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Isotope identity experiments in JET-ILW

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1.INTRODUCTION. Dimensionless identity experiments test the invariance of plasma physics to changes in the dimensional plasma parameters, e.g. electron density and temperature n_e and T_e, when the canonical dimensionless plasma physics parameters ρ^*, ν^*, β, q are conserved [1] [2]. Plasmas with dissimilar control parameters but identical dimensionless parameters should have an identical amount of transport, with the appropriate normalization to make it dimensionless [2]. However, conditions at the plasma boundary, such as influx of neutral particles, may introduce additional physics. $\rho^* \sim \sqrt{(A\ T_i)} / (a\ B)$ is the Larmor radius of thermal ions normalized to the plasma minor radius (A is the isotope ion mass, T_i the ion temperature, a the plasma minor radius and B the magnetic field); $\beta \sim n\ T / B^2$ is the plasma pressure normalized to the magnetic pressure (with n the plasma density); $\nu^* \sim n_e\ R\ Z_{eff} / T_e^2$ is the normalized electron-ion collision frequency (with Z_{eff} the plasma effective charge, R the major radius); $q \sim B / (I\ R)$ is the safety factor (with I the plasma current). The thermal energy confinement time can then be expressed in dimensionless form, as a function of the plasma dimensionless parameters: $\Omega_i\ \tau_{E,th} = (\rho^{*-\alpha\rho}\ \beta^{-\alpha\beta}\ \nu^{*-\alpha\nu}\ q^{-\alpha q}\ A^{-\alpha A} \ldots)$ [2], with $\Omega_i = eB/A$ the ion cyclotron frequency (e is the particle charge). Isotope identity experiments exploit the change in isotope ion mass to obtain plasmas with identical dimensionless profiles in the same tokamak. In order to keep ρ^*, β, ν^* and q profiles fixed when also varying the isotope mass, the plasma current, toroidal magnetic field and the density and temperature must scale, respectively, as: I_P, $B_T \sim A^{3/4}$; $n \sim A$ and $T \sim \sqrt{A}$ [3], [2]. Accordingly, the absorbed input power must scale as $P_{abs} \sim B_T^{5/3}$.

2. ISOTOPE IDENTITY EXPERIMENT IN JET-C. An isotope identity experiment was carried out in the JET tokamak with C wall (JET-C) with MkII-GB divertor, $\delta = 0.3$. Type I ELMy H-modes were obtained in H (1MA/1T, H-NBI) and D (1.7MA/1.7T, D-NBI) with matching ρ^*, ν^*, β and q profiles [3]. The scaled thermal energy confinement time, $B\ \tau_{E,th} /A$, scaled ELM frequency, $A\ f_{ELM} /B$ and scaled sawtooth frequency, $A\ f_{saw} /B$, were all matched in the H and D plasmas, indicating that the invariance principle was satisfied throughout the plasma radius, despite the different physical processes in the plasma centre, core confinement and edge regions [3]. The isotope purity in H, $n_H/(n_H+n_D) = 0.89$, was worse than in JET-ILW (see section 3). The identity experiment resulted in a weak, positive isotope mass scaling $\Omega_i\,\tau_{E,th} \sim A^{0.14}$ [2], largely consistent with the lack of mass dependence of global energy confinement, $\tau_{E,th} \sim A^{0.03\pm0.10}$, found in JET-C H, D, T ELMy H-modes at similar density and input power, which resulted from the combination of strong mass dependence for W_{PED} and weak, negative dependence in core $\tau_{th,core} \sim A^{-0.16}$ [4]. The scaled local heat diffusivities from power balance, $A\,\chi_{eff}/\,B$, were also similar in H and D [3], within experimental uncertainties in the TRANSP power balance (with χ the thermal diffusivity defined in terms of the temperature gradient and the heat flux $q = -\,n\,\chi\,\nabla T$).

3. ISOTOPE IDENTITY EXPERIMENTS IN JET-ILW. The isotope identity technique was revisited in recent experiments with H and D plasmas (isotope purity > 98%) in JET with the ITER-like Be/W wall (JET-ILW) and MkII-HD divertor geometry. Additionally, improved core and edge electron profile diagnosis with HRTS is available.

3.1. L-MODEs. An isotope identity pair was achieved at I_P/B_T = 2.5MA/3.0T in D and 1.48MA/1.78T in H, q_{95} = 3.4, δ = 0.2, strike points on divertor vertical targets. Fig. 1 shows the scaled kinetic profiles ($T_i = T_e$ within uncertainties of T_i from CXRS) and Fig. 2 the dimensionless parameters of the H and D pair. Similar scaled NB-power deposition profiles (TRANSP/NUBEAM) were achieved, with D-NBI (beam energy: 82-91 keV) and H-NBI (beam energy: 64-71 keV), respectively. The line averaged Z_{eff} (with Be the main impurity), the scaled thermal energy confinement times $B\,\tau_{E,th}/A$ and scaled core plasma effective heat diffusivities from TRANSP power balance, $A\,\chi_{eff}/\,B$, were also similar within experimental uncertainties (Table 1, Fig. 3), indicating that the invariance principle is satisfied in the L-mode core confinement region. The isotope identity results in $\Omega_i\,\tau_{E,th} \sim A^{0.05}$. This is not inconsistent with the weak, positive mass dependence of $\tau_{E,th} \sim A^{0.15\pm0.02}$ reported for the L-mode power scans at constant density in H and D, where heat and particle transport coefficients were found to be larger in H than in D only in the edge region, inside and outside the LCFS [5]. Unlike in the JET-C type I ELMy H-mode case, the scaled sawtooth frequencies were different in the H and D JET-ILW L-mode identity pair: $A\,f_{saw}\,/\,B_T$ = 7.5 Hz/T (H), 4.7 Hz/T (D). The sawtooth inversion radius, evaluated from ECE, is located at ρ_{tor} ~ 0.22 – 0.26, where q_ψ ~ 1. Flux-driven JETTO-TGLF (SAT1) predictive modelling of these discharges is in very good agreement with experiment for both isotopes (between ρ_{tor} = 0.8, where the boundary conditions are set from experiment, and ρ_{tor} = 0.2): it results from the local, gyro-Bohm scaling and the stiff heat transport. ITGs are the dominant instabilities. Effects of collisions and *ExB* shearing are included. The L-mode isotope identity discharges have low beta (β_N ~ 0.5) and low momentum input, with negligible effect of toroidal rotation v_{tor} and *ExB* shearing on the predicted heat and particle transport channels. Therefore, the - less than a factor of 2 - mismatch in Mach number $M \sim \omega_{tor}\,R\,\sqrt{A}\,/\sqrt{T_e}$ (toroidal rotation velocity normalized to ion sound speed) is not significant in this case and does not invalidate the achieved dimensionless profiles identity. The H and D identity pair have, by definition, similar density profile peaking (Fig. 1a) at same ρ^*, ν^*, β and q. The scaled NBI particle source (TRANSP/NUBEAM) is, however, somewhat larger in H than in D for ρ_{tor} < 0.5. Predictive modelling indicates that, in addition to the pinch term, the NBI particle source also contributes to the core density peaking in these discharges (by approximately 40% with pedestal contribution subtracted). Pure gyro-Bohm transport models (weak ν^* and β) predict identical, zero flux density peaking R/L_n independent of A. With collisional effects included, slightly larger density peaking is predicted for H than for D for ITG dominated transport [6], also found in the JETTO-TGLF predictive modelling.

3.2. TYPE I ELMy H-MODES. The experiments were in type I ELMy regime, at I_P/B_T = 1.7MA/1.7T (D) and 1.0MA/1.0T (H), q_{95} = 3, δ = 0.2, strike points in divertor corners, with D-NBI (beam energy: 95 keV) and H-NBI (beam energy: 70 keV), respectively. The input power and injected (H or D, respectively) gas rate were varied, to obtain variations in the resulting density and temperature profiles and ELM frequencies - a technique similar to that utilized in the JET-C experiments - to match the scaled quantities in H and D. This, however, proved very difficult. The profiles of the H and D pair with the closest match in ρ^*, β, ν^* and M (the q profile is trivially matched when I_P and B_T are appropriately scaled with isotope mass) are shown in Fig. 3. The isotope identity is not achieved due to a mismatch in the scaled n_e and T_e (~ T_i) profiles in H and D, as highlighted by the ν^* profiles. It is interesting that the Mach number is matched from mid-radius outwards, although v_{tor} is not controlled in these experiments. In the pair of Fig. 3, the D pulse is from a gas scan at constant input power and the H pulse is the shot at lowest power in the power scan at lowest gas rate, which results in the Hydrogen type I ELMy data at lowest density. Although the scaled confinement times $B_T\ \tau_{E,th}/A$ in H and D are within 20% from each other, $A\ f_{ELM}\ /B_T$ is three times larger in H than in D at the same $P_{abs}/B_T^{5/3}$. Comparative analysis of the H 1MA/1T pulses in JET-C (performed at the natural H-mode density) and JET-ILW (Γ_H = 2.6 x 10^{21} e/s) has revealed lower n_e in type I H-modes in JET-ILW. In addition to the lower δ = 0.2 in the JET-ILW pulses, different wall recycling [7] and lower long-term fuel retention [8] with the metallic wall is the likely cause for the lower density in Hydrogen in JET-ILW. This exemplifies the impact of plasma boundary conditions on pedestal and, therefore, global confinement. For the isotope pair in question, this leads to – in dimensional terms - the H shot being close to the low density, high power TypeIII-TypeI ELMy boundary (lower f_{ELM}) and the D shot being far from the high density, low power TypeIII-TypeI ELMy boundary (higher f_{ELM}) for the same $P_{abs}/B_T^{5/3}$. This explains the large difference in scaled f_{ELM}, despite the similar scaled energy confinement times, and highlights the importance of knowing $P_{L\text{-}H}$ and $P_{TypeIII\text{-}TypeI}$ of the dimensional operating spaces when carrying out dimensionless similarity experiments. Other H and D pairs in the dataset, with similar scaled f_{ELM} (H shots at higher n_e, obtained at higher Γ_H values), have however dissimilar dimensionless profiles. Potential optimization in profiles match in H and D type I H-modes will be further attempted in the upcoming JET D campaign, via tuning of the D-NB voltage and/or external gas puffing rates. However, it is not excluded that conditions at the plasma boundary, strongly affected by edge recycling neutrals, which play an important role in pedestal confinement and stability in JET-ILW [9], may invalidate the isotope identity technique in H-mode.

4. OUTLOOK. JET-ILW experiments in T are crucial, not only to add a 3rd isotope (by far a non-trivial achievement per se), but because the physics underlying the 'isotope effect' is complex and non-linear: it involves interaction between the local scales, where gradient driven instabilities arise, and global scales, where e.g. stiff heat transport and density profile peaking are important. As T plasmas will have similar or better confinement than D, and not worse as in H [5], studying D and T means focussing on the fusion-relevant isotope pair.

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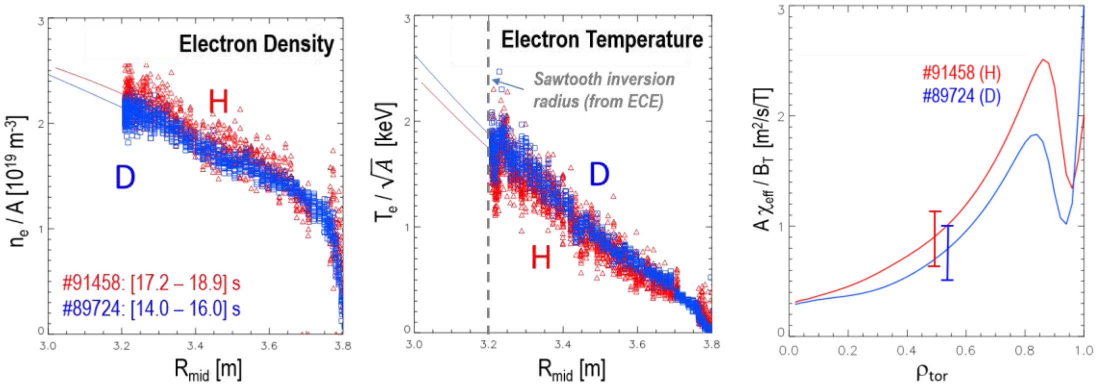

Figure 1. *From left to right: scaled (a) n_e and (b) T_e profiles from HRTS, (c) scaled effective heat diffusivity for the JET-ILW L-mode isotope identity pair in H (red) and D (blue), with parameters as in Table 1.*

Pulse #	**#91458**	**#89724**
Isotope	H	D
Time interval [s]	17.2 – 18.9	14.0 – 16.0
B_T [T]	1.74	2.95
I_P [MA]	1.44	2.46
P_{abs} [MW]	2.56	6.24
$P_{abs}/B_T^{5/3}$ [MW/T$^{5/3}$]	**1.02**	**1.03**
Z_{eff}	**1.4**	**1.35**
$\tau_{E,th}$ [s]	0.155	0.19
$B_T\,\tau_{E,th}$ / A [T/s]	**0.27**	**0.28**

Table 1. *Main parameters of the JET-ILW L-mode isotope identity pair.*

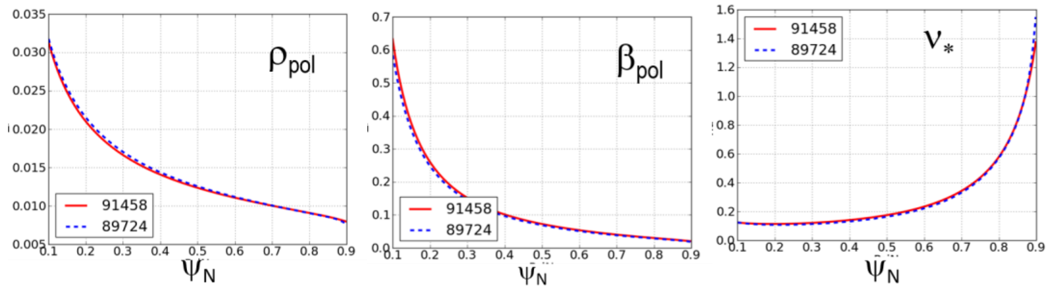

Figure 2. *ρ^*, β, ν^* profiles vs ψ_N for the JET-ILW L-mode isotope identity pair in H (red) and D (blue).*

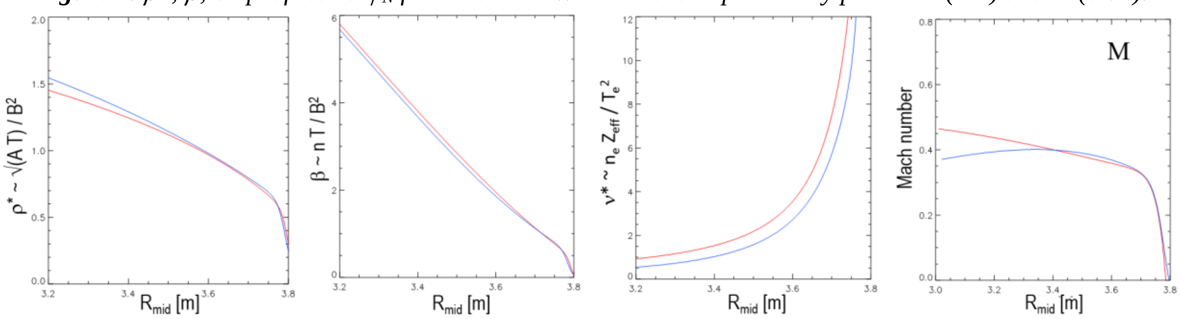

Figure 3. *ρ^*, β, ν^* and Mach number profiles vs R_{mid} for the JET-ILW type I ELMy H-mode pair in H (red) and D (blue) with closest match in dimensionelss profiles, but largely different scaled f_{ELM} (see text).*