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Determination of hydrogen/deuterium ratio with neutron measurements on MAST[a)]

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On MAST, compressional Alfvén eigenmodes can be destabilized by the presence of a sufficiently large population of energetic particles in the plasma. This dependence was studied in a series of very similar discharges in which increasing amounts of hydrogen were puffed into a deuterium plasma. A simple method to estimate the isotopic ratio n_H/n_D using neutron emission measurements is here described. The inferred isotopic ratio ranged from 0.0 to 0.6 and no experimental indication of changes in radial profile of n_H/n_D were observed. These findings are confirmed by TRANSP/NUBEAM simulations of the neutron emission. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4889910]

I. INTRODUCTION

In ITER, an intense population of energetic α particles generated by the deuterium - tritium fusion reactions may lead to the excitation of Alfvén cyclotron instabilities. Such instabilities can manifest themselves in spherical tokamaks as Compressional Alfvén Eigenmodes (CAEs).[1,2] On MAST, CAEs are driven unstable by super-Alvénic deuterium neutral beams and are observed across a wide range of frequencies extending up to the ion cyclotron frequency and beyond. It is well known that plasmas containing two dominant ion species with unequal charge to mass ratios can support additional hybrid modes whose presence may affect the transport and confinement of the fast ions themselves. Puffing hydrogen into deuterium plasmas in MAST provides therefore an opportunity to simulate effects that are likely to occur in burning tokamak plasmas. Such study was recently carried out at MAST in an experiment in which increasing amounts of hydrogen were puffed into deuterium plasma discharges. Accurate modelling of CAEs' behaviour requires the estimate of the plasma isotopic composition n_H/n_D where $n_{H,D}$ indicates the density of hydrogen and deuterium, respectively. A simple method to estimate n_H/n_D is here presented. This method takes advantage of the fact that, on MAST, neutron emission is dominated by the beam-thermal component of the D-D fusion reaction and therefore any dilution of the thermal deuterium due to puffed hydrogen will strongly reduce it.

II. EXPERIMENTAL OBSERVATIONS

MAST is a medium-sized spherical tokamak whose major and minor radii are $R_0 = 0.85$ m and $a = 0.65$ m, respectively, which can be operated with $I_p \leq 1.5$ MA, moderate toroidal field on axis $B_\phi \leq 0.6$ T and 5 MW of heating delivered by two NBI systems. In this experiment, a deuterium-only plasma discharge for which observable CAEs were known to be destabilized was selected as reference (pulse 30457). This plasma discharge is characterized by a plasma current I_p of approximately 600 kA and by a toroidal magnetic field on axis B_ϕ slowly decreasing from 0.42 to 0.31 T. Additional heating is provided by one 70 keV deuterium neutral beam delivering a total of 2 MW. The core electron density n_e and temperature T_e on axis are respectively $n_e \approx 2 \times 10^{19}$ m^{-3} and $T_e \approx 1$ keV. CAEs induced fluctuations of the edge magnetic field are measured by the Outboard Mirnov Array for High Frequency Acquisition (OMAHA) with frequencies in the range 1–3 MHz as shown in panel (a) of Fig. 1. The total neutron rate (Y_n) is measured by

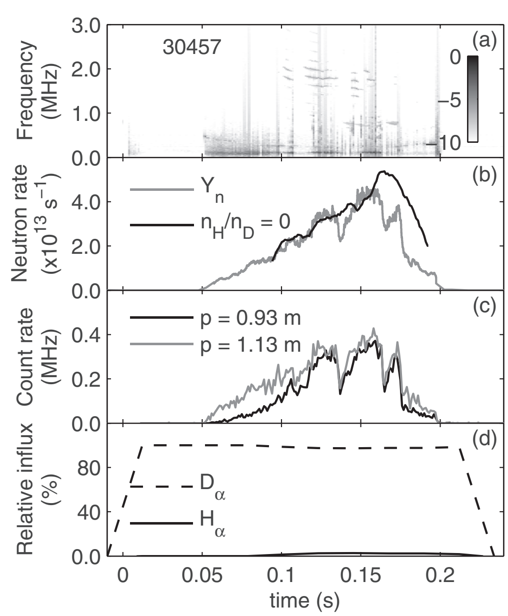

FIG. 1. Reference plasma discharge (30457): (a) OMAHA spectrogram: CAEs can be seen between 1 and 3 MHz; (b) total neutron rate: experimental and simulated ($n_H/n_D = 0$); (c) neutron count rates measured by the NC for $p = 0.93$ m and $p = 1.13$ m; and (d) hydrogen and deuterium relative influx.

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TABLE I. n'_H/n'_D ratio determined from the total neutron rates measured by the FC and from the beam-thermal neutron rate predicted by TRANSP.

Plasma discharge	Hydrogen puff (ms)	n'_H/n'_D Eq. (1)	n'_H/n'_D TRANSP
30457	0	0	0
30460	40	0.08	0.09
30464	65	0.30	0.29
30458	75	0.55	0.55

an absolutely calibrated Fission Chamber[3] (FC) while a Neutron Camera[4] (NC) provides the collimated neutron flux count rate of two detectors looking at the plasma core in tangential direction on the equatorial plane. The two lines of sight of the NC are characterized by a tangency radius p of 0.93 m and 1.13 m. Time traces of the total and local neutron rates are shown in panels (b) and (c) of Fig. 1, respectively. Drops in the neutron rates of about 50% are observed but are not caused by CAEs as explained below. Finally, the hydrogen and deuterium relative influx obtained from the intensity of the Balmer emission from neutral hydrogen (H_α) and deuterium (D_α) measured by a spectrometer is shown in panel (d) of Fig. 1: the small amount of hydrogen that is measured originates mainly from wall recycling and dissociation of water molecules.

The plasma isotopic composition was then changed in three plasma discharges by puffs of hydrogen of different duration from the low field side in the early phase of each discharge. In these plasmas, deuterium gas was injected from the high field side to refuel the plasma only after the end of the hydrogen puff. These three pulses were then repeated with the NC looking at p of 1.00 m and 1.20 m to provide a coarse profile measurement of the neutron emission. The hydrogen puff duration for three plasma discharges is indicated in Table I while Fig. 2 shows the same data as Fig. 1 but for

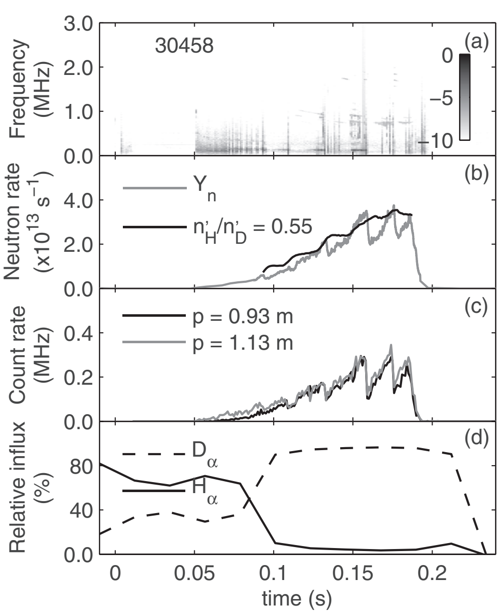

FIG. 2. Plasma discharge with hydrogen puff (30458): (a) OMAHA spectrogram: CAEs are suppressed above 1 MHz; (b) total neutron rate: experimental and simulated ($n'_H/n'_D = 55$); (c) neutron count rates measured by the NC for $p = 0.93$ m and $p = 1.13$ m; and (d) hydrogen and deuterium relative influx.

the plasma in which most hydrogen was puffed (pulse 30458). The effect of hydrogen puffing is clearly seen in the almost complete suppression of the CAEs (panel (a)) and in the reduction of the global (panel (b)) and local (panel (c)) neutron emission. It is interesting to observe how drops of approximately 50% in the neutron emission also occur in this plasma discharge (and in all the other studied in this experiment) at roughly the same time as in the reference discharge. Since CAEs appear to be suppressed (at least up to the 5 MHz frequency limit accessible to the OMAHA diagnostics), we concluded that these large drops are associated with other plasma instabilities affecting the global plasma equilibrium and not related to CAEs.

III. ISOTOPIC COMPOSITION ESTIMATION

A. Determination of the n_H/n_D ratio using neutron diagnostic

The beam-thermal dominated nature of the neutron emission on MAST allows to express the neutron rate Y_n as a function of the plasma background deuterium density n_D according to the simple relation $Y_n = kn_D$, where the constant k depends on the beam density and on the reaction parameter $\langle \sigma v \rangle$. Under the assumptions that (i) the only impurity in these plasma discharges is carbon (Z_c), (ii) the electron density is the same as in the reference pulse, (iii) Z_{eff} is the same with and without gas puffing and that (iv) the constant k is unchanged (due to the fact that reference plasma discharge and the ones with gas puffing have very similar electron densities and temperatures), then it can be shown that

$$\frac{n'_H}{n'_D} = \frac{\Phi - \Phi'}{\Phi'}, \tag{1}$$

where the prime symbol indicates quantities in plasma discharges with hydrogen puff and where $\Phi = \int Y_n dt$ is the total neutron fluence calculated over the entire plasma discharge (which is comparable in all the pulses studied here and on average 200 ± 7 ms). The choice of Φ over Y_n was made to eliminate the effect of the large drops in the neutron rates, occurring at slightly different times in different plasma discharges. Table I summarizes the inferred n'_H/n'_D while Fig. 3 shows the experimental ratio $(\Phi' - \Phi)/\Phi$ plotted against n'_H/n'_D.

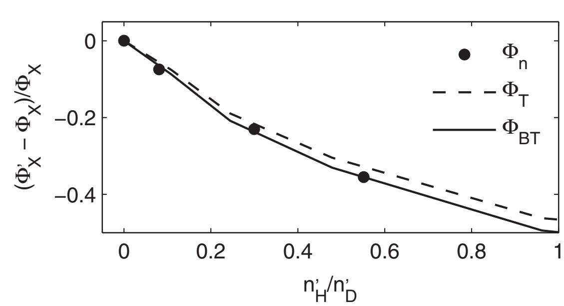

FIG. 3. Relative changes in the fluence Φ_X as a function of the n'_H/n'_D ratio determined from Eq. (1) (solid circles) together with the relative changes in the simulated total ($\Phi_X = \Phi_T$, dashed black) and beam-thermal ($\Phi_X = \Phi_{BT}$, solid black) neutron fluences.

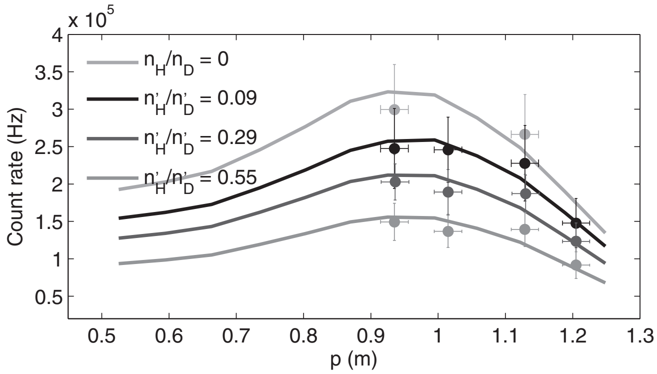

FIG. 4. Comparison of the measured (solid circles) and simulated (solid lines) NC count rate profiles as a function of the tangency radius for different $n'_{\mathrm{H}}/n'_{\mathrm{D}}$ ratios.

Figure 4 shows the coarse radial count rate profile of the NC for the pulses in Table I: no change in the profiles, within the experimental uncertainties, can be observed. This suggest that puffing hydrogen does not change the profile shape of the neutron emission but only its amplitude.

B. Determination of the $n_{\mathrm{H}}/n_{\mathrm{D}}$ ratio using TRANSP and NUBEAM

In order to confirm these findings, TRANSP and NUBEAM[5] simulations were carried out for the reference plasma discharge by varying $n'_{\mathrm{H}}/n'_{\mathrm{D}}$ in the range from 0 to 1 and without imposing any anomalous fast ion diffusion. The simulated neutron rate for $n'_{\mathrm{H}}/n'_{\mathrm{D}} = 0$ matches quite well the experimental one as shown in panel (b) of Fig. 1 except where the background plasma instabilities caused large drops in the neutron rate. The beam-thermal, beam-beam, and thermonuclear components of the neutron emission were estimated by TRANSP to be approximately 91%, 8%, and 1% of the total neutron emission thus supporting the simplistic expression used in Sec. III A for Y_n. The simulated $(\Phi'_T - \Phi_T)/\Phi_T$ agrees well with the experimental one as shown in Fig. 3. The isotopic ratio was estimated from these simulations by inverse interpolation of the experimentally measured $(\Phi' - \Phi)/\Phi$ ratio on the simulated ratio $(\Phi'_T - \Phi_T)/\Phi_T$. The values so obtained, listed in Table I, agree with those obtained using Eq. (1). The plasma isotopic compositions so obtained were then used as input to TRANSP and NUBEAM simulations of the plasma discharges with hydrogen puff and good agreement in a trend between the experimental and simulated neutron rate was obtained as shown in panel (b) of Fig. 2, again without anomalous fast ion diffusion. The large drops in the neutron rate due to the background plasma instabilities were not modelled here. Finally, these TRANSP simulations were used to predict the NC count rate profiles, taking into account both the fact that fast ions are not a flux quantity and the NC viewing geometry,[6] and are shown in Fig. 4. The good agreement between the measured and modelled profiles found for the different $n'_{\mathrm{H}}/n'_{\mathrm{D}}$ ratios, averaged over the time interval 0.12–0.14 s, supports the hypothesis that the isotopic ratio is independent of the plasma radius.

IV. DISCUSSION

The method described in this work to estimate the plasma isotopic composition is based on the assumption that plasma discharges with and without hydrogen puff are very similar and that the MHD instabilities, that cause redistribution or losses of fast ions, are independent of it. CAEs do depend on the isotopic ratio but they do not affect the fast ions population. In this sense, Eq. (1) is a special case of a more general expression in which the electron and carbon densities variations from pulse to pulse are taken into account. This simple method can be generalized to situations in which the thermal component of the neutron emission becomes important (beam-beam emission is not directly affected by hydrogen puff). In such cases in fact, it is possible to write $Y_n = k_1 n_{\mathrm{D}} + k_2 n_{\mathrm{D}}^2$ and a more general expression of Eq. (1) can still be derived.

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[1] N. N. Gorelenkov, C. Z. Cheng, E. Fredrickson, E. Belova, G. Gates, S. Kaye, G. J. Kramer, R. Nazikian, and R. White, Nucl. Fusion **42**, 977 (2002).
[2] L. A. Appel, T. Fulop, M. J. Hole, H. M. Smith, S. D. Pinches, R. G. L. Vann, and the MAST Team, Plasma Phys. Controlled Fusion **50**, 115011 (2008).
[3] K. Stammers and M. J. Loughlin, Nucl. Instrum. Methods Phys. Res., Sect. A **562**, 521 (2006).
[4] M. Cecconello *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **753**, 72 (2014).
[5] A. Pankin, D. McCune, and R. Andre, Comput. Phys. Commun. **159**, 157 (2004).
[6] I. Wodniak *et al.*, *39th European Physical Society Conference on Plasma Physics* (Stockholm, Sweden, 2012), P5.077.