narrowly specified plasma parameters. If impurities could be retained well enough in the divertor, to radiate therein, main plasma optimization could be decoupled from power exhaust. Retention of non-recycling impurities, ionized close to the divertor plates, is predicted [4] to be excellent. However, recycling noble gases are most often used as radiators because they are easy to inject in a controlled manner. For these impurities, retention is thought to be determined by the location of ionization [4], therefore the geometry of each machine is important. TdeV provides a useful comparison since it is characterized by a narrow plasma fan, due to triplet coils, and a large closed plenum on the outboard side, where the neutrals can be thermalized (see Fig. 1). An unsettled question is the effect of detachment on retention: the location of the ionization front would be crucial, and retention could be seriously deteriorated by detachment.

In this paper we study divertor retention of a totally recycling impurity (Ne), and a partly recycling impurity (N_2), for both attached and detached plasmas [5]. TdeV ($R = 0.87$ m, $a = 0.26$ m, $B_T = 1.8$ T) was operated in the upper single-null mode with the ion ∇B drift pointing away from the X-point. The plasma current was 190 kA, and the feedback-controlled density was varied from 3 to 6×10^{19} m^{-3}. The L-mode plasmas were additionally heated by 700 kW of lower hybrid waves [6]. The divertor plenum was pumped by 6 cryosorption units giving effective pumping speeds of 6 m^3/s for D_2, 3.1 m^3/s for Ne and 3.6 m^3/s for N_2 (calibrated with gases at 300 K). The slanted graphite plates (hatched in Fig. 1), that separate the

---

* Corresponding author. Tel.: +1-514 562 8733; fax: +1-415 652 8625; e-mail: richard@ccfm.ireq.ca.

[1] MPB Technologies, Inc.

[2] INRS-Énergie and Matériaux.

[3] IREQ, Hydro-Québec.

PII S0022-3115(96)00602-2

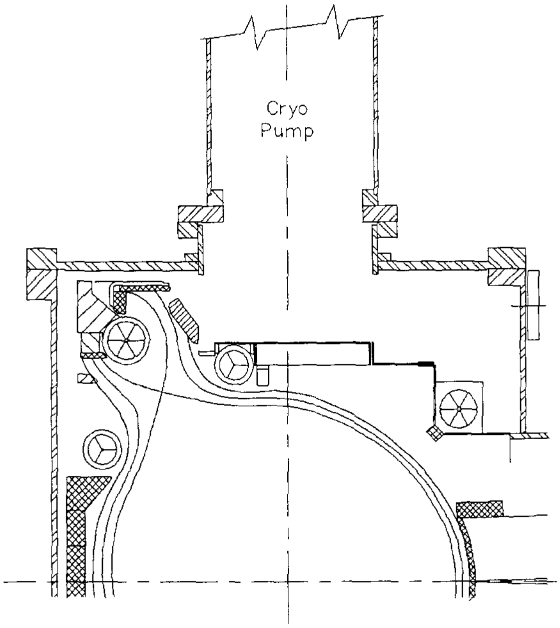

Fig. 1. Poloidal section of TdeV showing the divertor region.

divertor plasma from the plenum, actually cover only one third of the toroidal circumference. The resulting vacuum conductances between the plenum and the main chamber are 70, 32 and 27 m^3/s for thermalised D_2, Ne and N_2 respectively; the time constants τ_V (volume/conductance) are 7, 16 and 19 ms. The divertor cryoexhaust times τ_C (volume/pumping speed) are 85, 160 and 140 ms.

2. Neon injection

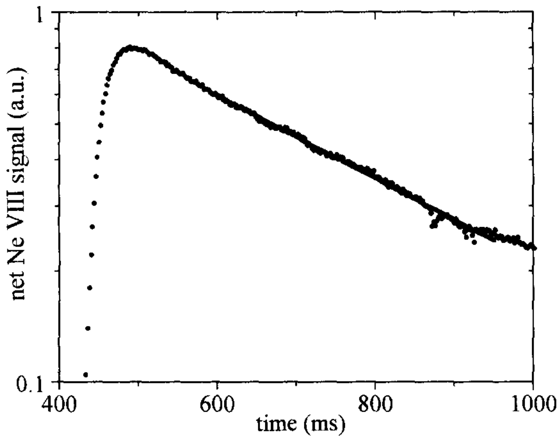

Fig. 2. Log plot and fit of the decay of the net Ne VIII signal in the main plasma following a short neon puff.

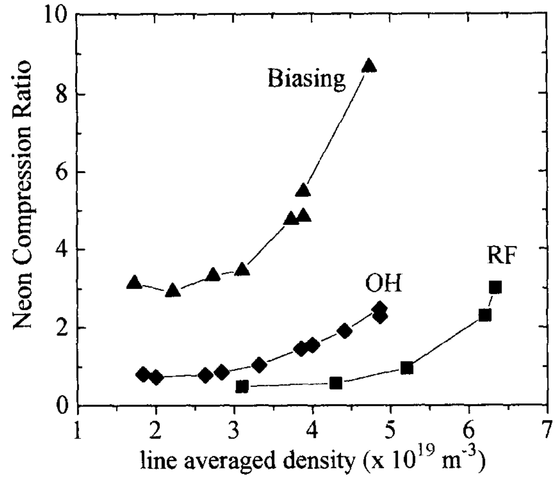

Fig. 3. Neon compression ratio as a function of main plasma density, in different experiments: (■) single-null, RF heating, and cryopumping, (◆) double-null, OH only, no pumping, (▲) double-null, OH only, no pumping, and with negative plate biasing.

Neon was introduced as a short (25 ms) calibrated puff in the main chamber, at a level ($n_{Ne}/n_e \ll 1\%$) that did not perturb the plasma parameters or the total radiation level. Its exhaust through cryopumping was observed by several spectroscopy diagnostics which all gave consistent results. The data from a VUV spectrometer tuned to Ne VIII (77.04 nm) is used for analysis. Neon shots were separated by blank shots to subtract the background ($\leq 10\%$). Fig. 2 shows typical neon evolution data. After the initial transient, an equilibrium between the divertor and the plasma is established. Using a simplified model where it is assumed that plasma refuelling is caused by divertor neutrals, the measured decay time τ^*_{Ne} of the main plasma neon ion content can be related to the divertor retention time τ_D for neon via Eq. (1):

$$\tau^*_{Ne} = \tau_C(1 + \tau_P/\tau_D) \qquad (1)$$

where τ_P is the main plasma neon confinement time, which is assumed to be equal to the deuterium main plasma confinement time in the absence of independent

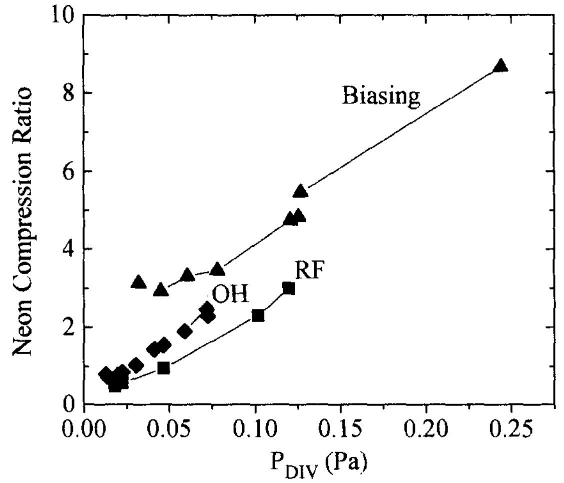

Fig. 4. Same data as in Fig. 3 plotted as a function of the divertor neutral pressure.

measurement. The compression ratio, defined as the ratio of the neon densities in the divertor and the plasma, is obtained from Eq. (1) and the respective volumes (divertor = 0.5 m^3, plasma = 1 m^3). This ratio (■) is plotted as a function of the main plasma density in Fig. 3. The compression ratio increases rapidly with density, even though detachment starts between 4 and 5×10^{19} m^{-3}, and is fully developed at 6×10^{19} m^{-3} [5]. The particle plasma confinement time has not been measured precisely in these RF-heated conditions. However, a rough value $\tau_P \approx 13$ ms can be inferred from the level of D_α radiation relative to that in well-analyzed data. On this basis, τ_D would vary from ≈ 3 ms at the lowest density to ≈ 18 ms at the highest density. At low density, τ_D is much smaller than the vacuum retention time τ_V of 16 ms. On ASDEX Upgrade, a relation between τ_D and the divertor neutral pressure was found ($\tau_D \sim P_D^{1.4}$) [7], and P_D was proposed as the main predictor of retention [8]. Fig. 4 is a plot of the compression ratio versus P_D. We also see a correlation between τ_D and P_D, and in the single-null, RF-heated discharges, we found that $\tau_D \sim P_D^{1.5}$.

For comparison purposes, earlier Ohmic data with (▲) and without (◆) divertor biasing (−130 V) [9], are also shown in Figs. 3 and 4. These data were obtained in a double-null configuration, no cryopumping, and with the $E \times B$ flow induced by divertor plate biasing directed to the upper divertor. On Fig. 4 we see that, with biasing, τ_D is enhanced by a large factor, compared with the OH data, for the same P_D value. It is then clear that retention does not depend only on divertor neutral pressure.

3. Nitrogen injection into the divertor chamber

Since nitrogen ions, like deuterium ions, can be trapped by the divertor plates and then partly reemitted, the location of N_2 injection becomes important. We injected nitrogen through 4 calibrated, rapidly opening (≈ 2 ms) piezoelectric valves, located around the plenum to insure a uniform injection. A mixture of 20% N_2 in D_2 was used because the valves do not operate reproducibly at low flow rates. The nitrogen 'plate pumping' speed being large but unknown, the puff and decay technique is inapplicable for our purpose. Instead, a constant flow rate (0.4 to 2×10^{20} N/s) was injected, starting at a precise time during the discharge flat-top. By valving off the cryopumps, we found that 'plate pumping' dominated over cryopumping, as expected. The time evolution of the nitrogen ions in the plasma was measured using a VUV line of N V (123.8 nm). Fig. 5 shows typical signal rise data. Because of nitrogen accumulation in the divertor plates, cleaning with glow discharges or a series of low density discharges was necessary between injection shots.

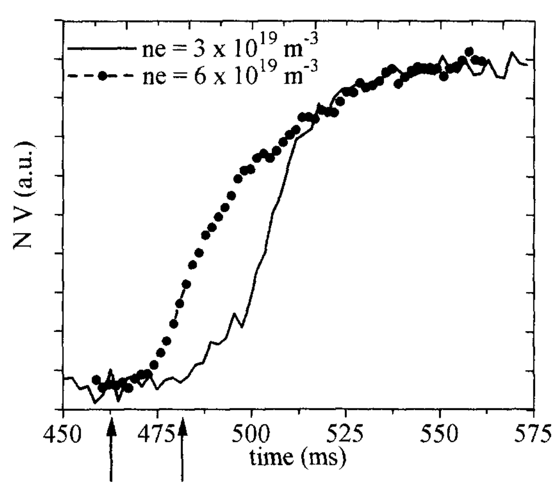

Fig. 5. Initial evolution of N V signal following injection of a constant flow of D_2–N_2 (20%) mixture in divertor: (————) attached plasma, $\bar{n}_e = 3 \times 10^{19}$ m^{-3}, injection time ≈ 481 ms; (· · ·) detached plasma, $\bar{n}_e = 6 \times 10^{19}$ m^{-3}, injection time $\approx$ 462 ms.

For $t \ll \tau_C$, the initial rise of the nitrogen ion density in the plasma is unaffected by cryopumping in the first approximation. Thus, in a simplified model, nitrogen evolution in the main plasma and in the divertor is described by the equations:

$$dN_P/dt = -N_P/\tau_P + N_D/\tau_D,$$

$$dN_D/dt = RN_P/\tau_P - N_D/\tau_D + Q \qquad (2)$$

where Q is the nitrogen input from the valves and R the coefficient of nitrogen reemission, including reflection, from the plates; $(1 - R)$ describes 'plate pumping'. If we make the further assumption that R is constant during the initial phase, the solution for the plasma nitrogen content is:

$$N_P(t) = Q\tau_P\left[\tau_L(1 - \exp(-t/\tau_L)) - \tau_S(1 - \exp(-t/\tau_S))\right]/\left[(\tau_L - \tau_S)(1 - R)\right] \qquad (3)$$

where τ_L (τ_S) is the longest (shortest) of the time constants $\tau_{1,2}$:

$$\tau_{1,2} = -2\tau_P\tau_D \Big/ \left[-(\tau_P + \tau_D) \pm \sqrt{(\tau_P - \tau_D)^2 + 4R\tau_P\tau_D}\right] \qquad (4)$$

When $R \ll 1$ (conjectured to be true initially), τ_1 and τ_2 are reduced to:

$$\tau_1 \approx \tau_P/\left[1 - R\tau_P/(\tau_P - \tau_D)\right] \approx \tau_P$$

$$\tau_2 \approx \tau_D/\left[1 + R\tau_D/(\tau_P - \tau_D)\right] \approx \tau_D \qquad (5)$$

Thus, τ_L will be very roughly equal to τ_P or τ_D, whichever is the longest.

Fig. 5 shows the rise of the N V signal for a low density shot (3×10^{19} m^{-3}, solid line), and a high density shot (6×10^{19} m^{-3}, dots); the D_2–N_2 valve opening times are indicated by arrows. At low density, the plasma fills

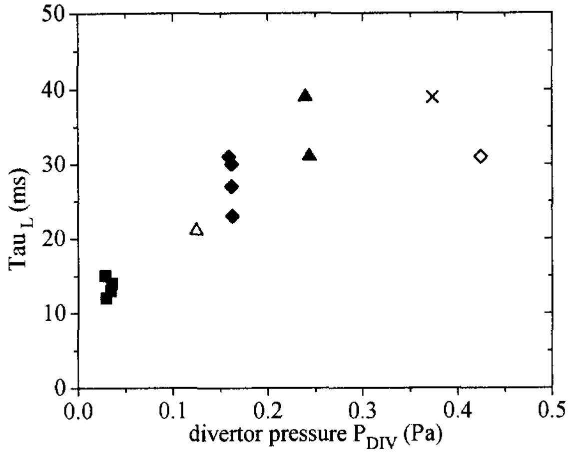

Fig. 6. τ_L as a function of divertor neutral pressure, for different conditions: (■) 3×10^{19} m^{-3}, OH or OH+RF; (△) 6×10^{19} m^{-3}, RF, intense puffing of pure N_2 ('radiative plasma' [14]), (◆) 6×10^{19} m^{-3}, OH only; (▲) 6×10^{19} m^{-3}, RF; (x) 6×10^{19} m^{-3}, RF, no cryopumps, (◇ 6×10^{19} m^{-3}, RF, more D_2+N_2 puffing.

with nitrogen ions within one or two τ_P's (assumed to be equal to the τ_P for deuterium, so $\tau_P \approx 13$ ms), whereas at high density, divertor retention delays the inflow of nitrogen into the plasma core, in spite of detachment. Because of the uncertainty in R, which certainly varies with density and time, it is impossible to extract precise values of τ_D from the data. But values of τ_L can be found by fitting Eq. (3) to the experimental data. Doing so, we find that τ_L is ≈ 14 ms for the low density shots and ≈ 30 ms for the high density shots. Thus, at low density, $\tau_L \approx \tau_P$, and from the above arguments, $\tau_D \leq \tau_P$. This finding is similar to the case of neon (see Fig. 3). At higher density, τ_L must be connected with τ_D, which implies a τ_D/τ_P of ≈ 2.3 and a compression ratio of ≈ 4.6. Thus, the compression for nitrogen is similar to that of neon (Fig. 4).

Fig. 6 displays τ_L as a function of the divertor pressure P_D in a variety of experiments. We see that by varying conditions such as additional heating, pumping, and D_2 and N_2 puffing, the neutral pressure P_D can be varied several fold, at high density, without affecting divertor retention very significantly.

4. Discussion and conclusion

For low density shots, the small τ_D ($< \tau_V$) found for neon implies that plasma refuelling is not caused mainly by thermalized neutrals. It is either due to fast neutrals reinjected in the main plasma or/and by neon atoms that are ionized in the divertor but are not driven back to the plates. For nitrogen, the same behavior seems to occur although the uncertainty in the analysis allows only one to say that $\tau_D \leq \tau_V$. It has to be noted that the simplified model used to deduce τ_D does not include ion refuelling. If the latter is important, then by using the simplified model we would actually underestimate the retention time of the neutrals in the divertor.

For high density shots, when the plasma is detached, we found, for both Ne and N_2, $\tau_D \geq \tau_V$. Main plasma refuelling would then be caused by thermalized neutrals (consistent with a high measured Ne divertor pressure [9]), and by ions that are better retained in the divertor than in the low density case. Considering the Ne and N_2 ionization cross-sections [10–12], thermalized neutrals are likely to be ionized in the divertor. Despite plasma detachment, these ions appear to be driven back to the divertor plate by the friction force exerted by the incoming D^+ flow [13]. We do not have a direct measurement of this friction force. However, the six-fold increase in divertor neutral pressure at high density (6×10^{19} m^{-3}) compare to low density operation (3×10^{19} m^{-3}) is probably a good indication of the increase of the ion flow in the divertor. This fact could explain the Ne and N_2 retention results. It makes it worthwhile to attempt quantitative modelling.

As we saw, retention can vary considerably at fixed P_D (Fig. 4), or inversely, remain rather constant under P_D variation (Fig. 6). The retention-P_D correlation is unambiguous only in density scans, everything else being kept constant. The correlation is thus not basic though there is necessarily a link between P_D and retention. Each 'anomalous' case (biasing, etc.) calls for a different explanation to be discussed elsewhere. The point is that it seems possible to decouple retention from divertor neutral pressure to some extent.

Acknowledgements

Special thanks are due to S. Savoie and M. Gagné for the gas systems, J.-L. Lachambre for the particle confinement time estimate, and A. Kallenbach, R. Schneider, and P. Stangeby for discussions. The *Centre canadien de fusion magnétique* is a joint project of Atomic Energy of Canada Ltd., Hydro-Québec and INRS, in which MPB Technologies Inc. and Canatom Inc. also participate. It is funded by AECL, Hydro-Québec and INRS.

References

[1] A.M. Messiaen et al., Nucl. Fusion 36 (1996) 39.
[2] Report of the Fourth ITER Divertor Physics and Divertor Modelling and Database Expert Group Workshop, San Diego, CA, March 11–15 (1996).
[3] D. Post et al., Bull. Am. Phys. Soc. 40 (1995) 1729.
[4] P.C. Stangeby and J.D. Elder, Nucl. Fusion 35 (1995) 1391.
[5] B.L. Stansfield et al., these Proceedings, p. 739.
[6] Y. Demers et al., Control. Fusion Plasma Phys. 18B III (1994) 1086.
[7] R. Dux et al., Measurement and modelling of neon radiation profiles in radiating boundary discharges in ASDEX Upgrade, Plasma Phys. Control. Fusion, submitted.

[8] A. Kallenbach et al., Nucl. Fusion 35 (1995) 1231.
[9] B. Terreault et al., Nucl. Fusion 34 (1994) 777.
[10] T. Kato, K. Masai and M. Arnaud, Comparison of Ionization Rate Coefficients of Ions from Hydrogen through Nickel, National Institute for Fusion Report NIFS-DATA-14, Nagoya (1991).
[11] R.L. Freeman and E.M. Jones, Atomic Collision Processes in Plasma Experiments, UKAEA Culham Report CLM-R 137.
[12] R.K. Janev et al., Survey of Atomic Processes in Edge Plasmas, Princeton Plasma Physics Laboratory Report (unnumbered and undated).
[13] J. Roth et al., Nucl. Fusion 32 (1992) 1835.
[14] B. Terreault et al., these Proceedings, p. 755.