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A MEASUREMENT OF HYDROGEN TRANSPORT IN DEUTERIUM DISCHARGES USING THE DYNAMIC RESPONSE OF THE EFFECTIVE MASS

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ABSTRACT. Particle tagging in a tokamak provides an attractive method for studying transport mechanisms. The injection of test particles at the plasma edge and the subsequent measurement of the evolution of their concentration at the centre can be used to quantify the underlying transport mechanisms. This has been carried out on the TCA tokamak by injecting hydrogen into a deuterium discharge, and simultaneously measuring the temporal evolution of the central effective mass and the edge ionisation rate.

1. INTRODUCTION

Various perturbation methods have been proposed for studying particle transport in tokamaks. These methods rely either on the analysis of the working gas dynamics [1, 2], or on the monitoring of the line emission from impurities, as they are transported within the plasma following a pulsed injection [3]. Little is however known about the transport of isotopes of the working gas (eg. deuterium transport in a hydrogen fuelled discharge), which may not necessarily be the same as that of higher Z particles.

On the TCA tokamak (R, a = 0.61 m, 0.18 m, $I_p \leq 170$ kA, $B_\phi = 1.5$ T, $\bar{n}_e \leq 10^{20}$ m^{-3}), two measurement techniques are used to monitor the ratio of the hydrogenic species. By measuring the hydrogen concentration following hydrogen puffing into deuterium fuelled plasmas, both at the centre and at the edge, information on the hydrogen transport can be obtained.

Section 2 of this paper describes the two diagnostics which are used to measure the isotope concentrations of two different regions of the plasma. The dynamic response of the concentration following a gas puff and a comparison with a simple transport model are presented in sections 3 and 4 respectively. Finally, section 5 summarises the results, and compares them with other measurement techniques.

2. MEASUREMENT OF THE HYDROGEN CONCENTRATION

The hydrogen concentration at the plasma centre is inferred from the effective mass, which for different ion species with mass A_k and relative concentration $\eta_k = n_{ik}/n_e$, can be defined as :

$$A_{eff} = \sum_k \eta_k A_k \tag{2.1}$$

A_k is 1 for hydrogen, 2 for deuterium ions and close to 2 for most fully ionised impurities. Hence for impurity-free plasmas, a real-time measurement of A_{eff} provides a measurement of the ratio of hydrogenic species.

On the TCA tokamak, the central effective mass is measured by frequency tracking a global Alfvén eigenmode [4]. The Alfvén waves are launched by a small antenna, which is fed by a 100 W generator in the 1-6 MHz range. The phase of the RF wavefield, detected by a magnetic pickup coil, is used in a

In conditions in which the particle absorption at the tokamak vessel wall is small, conservation of the gas particles is satisfied, in which case R_A provides a measurement of the ratio of the hydrogenic species at the plasma edge. Since the impurity concentration is small enough to be neglected, and the following analysis is based on small mass changes, ΔR_A and ΔA_{eff} both provide a localised measurement of a change in the hydrogen concentration.

3. DYNAMIC RESPONSE ANALYSIS

When a small amount of hydrogen is injected into a deuterium fuelled plasma, a decrease in the edge mass ratio is seen and the response of the central effective mass is delayed, Fig. 2. For relatively small density increases ($\Delta n_e/n_e \lesssim 30\%$), ΔR_A and ΔA_{eff} are proportional to the local density change of the injected gas. The two dynamic responses should therefore reveal the dominant hydrogen transport processes.

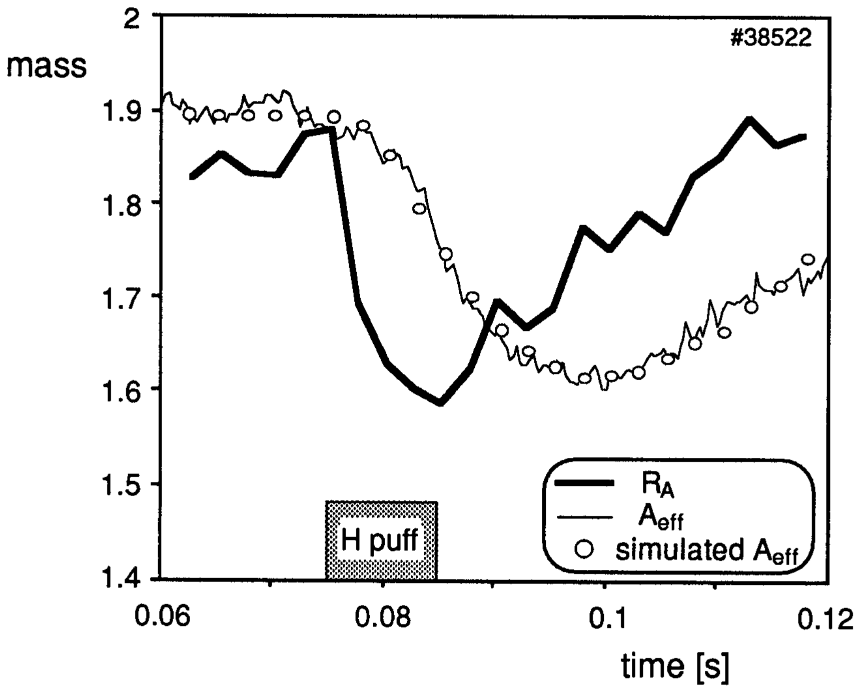

Figure 2 *Temporal evolution of the central effective mass (A_{eff}) and the mass ratio at the edge (R_A), during a hydrogen injection in a deuterium plasma. The simulated central mass is obtained from the transfer function expressed in Fig. 3.*

To study these dynamic responses, we extract the transfer function which links the stimulus (ΔR_A) to the output (ΔA_{eff}) :

$$H(\omega) = \frac{\Delta A_{eff}}{\Delta R_A} \tag{3.1}$$

This extraction is done by performing a system identification analysis in which a mathematical model of the the dynamic system is built, based on the observed data [6]. The resulting transfer function can be expressed by its gain $|H(\omega)|$ and its phase $\angle H(\omega)$, which are obtained over a continuous frequency range :

$$0 < f = \frac{\omega}{2\pi} < \frac{1}{2\tau} \tag{3.2}$$

τ is the discrete sampling period. The experimental estimate of the transfer function can then be compared with the one obtained from a particle transport model.

4. COMPARISON WITH A PARTICLE TRANSPORT MODEL

To obtain a simple model for the dynamic response of the mass, we shall assume that the transport of each of the hydrogenic species can be described by a spatially uniform diffusion coefficient and a linearly increasing inward drift velocity $v^* = -v\, r/a$ [1,7] :

$$\frac{\partial n_k}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(r\, D_k \frac{\partial n_k}{\partial r}) - \frac{1}{r}\frac{\partial}{\partial r}(r\, v_k^*\, n_k) + Q_k(r) \tag{4.1}$$

Here $Q(r)$ is the particle source, and the subscript k refers either to hydrogen (H), deuterium (D) or a mixture of the two (HD). In the present experiment, we have $n_e \cong n_{HD} = n_H + n_D$. The effect of the injected gas is analysed as a time-dependent perturbation of the density

$$n_k(r,t) = \bar{n}_k(r) + \tilde{n}_k(r)e^{-j\omega t} \tag{4.2}$$

The homogeneous solution of Eq. 4.1 can be expressed in terms of confluent hypergeometric functions,

$$\tilde{n}_k(r) = \tilde{n}_{k0}\, M\left(-\frac{j\omega a}{2v_k}, 1, \frac{r^2 v_k}{2aD_k}\right) e^{-\frac{r^2 v_k}{2aD_k}} \tag{4.3}$$

from which the stationary density profile is obtained by setting $\omega = 0$

$$\bar{n}_k(r) = \bar{n}_{k0}\, e^{-\frac{r^2 v_k}{2aD_k}} \tag{4.4}$$

We now calculate the mass as a function of the densities of the hydrogenic species. Both the central effective mass and the edge mass ratio can be expressed as

$$A = \frac{n_H + 2\, n_D}{n_{HD}} = 2 - \frac{n_H}{n_{HD}} \tag{4.5}$$

Only a small amount of hydrogen is present in the plasma. Therefore $|\bar{n}_H| << |\bar{n}_{HD}|$ and $|\tilde{n}_H| \sim |\tilde{n}_{HD}| << |\bar{n}_{HD}|$ so that the perturbed mass term becomes

$$\tilde{A}(r) \cong -\tilde{n}_H(r) \,/\, \bar{n}_D(r) \tag{4.6}$$

which with Eq. 4.3 and 4.4 gives

$$\tilde{A}(r) = -\frac{\tilde{n}_{H0}}{\bar{n}_{D0}}\, e^{-\frac{r^2}{2a}\left(\frac{v_H}{D_H} - \frac{v_D}{D_D}\right)}\, M\left(-\frac{j\omega a}{2v_H}, 1, \frac{r^2 v_H}{2aD_H}\right) \tag{4.7}$$

The transfer function which links the response of the central mass to the edge mass is

$$H(\omega) = \frac{\tilde{A}(r=0)}{\tilde{A}(r=a)} \tag{4.8}$$

which can be expressed as a function of the transport coefficients

$$H(\omega) = \frac{e^{\frac{a}{2}\left(\frac{v_H}{D_H} - \frac{v_D}{D_D}\right)}}{M\left(-\frac{j\omega a}{2v_H}, 1, \frac{a\, v_H}{2D_H}\right)} \tag{4.9}$$

This transfer function is mainly determined by the hydrogen transport parameters D_H and v_H. In order to estimate these parameters, a non-linear optimisation procedure is used. The model which best fits the measured phase and gain is obtained by adjusting the values of D_H, v_H and of the numerator in Eq. 4.9. The latter is simply given by the DC value of the gain $|H(\omega=0)|$. As an indication of the sensitivity of the calculated transfer function on the transport coefficients, different Bode plots are shown in Fig. 3, in which the best fit is compared with results obtained assuming a 10 % decrease in D_H or a 100 % decrease in v_H. A 10 % change in the diffusion coefficient has a marked effect on the frequency dependence of both the phase and the gain. Due to this good sensitivity to D_H, D_H can be accurately measured experimentally. The convective velocity, however, is more difficult to extract. Since it has a smaller effect on the phase and the gain of the dynamic response, it is measured with a larger uncertainty.

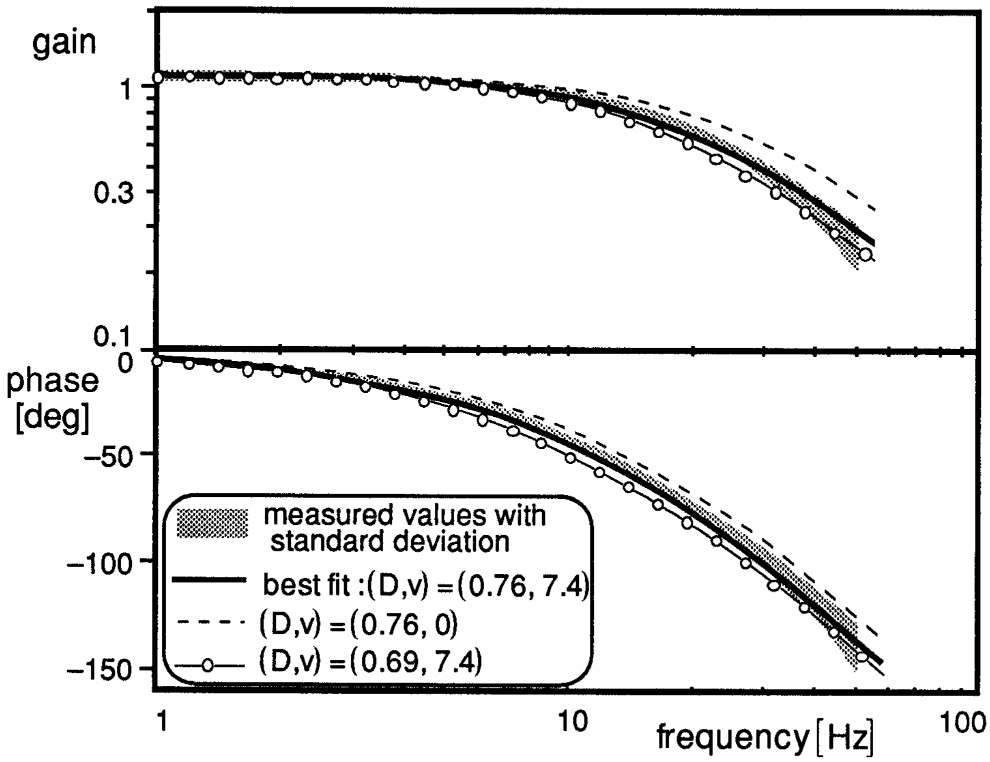

Figure 3 *Bode plots of the measured transfer function and the best fit obtained with* D_H=0.76 m^2s^{-1} *and* v_H=7.4 ms^{-1}. *Also shown are the calculated transfer functions with* v_H=0 *and with a 10% decrease in* D_H.

The good agreement which is obtained between the measured and the modelled transfer functions (Fig. 3) justifies the use of the simple transport model. The information which is contained in the frequency dependence of the phase and the gain allows both hydrogen average transport parameters D_H and v_H to be determined independently. The class of models used in Eq. 4.1 can be expanded to include a radial dependence of v and D. This leads to a slight improvement in the fit but then also excludes any uniqueness in the solution.

5. EXPERIMENTAL RESULTS

The dynamic response measurements were made with two different torus wall conditions which have important implications on the validity of the measured particle transport.

1) The first results were obtained in a tokamak which had been conditioned by Taylor-cleaning; little gas absorption at the vessel wall was observed. We could therefore assume particle conservation during recycling at the edge and the edge ionisation ratio could be used to determine the edge hydrogen isotope concentrations. Measurements for a typical shot with $\bar{n}_e = (3 - 4.5) \times 10^{19}\ m^{-3}$ and $q_a=3.1$ gave the following results :

$$D_H = 0.76 \pm 0.06\ m^2s^{-1}$$
$$v_H = 7.4 \pm 3.2\ ms^{-1}$$

The error bars are obtained from the standard deviation of the measured transfer function.

The particle transport has also been analysed for similar plasma and torus wall conditions using laser ablated aluminium injection and harmonic modulation of the deuterium gas feed. The diffusion coefficients measured with these other two techniques were :

$$D_{Al} = 0.73 \pm 0.10\ m^2s^{-1} \quad \text{aluminium transport}$$
$$D_D = 0.70 \pm 0.20\ m^2s^{-1} \quad \text{deuterium transport}$$

The excellent agreement which is obtained between the diffusion coefficients, as measured with different techniques, supports the validity of the analysis. The same experiment could be carried out with other gases, provided their effective masses are different. In particular, it could be performed by injecting deuterium into a hydrogen fuelled discharge. The present experimental results may also provide an indirect quantification of the deuterium transport. To do so, we first consider the dimensionless strength of the convection, which is defined as positive for inward drifts :

$$S_k = \frac{av_k}{D_k} \qquad (5.1)$$

This parameter is commonly used to characterise particle transport, as modelled in Eq. 4.1. In this experiment $S_H = 1.7 \pm 0.6$ is measured for the hydrogen transport, in reasonable agreement with other tokamaks, where values of $S_H = 1.5 - 2.5$ have been obtained [1, 2]. A measurement of the value for deuterium, S_D , can be deduced from the numerator in Eq. 4.9, which contains the difference $S_H - S_D$:

$$S_H - S_D = 0.10 \pm 0.15$$

The large relative error bar of this difference is due to the calibration uncertainty of the two separate mass measurements. Despite this error bar, we can conclude that the dimensionless strength of the convection is similar for hydrogen and for deuterium. Its value does not differ by the mass ratio, or even its square root. This implies that after the injected hydrogen has been allowed to diffuse into the deuterium plasma, its concentration becomes uniform.

2) Subsequent experiments were performed after the tokamak had been boronised. This process deposited a film of boron carbide on the machine wall which led to a significantly enhanced working gas retention, followed by a partial release during subsequent discharges [8]. Unfortunately, the H_β and D_β line intensities were dominated by the local edge recycling, and particle conservation could no longer be assumed in these conditions. The consequent absence of a credible measurement of the mass ratio at the plasma edge prohibited further use of our analysis technique.

6. CONCLUSION

The dynamic response of the effective mass provides a method to quantify the transport of isotopes of the working gas in a tokamak plasma. Measurements of hydrogen transport in a deuterium fuelled plasma allowed both average convective and diffusive hydrogen transport coefficients to be determined. The latter is measured with good accuracy and is in close agreement with values obtained from gas feed modulation for deuterium, or laser-ablated aluminium injection for impurity ions. This suggests that the diffusive processes responsible for the transport of hydrogen, deuterium of higher-Z atoms are equally fast. Further comparison of the dimensionless strength of the convection indicates that the deuterium and the hydrogen convective velocities are similar. Hence no dependence on the ion mass can be detected within the accuracy of this experiment, in opposition to other tokamaks where a faster diffusion coefficient is measured for impurities than for deuterium [9].

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