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Behaviour of hydrogen in JET deuterium plasmas

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Abstract

Hydrogen as an impurity in deuterium discharges has been studied using three different experimental methods on a pulse by pulse basis over seven months of JET operation as well as regarding its behaviour during single pulses. Evidence concerning the primary sources and the dynamics of recycling and removal of hydrogen has been obtained. A transient enrichment of hydrogen in high performance plasmas has been found and studied.

Keywords: JET; Impurity source; Neutral particle diagnostic; Line emission diagnostic; Wall particle retention

1. Introduction

Deuterium plasmas in JET are always contaminated by a varying fraction of hydrogen which is trapped in the walls and released and recycled during plasma operation. Evaluation of its relative concentration is important for understanding the reduction of fusion reactivity to be expected and for preparation of proper target plasma conditions for ICRF hydrogen minority heating. It is the objective of this paper to identify the main sources of hydrogen in the vessel, to find out what its relative concentration in the plasma depends on, to characterize the dynamics of hydrogen trapping and outgassing in the vacuum vessel walls, to determine the lowest possible level of hydrogen attainable, and to study the behaviour of the H-to-D ratio in high performance plasmas.

The investigation, concerning the 1994–1995 experimental campaign, is based on neutral hydrogen/deuterium efflux (time-of-flight neutral particle analyser: NPA), visible light spectroscopy (H_α and D_α Balmer line intensities), and the before and after pulse difference of the in-vessel gas pressure with the cryopump operated at liquid helium temperature.

2. Methodical aspects

2.1. Neutral particle analysis

The time-of-flight neutral particle analyser (TOF-NPA) measures the neutral efflux due to passive charge exchange and radiative recombination (for details see [1]). Special features are:

1. One line of sight along the major radius, 28 cm above torus midplane.
2. 15 energy channels by electrostatic deflection, mass selection by time of flight.
3. Useful energy range for H/D determination: 6–10 keV (channels 3, 4, 5) corresponding to 0.3–0.6 m depth into an ohmic plasma.
4. The data used in this study have been selected according to the requirement that at least 20 H particles are seen in each of the three channels leading to an error of less than 12.9%.
5. The conversion of measured H-to-D flux ratios into H-to-D density ratios, n_H/n_D, requires a simulation [1] based on profiles of electron density, ion densities

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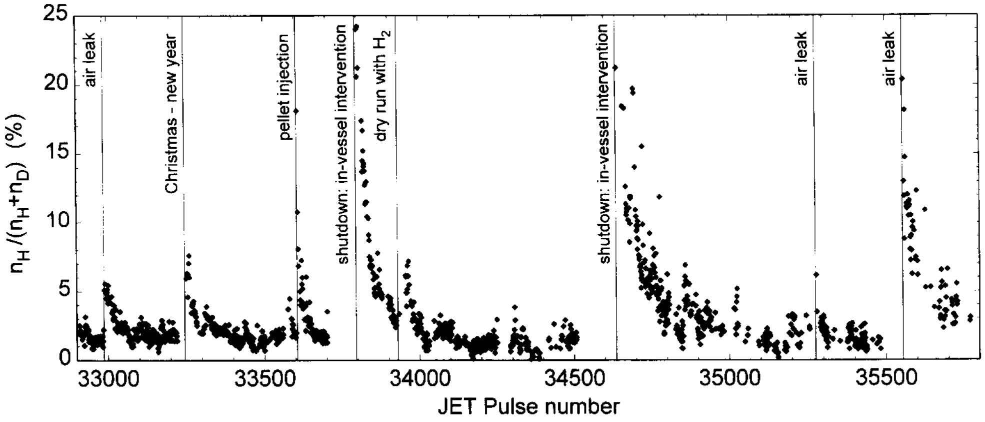

Fig. 1. Fraction of hydrogen, measured by NPA, in JET plasmas from 8/12/94 (No. 32908) to 19/6/95 (No. 35770) derived from H, D fluxes in channels 3, 4, 5 (6.0 to 9.7 keV) during ohmic phases (2.5 to 7.5 s). Data points represent three-channel averages.

(assumption H α D), electron and ion temperatures, and charge exchange donor neutrals. A simplified conversion for the energy range 5 keV to 10 keV applicable to ohmic plasmas only has been used for the present work [1]:

$$\frac{n_\mathrm{H}}{n_\mathrm{D}} = C\frac{\mathrm{FLUX}_\mathrm{H}}{\mathrm{FLUX}_\mathrm{D}} \quad (C = 0.5 \text{ to } 0.8 \text{ in most cases}) \tag{1}$$

where the conversion factor C is approximated by

$$C = \exp\left(-0.132\mu_\mathrm{D}^{0.82}\alpha^{0.19}\right)$$
$$\mu_\mathrm{D} = 3.3\times10^{-19}a\bar{n}_\mathrm{e}\sqrt{2/T(0)} \tag{2}$$

a (m) is the minor radius, $\bar{n}_\mathrm{e}$ (m^{-3}) the volume averaged density, $T(0)$ (keV) the central ion temperature ($T_\mathrm{i} \approx T_\mathrm{e}$), and α is a profile factor obtained by fitting according to $T(r) = T(0)(1-(r/a)^2)^\alpha$.

2.2. Visible light spectroscopy

The H/D concentration ratio is obtained by measurement of the Balmer H_α and D_α line intensities using a spectral fit that includes the Zeeman splitting to confirm the location of emission: the divertor which is viewed from top. Therefore, this signal depends on the X-point configuration. The error has been estimated to be 5% or 0.03 absolute error in H/D, whichever is larger.

2.3. In-vessel pressure gauging

The pressure measured by Penning gauges can be used to obtain an indicator of the degree of hydrogen contamination if the cryopump is in operation: At ~ 5 K the saturation vapour pressures of H_2 and D_2 are 3×10^{-5} mbar and 1.5×10^{-8} mbar [2], respectively, so that a few seconds after the current ramp down the remaining gas

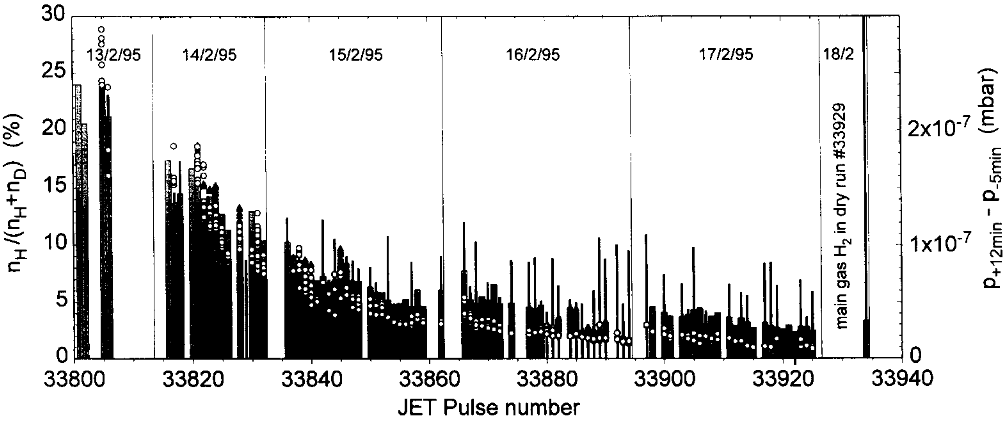

Fig. 2. Behaviour of the hydrogen fraction during the restart period after shutdown. Shaded bars: NPA data corresponding to Fig. 1. Symbols: $\mathrm{H}_\alpha/\mathrm{D}_\alpha$ Balmer line intensity (ohmic phase – open circles, NBI phase – closed triangles). Heavy bars: in-vessel pressure difference (right-hand scale).

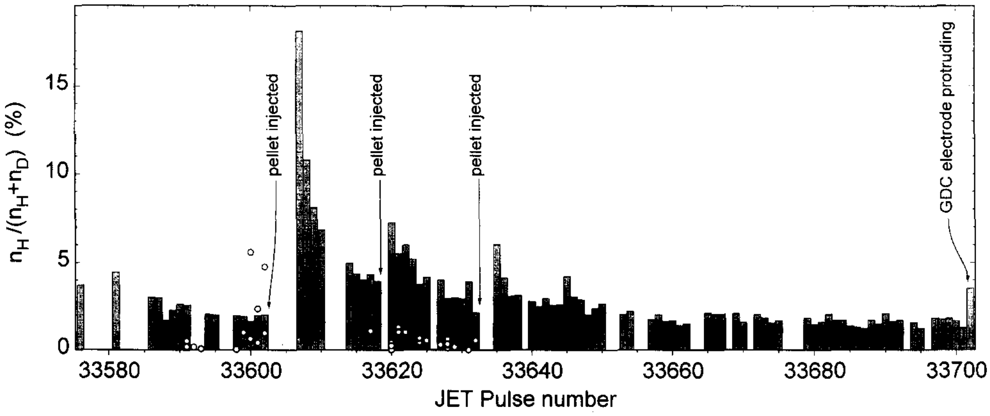

Fig. 3. Behaviour of the hydrogen fraction in response to pellet injections. Shaded bars: NPA data corresponding to Fig. 1. Symbols: H_α/D_α Balmer line intensity (ohmic phase – open circles, NBI phase – closed triangles).

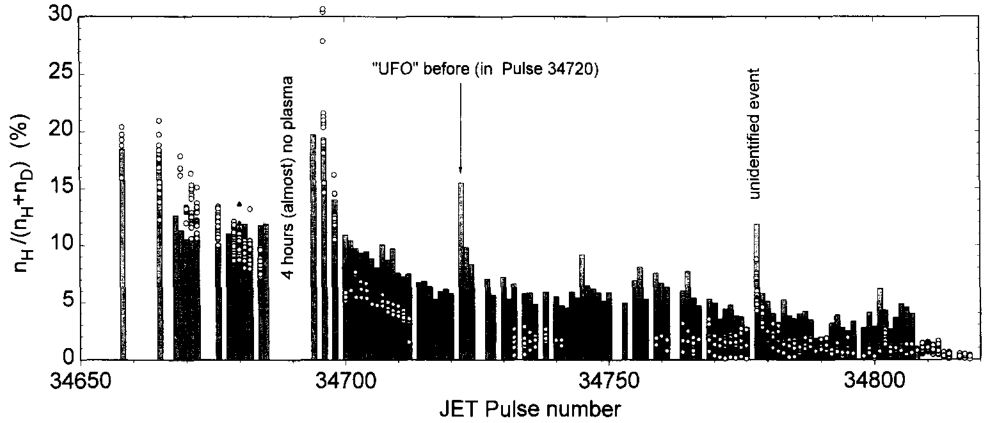

Fig. 4. Behaviour of the hydrogen fraction during the restart period after shutdown (beryllium target plates installed). Shaded bars: NPA data corresponding to Fig. 1. Symbols: H_α/D_α Balmer line intensity (ohmic phase – open circles, NBI phase – closed triangles).

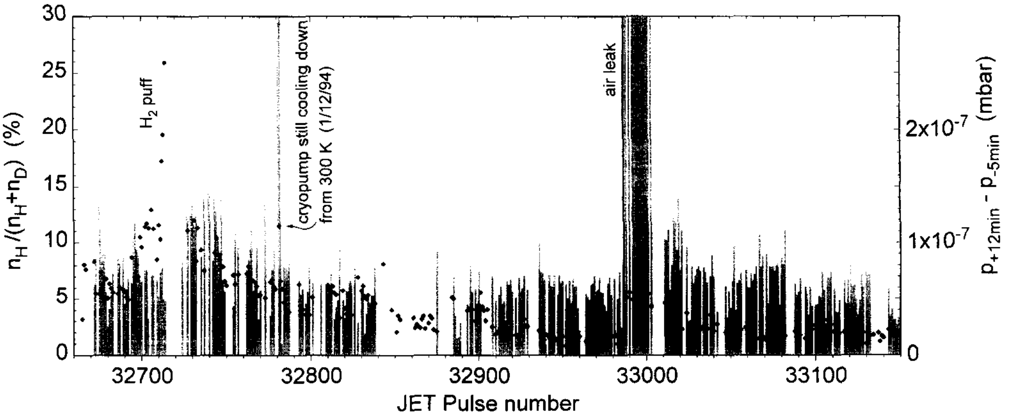

Fig. 5. Behaviour of the hydrogen fraction during H_2 puff in the ohmic phase and an air leak. (◆) NPA data corresponding to Fig. 1. Shaded bars: in-vessel pressure difference (right-hand scale).

Table 1
Parameters describing the behaviour of the H fraction after 'events'

Date	Event that caused increase of hydrogen fraction	First plasma afterwards	% of H according to fit	e-folding number of pulses
26/11/94	H_2 puff in three pulses	No. 32724	12.5%	62.8
11/12/94	two air leaks	No. 32988	6.5%	45.0
25/01/95	pellets and an 'UFO'			6.3
30/01/95	2 weeks shutdown	No. 33793	26.7%	47.0
18/02/95	accidental H_2 fill (No. 33929)	No. 33944	11.2%	25.4
17/03/95	5 weeks shutdown	No. 34631	26.3%	68.2
25/05/95	two air leaks	No. 35278	7.3%	14.3
09/06/95	air leak	No. 35557	15.2%	85.3

will almost only consist of hydrogen which will then be pumped out much more slowly by the turbomolecular pumps. For details see [3].

To allow for varying basic pressure conditions depending on the vessel conditioning, the difference of the pressures p before and after a plasma pulse has been used as the 'H-signal'. 30 s time resolution of the pressure data allows smoothing of $p(t)$: $t = t_0 + \tau$ where $\tau = -9$ min to -1 min ($p_{-5\,\mathrm{min}}$) and $\tau = +7$ min to $+17$ min ($p_{12\,\mathrm{min}}$) has been chosen in what follows.

3. Evaluation of H/D during most of the 1994–1995 experimental campaign

Fig. 1 shows a global overview based on NPA data. Restriction to the ohmic phase guarantees homogeneity of the data (see Section 4) and allows the simple conversion (Eq. (1)). Major 'events' which obviously cause a general hydrogen contamination of the vessel are clearly displayed as are a few pellet injections where hydrogen gas was used as a propellant. These deposits on the wall components are then gradually removed by erosion, recycling, and pumping, but the flatting out level reached after long quiet periods is always ~ 1%, although the data have been corrected by 1% to take account of D to H mass channel overlap in the NPA [1].

It is likely that the hydrogen trapped in the metal components of the wall (inconel, partly uncovered) accounts for this constant and inexhaustible source of hydrogen due to both outgassing at ≥ 250°C and sputtering by cx-neutral bombardment. A basic outgassing rate of $3 \times (10^{16}\text{–}10^{17})$ H atoms/s has been found in [3]. A fortnight interruption of operation (Christmas – new year) has raised the H fraction to 8%, although the vessel was continuously pumped and baked, which can be explained by bulk diffusion of hydrogen to the previously depleted metal surface. This picture is supported by the facts discussed in Section 4.2: Hydrogen entering the plasma directly from the walls, not the target plates, becomes transiently 'visible' owing to the very good particle confinement during ELM-free H-modes.

Alternatively, or additionally, water vapour constantly entering the vessel through the pump ducts and also by wall diffusion may account for the basic 1% H level as well. The greater part of it would normally by trapped by the cryopumps, to be sure, whose occasional regeneration at room temperature causes an increase of hydrogen in the plasma, indeed. Furthermore, as the cryopumps were not in operation during the above-mentioned fortnight interruption, the subsequently increased H level might also be due to the water accumulated in the vessel (absorption by the walls) during this non-operational period.

Fig. 2 exhibits the monotonic decay of hydrogen after an in-vessel intervention, apart from slight overnight recurrence effects confirming the interpretation given above. It also demonstrates the good agreement between the NPA and spectroscopy data as long as H/(H + D) is large enough, while the latter diagnostic underestimates the hydrogen component systematically upon approaching its sensitivity limit. On the other hand, it indicates a tendency of hydrogen increase during the beam-heated phase which is not covered by the NPA data shown.

The in-vessel pressure method is seen to provide a well correlating hydrogen indicator, notwithstanding the large scatter involved.

Figs. 3 and 4 confirm the previous statements and show the consequences of some 'minor events'. Due to the timing of pellets, the H_2 propellant is always seen in the subsequent pulses [1].

Results of exponential fits of the NPA data for a number of events (see Fig. 1), assuming an 1.3% offset, are shown in Table 1.

Fig. 5 confirms the suitability of the in-vessel pressure

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[1] It should be emphasized that deuterium pellet injections are accompanied by hydrogen puff only if the pellet injector cryopump is not in operation.

as a hydrogen indicator and its dependence on the cryopump, while H_2 puffs at an early stage in the discharge have no immediate effect.

4. Enrichment of hydrogen in ELM-free hot-ion H-mode plasmas

4.1. Experimental facts

During ELM-free phases of neutral beam heated hot-ion H-modes the NPA observes a steady growth of the hydrogen fraction in the plasma which can be described as follows (Fig. 6):

1. The direct observation is possible only for $E < 10$ keV since otherwise there is an interference by non-thermal deuterons.
2. The restricted energy range provides evidence only regarding the very edge of the bulk plasma.
3. The increase of the H/D flux ratio is nearly linear; the small initial peak is due to an initially small conversion factor C.
4. The first giant ELM restores the former target plasma H/D ratio instantaneously. It is the H flux, not the D one, that changes quickly.
5. Subsequent ELM-free phases, if long enough, can cause the hydrogen to increase again.
6. Sometimes MHD events that trigger R_{DD} roll-overs terminate the H/D effect.
7. The spectroscopic signal (H_α/D_α line intensity) does not vary throughout the time in question, i.e. the recycling gas in the divertor remains unchanged.

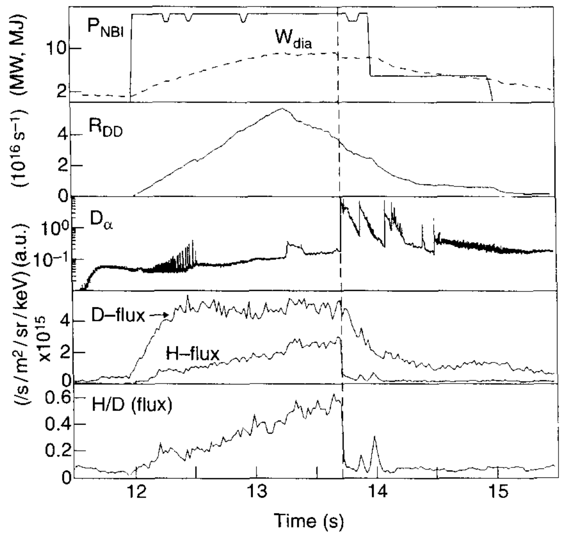

Fig. 6. Pulse 33648. Time traces of (top to bottom) the neutral beam power and diamagnetic energy, D-D reaction rate, D_α, NPA neutral fluxes at 7.8 keV, and corresponding H/D flux ratio.

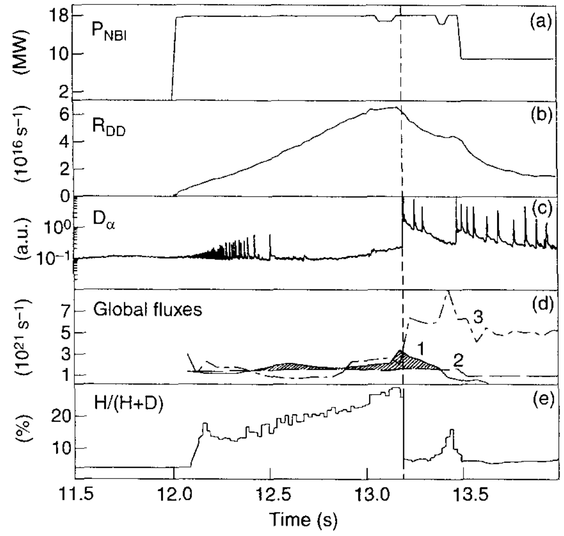

Fig. 7. Pulse 32924. Time traces of the (a) neutral beam power, (b) D-D reaction rate, (c) D_α, (e) NPA hydrogen flux fraction (3 channels average: 6.0-9.7 keV). For panel (d) see text.

4.2. An attempt of interpretation

Simulation studies [1] have shown that the hydrogen enrichment effect cannot be explained as an artefact caused by the changing temperature and density profiles during the H-mode in conjunction with the additional beam and beam halo cx-donor neutrals. Therefore, it should be considered as a genuine increase of the proton density which is likely to be restricted to some bulk plasma edge region of unknown extent. Evidence for the latter assumption is given in [1].

On the other hand, any selective confinement of protons over deuterons should be rejected.

Probably, the key of interpretation is the generally very good particle confinement in these H-modes confirmed by low gas pressure values in the divertor [4], i.e. reduced divertor recycling, in conjunction with the fact that the growth rate, dN/dt, of the total number of hydrogen isotope ions in the plasma exceeds the beam fuelling rate Φ_{NBI}. This is shown, as an example, in Fig. 7, panel (d): line 1 – dN/dt (measured, impurities $Z > 1$ deducted); line 2 – Φ_{NBI}, (measured, shine-through effect taken into account); line 3 – Φ_i, the ambipolar efflux to the divertor (estimated, making use of the angular momentum balance [2]).

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[2] Details of this approach, which is based on measurements of the rotational speed of the plasma, will be published elsewhere.

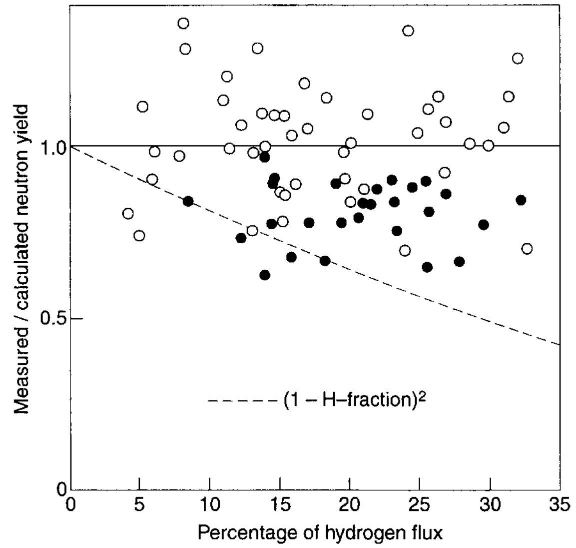

Fig. 8. Shortfall in fusion reactivity based on calculations for an H-free deuterium plasma versus neutral hydrogen flux percentage (NPA, 6.0–9.7 keV) during hot-ion H-modes (many pulses and time slices). Closed and open circles are for an expected D–D reaction rate larger and smaller than 6.3×10^{16} s^{-1}, respectively.

Assumptions:

1. The extra influx of particles, $dN/dt - \Phi_{NBI}$ (shaded area in Fig. 7), is due to wall desorption/erosion caused by cx-neutral bombardment, and this flux component contains a considerable fraction of hydrogen [3].
2. Φ_i — small before the ELM — is recycled one by one via the divertor, and almost pure deuterium is returned (no spectroscopic hydrogen signal from the divertor!).
3. The build-up of a hydrogen fraction in a certain edge layer of the plasma is a matter of balance between the influx (1) and the dilution effects due to Φ_{NBI} and the divertor recycling (2). The thinner the layer the stronger the growth of n_H.
4. The sudden increase of divertor recycling, D_α and Φ_i (Fig. 7c, d), during the ELM causes a rapid quenching of the H component by dilution. The thinner the layer the quicker the drop of H/(H + D).

The total amount of hydrogen involved may be small and can well be in keeping with the basic 1% level mentioned above as long as fast redistribution over targets and walls is taking place. Only the transient high confinement makes the hydrogen seemingly abundant for some time interval. Modelling based on these ideas is under way.

4.3. Correlation with shortfall in the observed D–D fusion reactivity

A hydrogen fraction in the plasma will reduce the D–D neutron yield. Too small neutron fluxes compared to calculations disregarding any hydrogen have repeatedly been observed just for the peak performance of JET hot-ion H-modes. Whether this discrepancy can be attributed to the hydrogen enrichment effect depends on the largely unknown extent of the plasma region affected. A corresponding TRANSP code simulation [5] for pulse 33643, assuming 20% hydrogen in the outer 25 cm of the plasma column, did not resolve the problem; other shortcomings are likely to be involved.

Alternatively, Fig. 8 shows an attempt to correlate the reactivity shortfalls with the hydrogen fractions measured. The dotted line represents the limiting expectation if the measured H/(H + D) could be considered a genuine density ratio ($C = 1$) and were true of the entire plasma. Only the closed circles indicate some correlation in accordance with the fact that the outer region of the plasma is relevant to neutron production only at very high performance.

5. Summary and conclusions

Neutral particle analysis is a suitable and very sensitive method to monitor the hydrogen fraction in the bulk plasma on a pulse by pulse basis. Restriction to the ohmic phases is most appropriate for this purpose and allows a simple conversion of the data into the hydrogen ion density percentage.

Visible light spectroscopy viewing the divertor provides valuable supplementary information on the dynamics of the hydrogen impurity. It is in quantitative agreement with the former method at high levels of contamination, but suffers from low sensitivity otherwise.

Owing to the properties of the cryopump, the in-vessel pressure before and after a pulse can be used to derive another signal that indicates the actual hydrogen contamination level.

The data obtained during the 1994/95 experimental campaign clearly exhibit, in remarkable detail, events and processes that affect the amount of hydrogen found in the plasma:

1. Hydrogen compound deposits due to major events (in-vessel interventions, air leaks, H_2 gas puffs) account for up to 30% of hydrogen in both the plasma and the divertor, and their depletion upon pulsing (erosion and vessel pumping) can be described by e-folding numbers of subsequent pulses.
2. Minor events like deuterium pellets propelled by H_2 gas, accidentally exposed wall structure parts, cryopump regeneration at 300 K etc. can have a considerable effect, but the decay is faster.

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[3] Outgassing of hydrogen from the metal walls could also play a role, but the rate is small: $3 \times (10^{16} - 10^{17})$ H atoms/s according to [3].

3. Even after apparently complete removal of any hydrogen that was due to 'events', a persistent minimum level of about 1% hydrogen is always found in the plasma. This points to a constant internal source which is likely to be the metal walls. Inconel is known to be abundant in bulk hydrogen.

During ELM-free phases of hot-ion H-modes a growing fraction of hydrogen in the plasma, not in the divertor, up to values around 30% (H/(H + D) flux ratio) has always been observed, followed by a very fast drop, coincident with a large ELM, down to the former target plasma value.

1. The 'hydrogen enrichment effect' is likely to be restricted to the outer region of the plasma column.
2. Given the high particle confinement properties of these plasmas, the effect can be explained by a transient retention of hydrogen isotopes that enter the plasma directly due to wall surface desorption, while the same process may account for the 1% basic level of H during normally high divertor recycling.
3. Correlations with shortfalls in the observed fusion reactivities at peak performance have been found.

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