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Isotope effects on L-H threshold and confinement in tokamak plasmas

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Abstract. The dependence of plasma transport and confinement on the main hydrogenic ion isotope mass is of fundamental importance for understanding turbulent transport and, therefore, for accurate extrapolations of confinement from present tokamak experiments, which typically use a single hydrogen isotope, to burning plasmas such as ITER, which will operate in deuterium-tritium mixtures. Knowledge of the dependence of plasma properties and edge transport barrier formation on main ion species is critical in view of the initial, low-activation phase of ITER operations in hydrogen or helium and of its implications on the subsequent operation in deuterium-tritium. The favourable scaling of global energy confinement time with isotope mass, which has been observed in many tokamak experiments, remains largely unexplained theoretically. Moreover, the mass scaling observed in experiments varies depending on the plasma edge conditions. In preparation for upcoming deuterium-tritium experiments in the JET tokamak with the ITER-like Be/W Wall (JET-ILW), a thorough experimental investigation of isotope effects in hydrogen, deuterium and tritium plasmas is being carried out, in order to provide stringent tests of plasma energy, particle and momentum transport models. Recent hydrogen and deuterium isotope experiments in JET-ILW on L-H power threshold, L-mode and H-mode confinement are reviewed and discussed in the context of past and more recent isotope experiments in tokamak plasmas, highlighting common elements as well as contrasting observations that have been reported. The experimental findings are discussed in the context of fundamental aspects of plasma transport models.

1. Introduction

The dependence of energy and particle transport on the main ion isotope mass (A) is of fundamental interest for the understanding of turbulent transport and, therefore, for accurate predictions of confinement in burning devices. Future experiments, such as ITER, will

operate in deuterium-tritium mixtures, while current experiments typically use a single hydrogen isotope, usually deuterium. Knowledge of the dependence of plasma properties on isotope species is important for the initial, low-activation phase of ITER operations (hydrogen or helium).

For the analysis of transport processes in tokamak plasmas one can think of three main regions of the plasma volume, as shown schematically in Figure 1. In the very core of the plasma, physics processes are determined primarily by sawteeth (core MHD events) and by collisional (neoclassical [1]) transport. The core confinement region carries most of the plasma volume and therefore plays a key role for the overall confinement. In this region turbulent transport – much higher than neoclassical – dominates and is thought to be due to small scale, ion Larmor radius size turbulence: $\rho \sim (A T)^{1/2} / B$, where T is the ion temperature and B the magnetic field. In this region the local heat transport is predicted by quasi-linear models to follow the gyro-Bohm scaling: $\chi_{gB} \sim \rho^*$ (with $\rho^* = \rho/a$ the normalized ion Larmor radius, a the plasma minor radius and χ_{gB} the gyro-Bohm heat diffusivity), which results in a dependence on isotope mass of $A^{1/2}$. In H-modes, characterized by a region with steep pressure gradient at the plasma edge and improved energy and particle confinement above L-mode values, the gyro-Bohm scaling has been confirmed in numerous experiments in D plasmas, for the local electron transport see e.g. [2] and references therein. The local ion heat transport is also consistent with gyro-Bohm scaling in conditions when electron and ion heat diffusivities can be resolved, but departs from it depending on the variation of the fractional heat flux in the electron and ion heat channels [2].

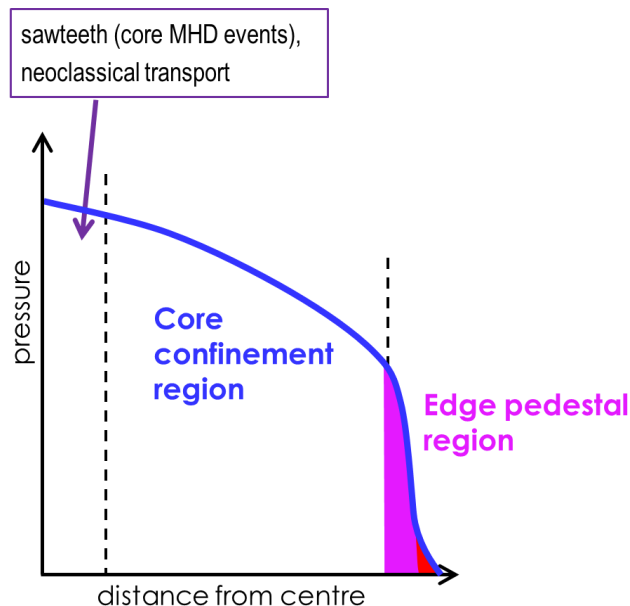


Figure 1. Schematic representation of the radial pressure profile in a tokamak H-mode plasma, from plasma core to edge. The two vertical dashed lines indicate the three main regions of plasma confinement: the very core, governed by sawteeth and neoclassical transport; the core confinement region, with small scale ion turbulent transport; the edge pedestal region, with ELMs controlling the pedestal pressure height and reduced transport levels inter-ELM.

In L-mode, tokamak experiments have shown in deuterium that the local transport follows the gyro-Bohm scaling for electrons and the Bohm scaling for ions, see e.g. [3],[4]: $\chi_i \sim \chi_B \sim T/ e B$ (with χ_B the Bohm heat diffusivity). The Bohm scaling is therefore consistent with the absence of isotope dependence in the ion heat channel: $\tau_E \sim 1/ \chi_B \sim A^0$.

The transition from low (L-mode) to high mode of confinement (H-mode) is characterized by a threshold in input power, P_{L-H} , whereby for input powers in excess of P_{L-H} ion scale turbulence is strongly suppressed at the plasma edge, leading to the formation of an edge transport barrier (ETB) for both density and temperature in a region with large velocity shear, see e.g. [5], [6]. In the edge pedestal region the transport is reduced to roughly neoclassical levels and periodic MHD events, the ELMs (Edge Localized Modes), limit the maximum pressure achievable at the top of the pedestal between subsequent ELM crashes. The pedestal region is strongly influenced by Scrape-off-Layer (SOL) physics: neutrals, radiation and impurity effects all have an impact on the pedestal. As the pedestal is influenced by SOL physics, also core and pedestal are strongly coupled in a wide range of H-modes, as observed in many tokamaks [7] and confirmed by modelling [8]: the pedestal pressure increases with the total plasma pressure as the core temperature gradients develop at constant gradient length, $L_T = \nabla T/T \cong \text{constant}$. The pedestal, therefore, sets the boundary condition in H-modes. The ELMy H-mode is chosen as the primary mode of operation for ITER.

Over the years, several tokamak experiments and theoretical work have addressed the plasma transport properties with varying hydrogen isotope mass, primarily in hydrogen and deuterium plasmas, see e.g [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]. The TFTR tokamak [19] and the JET tokamak (JET DTE1) [20] are the only two tokamaks to have conducted experiments also in tritium and in the 50:50 deuterium-tritium mixtures required for burning plasmas. Different dependencies of the energy confinement, τ_E , on isotope mass have been measured in L-mode and in H-mode [2]. The relationship between the local heat diffusivity and the global energy confinement is taken to be $\tau_E \sim a^2 / \chi$. Although the strength of the isotope dependence often varies from tokamak to tokamak experiment, even in the same mode of confinement, all experiments consistently find a positive isotope dependence of confinement, $\tau_E \sim A^\alpha$, with α ranging from 0 to 0.85, which projects favourably to deuterium-tritium burning plasmas. On the other hand, the isotope effects observed experimentally are in contradiction of theoretical predictions of the gyro-Bohm scaling, from which one would expect $\alpha = -0.2$ [13].

This discrepancy between theory and experiments still remains largely unexplained to date and presents a main challenge to the understanding of plasma turbulent transport. The main explanation put forward by theory regarding core heat transport has been linked to the effect of different isotopes on the shear flow and the resultant modification of the ion temperature gradient (ITG) driven turbulence [21]. Recently, gyrokinetic simulations with the GENE code have found a weak isotope effect in core heat transport in ITG/TEM (Trapped Electron Mode) regimes, but of smaller intensity than found in experiments [22]. Non-linear gyrokinetic simulations have shown that at high beta the core plasma micro-turbulence can depend on the isotope mass via multi-scale non-linear effects involving zonal flows,

electromagnetic effects and ExB shear, which counteract the intrinsic, local, gyro-Bohm scaling of plasma micro-turbulence [23].

As the JET tokamak prepares for new deuterium-tritium experiments in 2019/20, with improved edge, neutrons and fast particles diagnostics, as well as with the ITER-like Wall (W in the divertor and mainly Be in the main chamber), a thorough experimental investigation of isotope effects in hydrogen, deuterium and tritium plasmas is being carried out, in order to provide stringent tests to plasma energy and particle transport models. Experiments in deuterium, hydrogen and hydrogen-deuterium mixtures were carried out in 2016. Between 2018 and 2019 a series of campaigns will cover studies in deuterium and tritium plasmas, followed by a second campaign in hydrogen and hydrogen-tritium and hydrogen-deuterium mixtures. A final campaign in deuterium is then foreseen, to complete the scenario optimization before the deuterium-tritium phase.

In the next three sections of the paper the isotope effects on L-mode (Section 2), L-H threshold (Sections 3) and H-mode (Section 4) are briefly reviewed and recent findings of isotope effects in tokamak plasmas are presented and discussed. A summary and conclusions are drawn in Section 5.

2. L-mode

Over the past two decades several tokamak experiments have confirmed that in L-mode the local energy transport follows the short-wavelength gyro-Bohm scaling for electrons, $\chi_e \sim \chi_{gB}$, see e.g. [3], while the ions follow the long-wavelength Bohm scaling, $\chi_i \sim \chi_B$, see e.g the review of [2] and references therein. As the Bohm scaling is independent of isotope mass, $\tau_E \sim 1/\chi_B \sim A^0$ would be predicted for the ion energy transport, namely consistent with no isotope dependence. On the other hand, regression of multi-tokamak data for the L-mode thermal energy confinement time has yielded the ITER97-L scaling [24], $\tau_{E,th}(\text{ITER97-L}) = 0.023 I_p^{0.96} B_T^{0.03} P_{abs}^{-0.73} n_e^{0.40} A^{0.2}$ (with I_p the plasma current [MA], B_T the toroidal magnetic field [T], P_{abs} the absorbed input power [MW] and n_e the central line averaged density [10^{19} m^{-3}]), which exhibits a positive isotope mass dependence, in contradiction of both gyro-Bohm and Bohm scaling.

Recent L-mode experiments in ASDEX Upgrade (AUG) with electron cyclotron resonance heating (ECRH) have compared two L-mode discharges in hydrogen and in deuterium, where the normalized ion gyroradius ρ^* differed by $\sqrt{2}$, which is the square root of the mass ratio, while other dimensionless parameters were kept constant [17]. $\tau_E(\text{H}) = 83$ ms was lower than $\tau_E(\text{D}) = 110$ ms. Power balance and perturbative transport analyses revealed that the electron heat transport was unaffected by the change in isotope mass. Due to the central electron heating scheme used, $T_e > T_i$ in the plasma core, thus allowing for measurement of the electron-ion collisional exchange term in the energy balance equation with sufficient accuracy: $P_{e-i} \sim n^2 (T_e - T_i)/(A T_e^{3/2})$. Due to the mass dependence of P_{e-i} , $P_{e-i}(\text{H}) = 2 \times P_{e-i}(\text{D})$ and it is found that the additional ECRH heating required in hydrogen to match the profiles in deuterium is transported by the ion channel and $Q_i(\text{H}) > Q_i(\text{D})$, as shown in Figure 2 [17]. The hydrogen and deuterium ion heat diffusivities $\chi_i(\text{H})$ and $\chi_i(\text{D})$ are found to be the same, within experimental uncertainties in the ion temperature gradient

measurements. Therefore, the reduced τ_E in hydrogen in these low β plasmas (where β is the ratio of the plasma kinetic pressure to the magnetic pressure) is explained by the mass dependence in the collisional energy exchange between electrons and ions and not by a gyroradius effect. It is also noted in [17] that an increase in ion heat transport due to isotope mass effects is not expected for such ITG turbulence dominated plasmas. This result was also confirmed with ASTRA simulations, which show that the experimental profiles and global energy confinement can be reproduced when using the same coefficients for hydrogen and deuterium in the transport code [17].

This same mechanism is found to explain the weak, but positive isotope effect on thermal energy confinement observed from hydrogen to deuterium Ohmic discharges in JET-ILW, where $T_i < T_e$ is measured in the plasma core, although in this case an isotope effect on the ion heat transport is not excluded by the data [25].

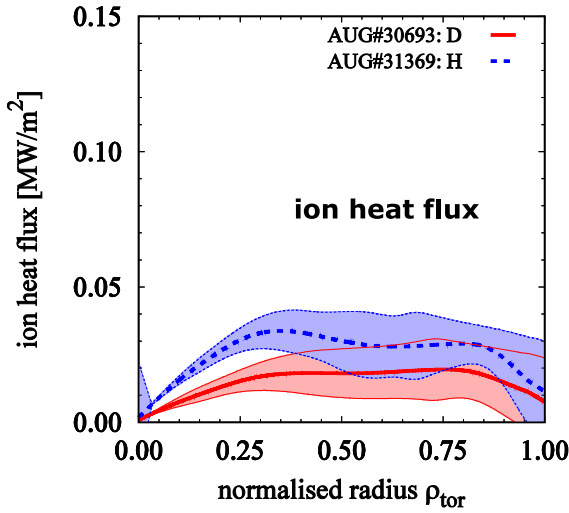


Figure 2. Radial profile of ion heat flux for deuterium (red) and hydrogen (blue) ECRH heated L-modes in AUG (reprinted from [17]).

The mass dependence of the collisional ion-electron heat exchange cannot, however, be invoked to explain the lower τ_E in hydrogen than in deuterium when $T_i \cong T_e$, that is when the ion-electron heat exchange term cannot be quantified within experimental uncertainties. This is the case of L-mode plasmas obtained in recent JET-ILW experiments with neutral beam (NBI) heating at 2.5MA/3.0T. The NBI power was scanned from 1 MW to 9 MW in both hydrogen and deuterium while keeping the plasma density constant to $n_e \sim 3.0 \times 10^{19} \text{ m}^{-3}$ (obtained with feedback control on the injected gas). A larger gas puff rate and NBI fuelling were needed in hydrogen to achieve the same density as in deuterium, indicating worse particle confinement in hydrogen. Higher NBI power was required in hydrogen to achieve the same total stored energy as in deuterium. After subtraction of the fast ion energy contribution from the stored energy inferred by the MHD equilibrium reconstruction EFIT, the thermal stored energy is still found to be lower in hydrogen than in deuterium and regression of the measured $\tau_{E,th}$ data gives: $\tau_{E,th} \sim A^{0.15 \pm 0.02} P_{abs}^{-0.63 \pm 0.02}$, as shown in Figure 3, in broad agreement with the mass dependence of the ITER97-L scaling. The thermal stored energy calculation described above is in agreement, within 10%, with that obtained by the TRASNP

code [26] with input the measured kinetic profiles integrated over the plasma volume. The positive isotope dependence of $\tau_{E,th}$ observed in JET-ILW L-modes is in contradiction of both gyro-Bohm and Bohm scaling.

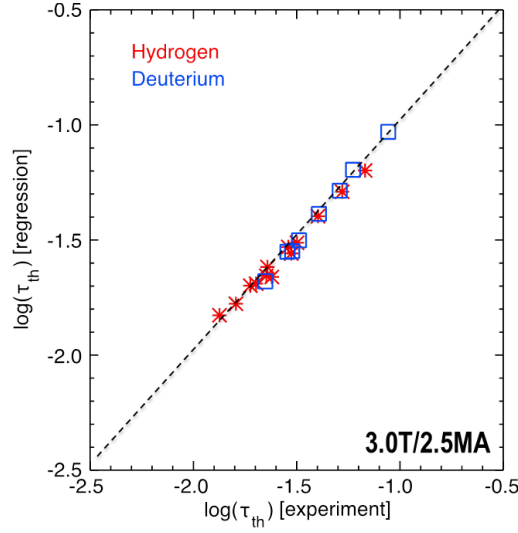


Figure 3. Log-log regression of the measured L-mode thermal energy confinement time in JET-ILW for hydrogen (red asterisks) and deuterium (blue squares) plasmas at 2.5MA/3.0T at constant plasma density with respect to isotope mass and absorbed power: $\tau_{E,th} \sim A^{0.15 \pm 0.02} P_{abs}^{-0.63 \pm 0.02}$.

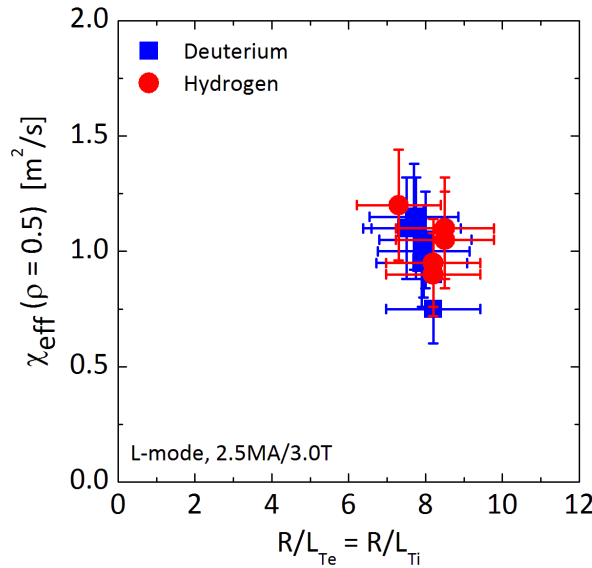


Figure 4. One-fluid effective heat diffusivity, χ_{eff} , vs $R/L_{Te} \cong R/L_{Ti}$ at $\rho_{tor} = 0.5$ for the L-mode power scans in hydrogen and deuterium at constant density, at 2.5MA/3.0T in JET-ILW: hydrogen (red circles) and deuterium (blue squares).

Both in hydrogen and in deuterium plasmas, $T_i \cong T_e$ within experimental uncertainties across the entire JET-ILW L-mode power scan and the same inverse normalized temperature gradient length is found for electrons and ions, $R/L_{Te} \cong R/L_{Ti}$, as shown in Figure 4. Therefore, electrons and ions are coupled and the electrons and/or ions are stiff. Power

balance analysis with TRANSP was carried out setting $T_i = T_e$, consistent with experimental error bars in the T_i data measurements, measured by Ne X, $n = 11-10$, charge exchange recombination spectroscopy (CXRS) and bulk ion CXRS, making it impossible to establish a species-resolved power balance. Only the one-fluid, effective heat diffusivity, χ_{eff} , can be extracted and Figure 4 shows that at mid-radius ($\rho_{\text{tor}} = 0.5$) hydrogen and deuterium plasmas have comparable χ_{eff} at all input power levels of the L-mode power scan, in contradiction of the gyro-Bohm dependence predicted by theory, $\chi_{\text{gB}} \sim A^{1/2}$. We note that at all NB power levels the ratio of electron to ion NB heating was the same in hydrogen and in deuterium, due to H-NBI operation at lower NB voltage than with D-NBI.

While no significant isotope effect is found in the L-mode core heat transport under these conditions, a strong isotope effect is found both in particle and heat transport at the plasma edge from detailed EDGE2D/EIRENE [27], [28] interpretative simulations. Two discharges of the 2.5MA/3.0T power scans were analysed, in the phase marked by the black, dashed rectangle in Figure 5, where higher NBI power was required in hydrogen to achieve the same total stored energy as in deuterium and larger gas puff rate and NBI fuelling were required in hydrogen to achieve the same central line averaged density as in deuterium.

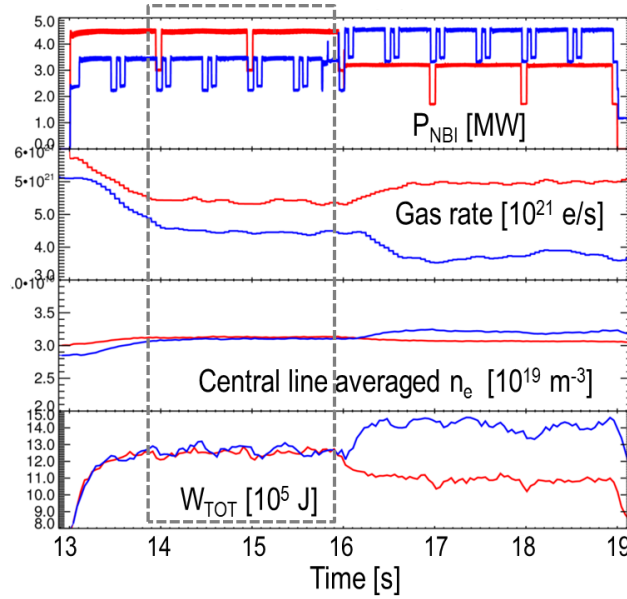


Figure 5. Time traces of main plasma parameters for two L-mode discharges in JET-ILW at 2.5MA/3.0T in hydrogen (red, #91450) and deuterium (blue, #89723). From top to bottom: NBI input power, injected gas rate, central line averaged density and total stored energy.

The edge anomalous transport coefficient of electron particle diffusion, D_{perp} ($\Gamma_e = -D_{\text{perp}} \nabla n_e$), and of ion & electron heat diffusivity, $\chi_{e,i}$ ($q_{e,i} = -n_{e,i} \chi_{e,i} \nabla T_{e,i}$) were obtained by fitting the EDGE2D/EIRENE solutions to the experimental upstream profiles. The latter were measured by profile reflectometry and Thomson scattering for n_e and by Thomson scattering for T_e . Figure 6 shows that larger transport coefficients D and $\chi_{e,i}$ are required in hydrogen than in deuterium - both inside and outside the Last Closed Flux Surface (LCFS) - to fit the modelled n_e and T_e profiles to the experimental data. In particular, the good spatial resolution

of the edge n_e profile measured with reflectometry allows for the computation of a radial structure in D_{perp} .

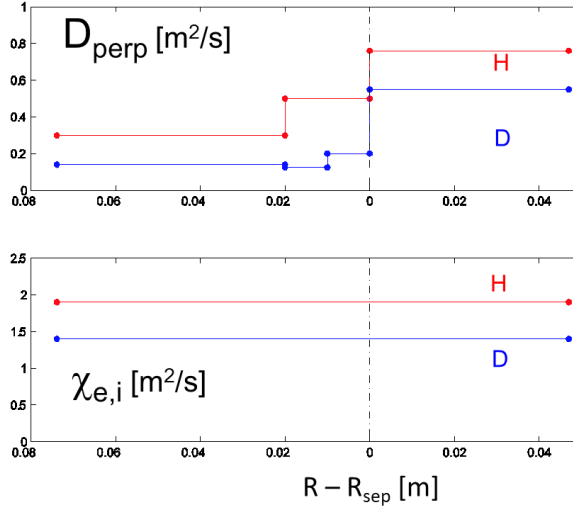


Figure 6. Radial profiles of perpendicular particle diffusivity (top) and electron & ion heat diffusivity (bottom) coefficients for hydrogen (red) and deuterium (blue) derived from interpretative EDGE2D/EIRENE simulations of the L-mode discharges of Figure 5, in the phase at comparable total stored energy (and larger NBI power and gas puffing in hydrogen than in deuterium), as indicated by the dashed black rectangle in Figure 5.

Consistent with the larger particle transport in hydrogen than in deuterium, larger edge density fluctuations (relative to their value in the Ohmic phase of the deuterium discharge) were measured with Doppler reflectometry [29] in hydrogen than in deuterium for the same P_{NBI} . The probed wavenumbers for the pulses in this paper are in the range $3\text{-}4 \text{ cm}^{-1}$. Figure 7 illustrates the case of two discharges in hydrogen and deuterium with $P_{\text{NBI}} = 3 \text{ MW}$, although this result was obtained at all power levels in the L-mode dataset.

In summary, recent experiments in the L-mode regime in hydrogen and deuterium plasmas show that in conditions where T_i and T_e are decoupled in the plasma core, such as ECRH heated plasmas in AUG or Ohmic plasmas in JET-ILW, the lower thermal energy confinement time measured in hydrogen can be explained by the isotope mass dependence of the i-e heat exchange term in the energy balance equation. On the other hand, this mechanism cannot be invoked with certainty to explain the isotope effect on $\tau_{E,\text{th}}$ in JET-ILW L-modes with NBI heating, where T_i and T_e are strongly coupled and therefore the e-i heat exchange term cannot be measured outside experimental error bars. In these plasmas a negligible isotope effect is found in the plasma core from transport analysis setting $T_i = T_e$ (within experimental error bars), while a strong, positive isotope effect is found at the plasma edge, both inside and outside the LCFS, on both energy and particle transport. The combination of negligible core and strong edge isotope effects yield the weak, but favourable isotope dependence on $\tau_{\text{th},E} \sim A^{0.15}$ measured in JET-ILW L-modes, in broad agreement with the isotope mass dependence of the multi-tokamak ITER-97L scaling ($A^{0.2}$).

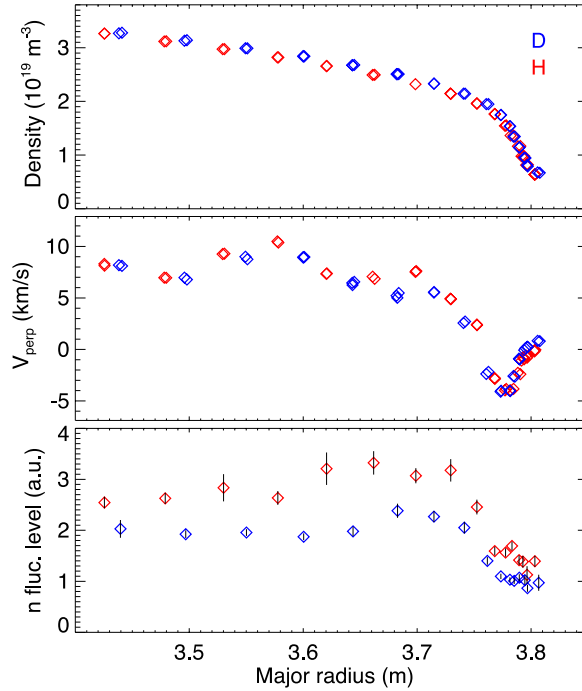


Figure 7. From top to bottom, radial profiles of: edge density (measured with profile reflectometry), v_{perp} and density fluctuation levels, measured with DBS, in JET-ILW in two L-mode discharges in hydrogen (red, #91450) and deuterium (blue, #89723) at 2.5MA/3.0T, $P_{\text{NBI}} = 3 \text{ MW}$. The density fluctuation levels are relative to those measured in the Ohmic phase of the deuterium discharge. The LCFS is at $3.79 (\pm 0.01) \text{ m}$.

3. L-H threshold

Despite much progress in theoretical work and a growing body of detailed experimental measurements on L-H transition dynamics in many tokamaks, a first principles physics model of the L-H transition with predictive capability is still missing. Extrapolations to future experiments therefore still rely on empirical scalings, such as the 2008 ITPA scaling: $P_{\text{L-H,08}} \sim n_e^{0.717} B_T^{0.803} S^{0.941}$ [30], with n_e [10^{20} m^{-3}] the line averaged density, B_T [T] the toroidal magnetic field and S [m^2] the plasma surface area. This scaling carries at least a factor of two uncertainty, due to additional dependencies of $P_{\text{L-H}}$ not included in the scaling.

It has been known for several decades that the H-mode power threshold has a favourable dependence on isotope mass: $P_{\text{L-H}} \sim 1/A$, as measured in many tokamak experiments in hydrogen and deuterium plasmas, see e.g. [9], [31], [32], [33] as well as in hydrogen, deuterium, tritium and deuterium-tritium in JET [34]. These observations typically pertain to the high density branch of $P_{\text{L-H}}$, namely where $P_{\text{L-H}}$ increases with density. This result projects to H-mode access in a fusion reactor with 50:50 deuterium-tritium mixture with about 20% less power than in a deuterium plasma.

Recent isotope experiments on the L-H threshold in JET-ILW in hydrogen and deuterium plasmas, with ICRH heating, have highlighted a stronger isotope dependence of $P_{\text{L-H}}$ in the low density branch [35], of order a factor of three, as shown in Figure 8, which may be indicative of edge L-mode turbulence of different nature in the low and high density branch

[36], [29]. The JET-ILW measurements differ from results reported from AUG, where the $\sim 1/A$ isotope dependence of P_{L-H} was observed both in the low and in the high density branch [33]. The difference in H-mode threshold between hydrogen and deuterium plasmas in JET-ILW is much larger for NBI-heated plasmas, reaching up to a factor of 4. It is currently being investigated whether this is due to an effect of NB torque on P_{L-H} , as observed on DIII-D [32], or to the partition between ion and electron energy fluxes at the L-H transition, as proposed in [37].

L-H transitions in 50:50 hydrogen-deuterium mixtures in JET-ILW resulted in P_{L-H} values intermediate between the pure hydrogen and deuterium cases, which had isotope purity $> 98-99\%$, as measured by Balmer- α spectroscopy at the plasma edge. The largest variation in P_{L-H} when varying the isotope ratio is observed at high and low $H/(H+D)$ ratios, while little variation is found for $0.2 < H/(H+D) < 0.8$ [35]. This was an unexpected result and remains as yet unexplained. The strong variation in P_{L-H} at small levels of hydrogen in deuterium and of deuterium in hydrogen plasmas may indicate a role of ion-ion collisions, where the product of the hydrogenic isotope densities gives a parabolic dependence for the collision rate [35]. An important implication of this finding is that it's imperative to achieve the highest isotope purity ($> 98\%$) in experiments when studying hydrogen vs deuterium plasmas, in order to prevent spurious conclusions from the experimental observations.

A similar, non-linear dependence on isotope mixtures is observed for H-mode energy confinement: the thermal stored energy, W_{th} , is lower in hydrogen than in deuterium (see Section 4) and the largest variations in W_{th} between the two species is observed for $0 < H/(H+D) < 0.1$ and $0.9 < H/(H+D) < 1.0$ [38].

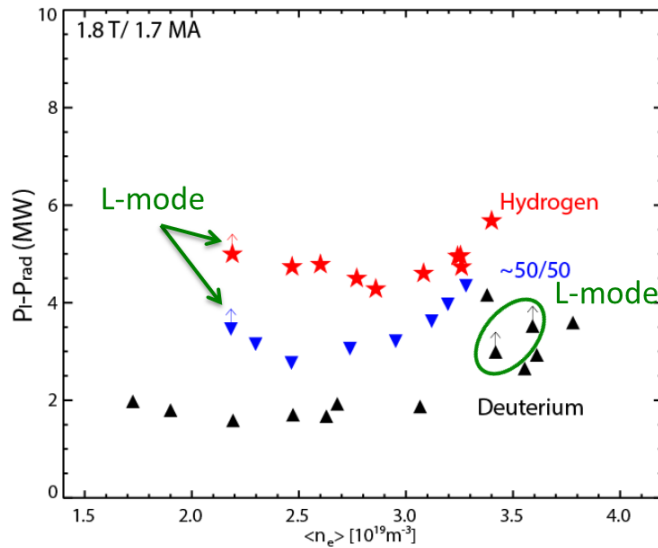


Figure 8. L-H transition power threshold in JET-ILW hydrogen (red stars), deuterium (black up-triangles) and 50:50 H-D mixture (blue down-triangles), with ICRH heating only at 1.8T/1.7MA.

The isotope dependence of P_{L-H} remains as yet unexplained. Here we put forward the hypothesis, based on the JET-ILW observations, that, at least in the high density branch, the isotope effect on P_{L-H} is a consequence of the isotope effect on transport at the L-mode edge.

As discussed in Section 2, the isotope effect is found in L-mode at the plasma edge, both for particle and heat transport and the ETB forms in the plasma region where the isotope effect is found in L-mode. In the high density branch, at the L-H transition, the same edge kinetic profiles (n_e , T_e) are measured in hydrogen and deuterium when $P_{\text{loss}}(\text{H}) \sim 2 \times P_{\text{loss}}(\text{D})$ [36], as shown in Figure 9. As evidenced by a large body of experimental and theoretical work, the L-H transition is triggered when the $E_r \times B$ shearing rate is of order of the growth rate of the L-mode edge turbulence, $\gamma_E = \nabla E_r / B \sim \gamma_{\text{turb}}$. In addition, considering that $E_r = \nabla p_i / (Z e n_i) - v_i \times B$ does not depend on isotope mass (except for mass effects in the coefficients for the neoclassical poloidal rotation), then the larger $P_{\text{L-H}}$ measured in hydrogen than in deuterium may only be a consequence of the larger input power required to suppress the higher levels of L-mode edge turbulence in hydrogen, via the dominant diamagnetic shear, and not of an isotope effect on the L-H transition per se.

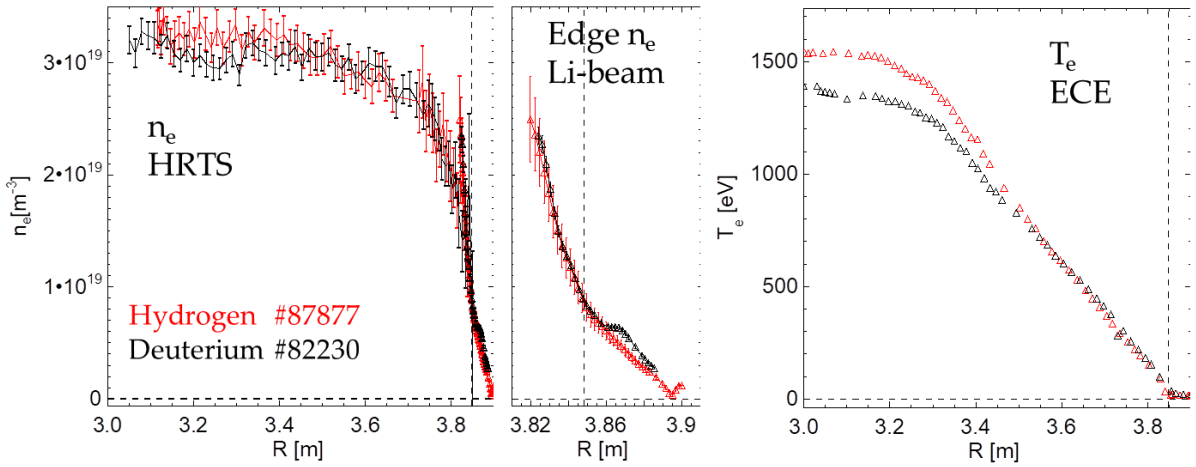


Figure 9. Comparison between hydrogen (red) and deuterium (black) n_e and T_e radial profiles in L-mode just before the L-H transition in JET-ILW. The vertical, dashed lines in the three panels indicate the position of the LCFS. T_i (as measured by edge CXRS) = T_e in the edge region (reproduced from ref. [36]).

4. H-mode

Isotope experiments in JET with the C wall (JET-C) in hydrogen, deuterium, tritium and deuterium-tritium showed for ELMy H-modes no isotope dependence of thermal energy confinement time $\tau_{E,\text{th}} \sim A^{0.03 \pm 0.1}$, due to strong, positive isotope dependence at the pedestal, $W_{\text{ped}} = 0.45 B^{1.2} (A/2)^{0.96}$ and weak, negative isotope dependence in the plasma core, $\tau_{\text{th,core}} \sim A^{-0.16 \pm 0.1}$ (the latter is in approximate agreement with the gyro-Bohm dependence, $\tau_{\text{gB}} \sim A^{-0.2}$) [13]. The strong isotope dependence at the pedestal was also supported by ELM losses measurements: in the type I ELMy H-mode regime larger ELMs were observed in tritium than in deuterium in discharges at 2.7T/2.6MA at the same input power of ~ 10 MW of NBI heating [39], while hydrogen discharges did not have type I ELMs due to the limited H-NBI power (and larger H-mode threshold). These experiments were, however, hampered by diagnostic resolution at the plasma edge.

A rather different picture, on the other hand, has been put forward by hydrogen and deuterium isotope studies in JT-60U, where, as in other tokamaks, τ_E is found to increase with isotope mass, but, unlike in JET-C, it is concluded that the isotope effect stems from the plasma core, with no direct isotope effect in the pedestal region [16], [15], [14]. Comparative hydrogen and deuterium type I ELMy H-modes were obtained with matching thermal stored energy, W_{th} , by raising P_{NBI} in hydrogen to match the electron and ion temperature profiles, while the n_e profile was automatically matched in the two species and the toroidal rotation profile was similar, although co-current in deuterium and ctr-current in hydrogen, as shown in Figure 10. It is thus likely that the radial electric field would be somewhat different in the two cases. The effective ion charge Z_{eff} increased for deuterium up to 2.4 at the maximum input power, while is remained approximately constant with power at $Z_{eff} = 1.5$ in hydrogen. The two H-modes in hydrogen and deuterium at same W_{th} had similar $Z_{eff} \sim 1.5$ [16]. The larger ion heat flux, Q_i , in hydrogen, at same W_{th} , resulted in larger χ_i in hydrogen than in deuterium over the entire plasma minor radius [16], see Figure 10. The same pedestal structure was measured in the edge T_i profile in hydrogen and deuterium (same pedestal height, width and gradient) at matched normalized pressure β_{pol} in the two ion species [14], but differing ρ^*_{pol} , which led to the conclusion that no direct isotope effect is observed in the pedestal region in JT-60U. The poloidal beta is defined as $\beta_{pol} = p / (\langle Bp \rangle^2 / 2\mu_0)$, with p the plasma kinetic pressure and $\langle Bp \rangle$ the average poloidal magnetic field. It is however always the case that when hydrogen and deuterium ELMy H-modes are compared at the same I_p/B_T and same input power a larger pedestal pressure is observed in deuterium than in hydrogen [16]. This is explained by: i) the measurement of a positive isotope effect of core ion heat transport [15], [16], whereby profile stiffness is observed in both hydrogen and deuterium H-modes, but with a smaller L_{Ti} for the heavier isotope mass, see Figure 11; ii) the pedestal pressure increasing with total β_{pol} in both hydrogen and deuterium; iii) deuterium plasmas achieving larger β_{pol} , due to reduction in core ion heat transport compared to hydrogen (see (i)) and larger fast ion energy, as the fast ion slowing down time, τ_S , increases with isotope mass: $\tau_S \sim A^{1/2} T^{3/2}$; iv) extension of the pedestal stability boundary with larger β_{pol} for deuterium than for hydrogen [16].

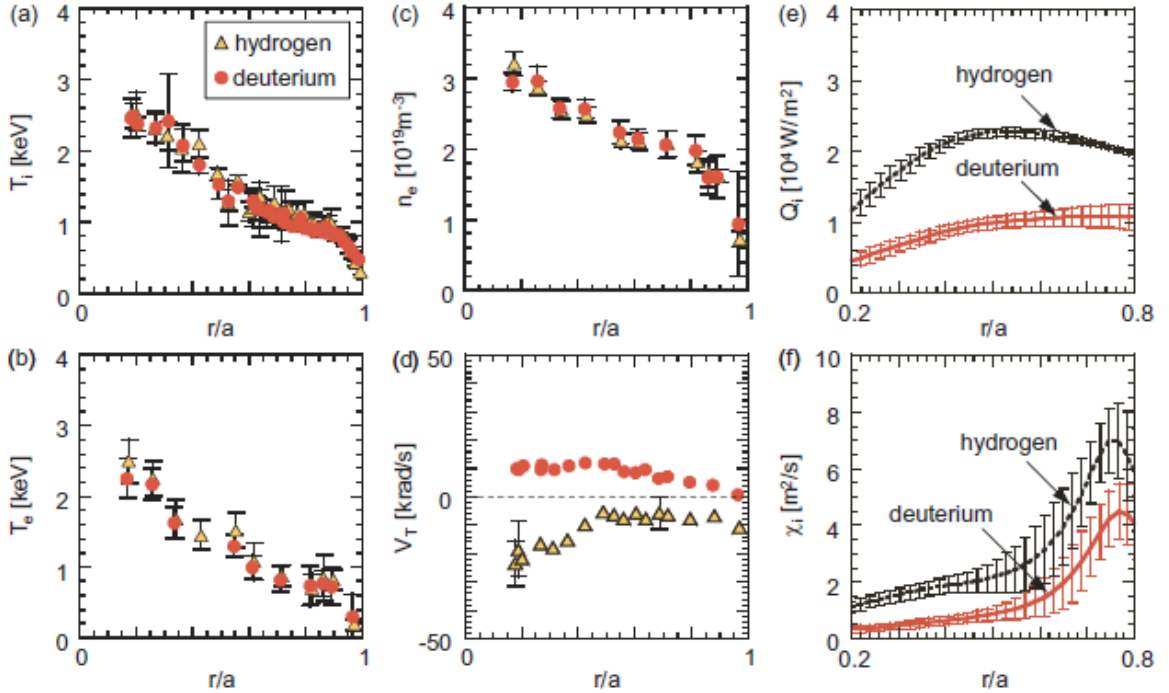


Figure 10. Radial profiles of (a) ion temperature T_i , (b) electron temperature T_e , (c) electron density n_e , (d) toroidal velocity v_T , (e) ion conductive heat flux Q_i and (f) ion heat diffusivity χ_i for hydrogen (yellow triangles) and deuterium (red circles) H-modes with the same W_{th} in JT-60U (reprinted from [16]).

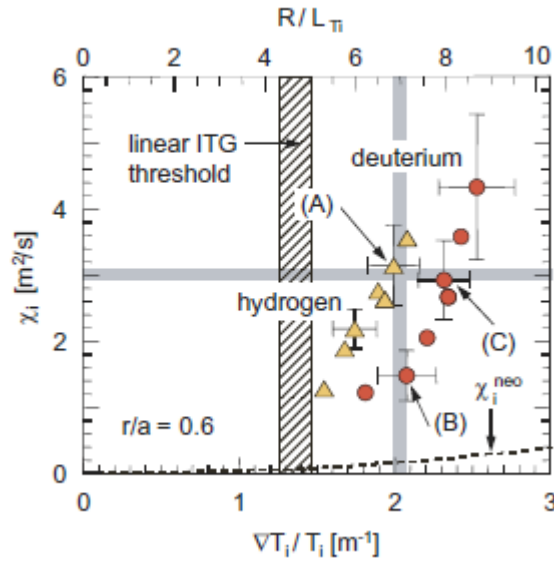


Figure 11. Ion heat diffusivity χ_i vs ∇T_i or R/L_{Ti} at $r/a = 0.6$ for power scans in hydrogen and deuterium H-mode plasmas in JT-60U (reprinted from [16]).

In recent isotope experiments in JET-ILW in hydrogen and deuterium plasmas, Type I ELMy H-modes could be obtained in hydrogen, both at 1MA/1T and at 1.4MA/1.7T. At 1MA/1T, H-mode discharges were obtained with H-NBI and D-NBI heating, respectively, while for the 1.4MA/1.7T dataset the discharges had NBI heating only in the deuterium plasmas and H-NBI (up to 10 MW) or a combination of H-NBI and ICRH (51 MHz, H

majority, 2nd harmonic) heating in the hydrogen plasmas. An additional deuterium dataset at 1.7MA/1.7T, with D-NBI, was also obtained.

As the input power is increased in experiment after the L-H transition, the plasma first enters the type III ELMy H-mode, at low input power above P_{L-H} and high ELM frequency, f_{ELM} . Subsequently, as the auxiliary heating is increased further, the type I ELMy H-mode regime is accessed, at higher β and confinement. The power threshold for the transition from type I to type III ELMs, characterized phenomenologically by f_{ELM} decreasing with power for type III ELMs and f_{ELM} increasing with power for type I ELMs [40], doubles from deuterium to hydrogen, as shown in Figure 12. This is in agreement with findings in JET-C [34] and consistent with the $1/A$ scaling found for the H-mode threshold in the high density branch. The variation in f_{ELM} at a given P_{loss} , shown in Figure 12, is a consequence of the varying injected gas rates in the hydrogen and deuterium power and gas scan experiments.

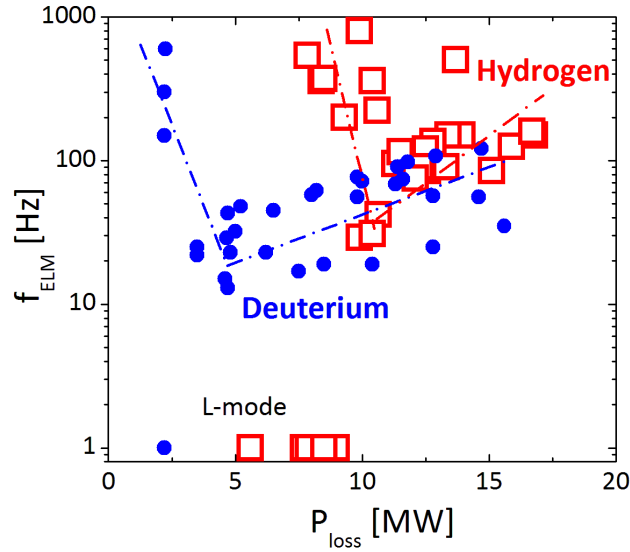


Figure 12. ELM frequency vs loss power for hydrogen (red open squares) and deuterium (solid blue circles) power and gas scans at 1.4MA/1.7T, low triangularity in JET-ILW, showing doubling of the power threshold for type III to type I ELMs from deuterium to hydrogen plasmas.

The thermal energy confinement is strongly reduced in hydrogen H-modes, in contradiction of the gyro-Bohm scaling, resulting in a stronger dependence with isotope mass, $\tau_{E,th} \sim A^{0.4}$, than for the IPB98(y,2) scaling $\tau_{E,th,IPB98(y,2)} = 5.62 \times 10^{-2} A^{0.19} I_p^{0.93} B_T^{0.15} R^{1.97} \epsilon^{0.58} k_a^{0.78} n_e^{0.41} P_{abs}^{-0.69}$ (with R the major radius [m], ϵ the inverse aspect ratio and k_a the plasma elongation) [41]. The hydrogen and deuterium JET-ILW dataset was obtained in plasmas with the same shape, therefore regressions of the $\tau_{E,th}$ data were performed with respect to I_p , B_T , P_{abs} and A , n_e and gas rate (or f_{ELM}). Although isotope mass, plasma density and gas rate (or ELM frequency) are correlated - in addition n_e and I_p are also correlated - the $A^{0.4}$ dependence of $\tau_{E,th}$ on the isotope mass is robust against which combination of this variables is chosen in the regression of the data.

A distinct feature of hydrogen plasmas is the lower plasma density and the fact that the density can be varied with injected gas rate, unlike in the deuterium H-modes, where the

density is weakly affected by gas injection [42]. This indicates degraded particle confinement with decreasing isotope mass, as observed in L-mode. H-modes in hydrogen and deuterium at the same thermal stored energy, W_{th} , do not have matched density and temperature profiles: in hydrogen the lower density is compensated by higher temperature. This contrasts JT-60U experiments, where the density and temperature profiles were matched for the two species when W_{th} was matched by raising the H-NBI heating, as discussed above. This difference suggests different particle transport in the two tokamaks and warrants further investigations in order to enable extrapolation of present-day experimental results to ITER and beyond.

Across the isotope dataset obtained in JET-ILW, the electron pedestal pressure, $p_{e,PED}$, is larger in deuterium than in hydrogen type I ELMy H-modes, as shown in Figure 13 for the 1.4MA/1.7T data. Similarly, also the ion pedestal pressure is larger in deuterium than in hydrogen, as $T_{i,PED} \sim T_{e,PED}$ consistently throughout the dataset for both ion species and Z_{eff} (primarily determined by the Be intrinsic impurity) varies between 1.1 and 1.4 in deuterium and between 1.1 and 1.7 in hydrogen, depending on I_p/B_T and input power. Interestingly, hydrogen and deuterium pedestals are found to react differently to variations in gas rate and input power: whereas hydrogen pedestals evolve along the same isobar, exchanging temperature for density as the gas rate is increased and/or the input power is reduced, in deuterium it is primarily $T_{e,PED}$ to be reduced with increasing gas rate, while $n_{e,PED}$ is little affected by varying levels of injected gas. An increase in input power in deuterium – at a given gas rate – leads to an increase in $T_{e,PED}$ and a decrease in $n_{e,PED}$ (via the increase in f_{ELM} for type I ELMs). Thus, especially at the lowest gas rate in the scan (see Figure 13) the pedestal pressure of deuterium plasmas increases with power, see e.g. [43].

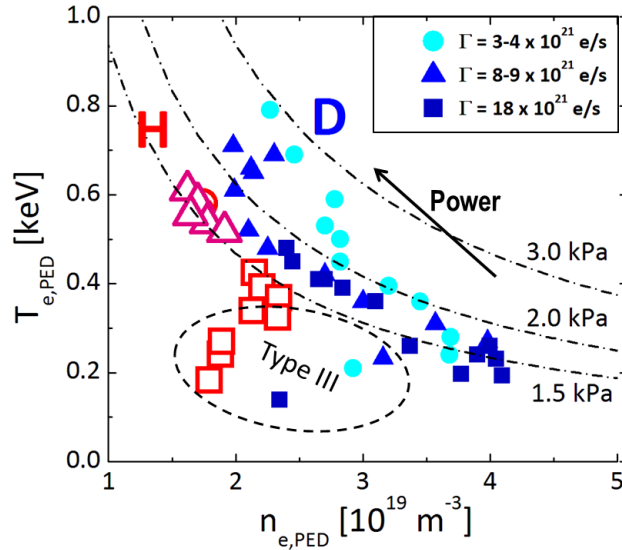


Figure 13. $T_{e,PED} - n_{e,PED}$ diagram for H and D power and gas scans at 1.4MA/1.7T, low plasma triangularity in JET-ILW.

Across the entire type I ELMy H-mode dataset, both in hydrogen and in deuterium, $T_i \sim T_e$ and all plasmas have similar $R/L_{Te} (\cong R/L_{Ti})$, for both plasma species. Therefore, also in type I ELMy H-modes electrons and ions are coupled and the ions and/or the electrons are stiff. In this sense, there is no difference between L-mode and H-mode core behaviour. Figure

14 shows the one fluid, effective heat diffusivity, χ_{eff} , at mid radius ($\rho_{\text{tor}} = 0.5$) for the hydrogen and deuterium type I ELMy H-mode dataset. There is little overlap in χ_{eff} in hydrogen and deuterium H-modes, due to the large difference in auxiliary heating required to access type I ELMy H-mode in the two species and due to the plasma density being systematically lower in hydrogen than in deuterium.

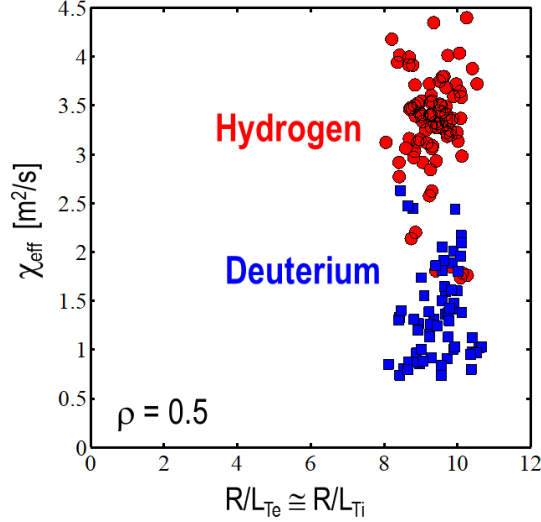


Figure 14. One-fluid effective heat diffusivity, χ_{eff} , vs $R/L_{Te} \cong R/L_{Ti}$ at $\rho_{\text{tor}} = 0.5$ for the JET-ILW type I ELMy H-mode isotope dataset: hydrogen (red) at 1.0MA/1.0T and 1.4MA/1.7T; deuterium (blue) at 1.0MA/1.0T, 1.4MA/1.7T and 1.7MA/1.7T.

In contrast to JT-60U, the combination of larger pedestal pressure in deuterium and constant R/L_T for both plasma species suggests for JET-ILW type I ELMy H-modes that the isotope effect on τ_{th} propagates from the pedestal through the plasma core via constant critical temperature gradient.

Possible contributing factors to the isotope effect observed in the pedestal region could be due to the isotope mass dependence in the edge bootstrap current, which plays a key role in the H-mode edge stability, and/or in the micro-instabilities that drive the residual edge transport levels inter-ELMs. Both these aspects will be addressed in future studies.

5. Summary and Conclusions

Recent isotope experiments in hydrogen and deuterium in JET-ILW have yielded a wealth of new results concerning the isotope effects on L-mode and H-mode confinement and transport and on the L-H power threshold.

In L-mode, τ_{th} is found to scale weakly with isotope mass, $\tau_{\text{th}} \sim A^{0.15}$, in contradiction of the gyro-Bohm (and the Bohm) scaling, and in analogy with findings from most tokamak L-mode experiments, as expressed by the ITER-97L scaling, $\tau_{\text{th}} \sim A^{0.2}$. A negligible isotope effect on heat transport is found in the plasma core and a strong, positive isotope effect is found at the plasma edge, both inside and outside the LCFS, on energy and particle transport. Larger edge density fluctuations in hydrogen than in deuterium at the same input power

corroborate the larger particle transport coefficient obtained by interpretative EDGE2D/EIRENE modelling of upstream edge density profiles. The $1/A$ scaling of P_{L-H} is confirmed in the high density branch in ICRH heated plasmas, whereas a stronger isotope dependence is observed in the low density branch, which is suggestive of L-mode edge turbulence of different nature in the two density branches of P_{L-H} . It is suggested that the isotope effect on P_{L-H} in the high density branch, $P_{L-H} \sim 1/A$, may be linked to the isotope effect on transport at the L-mode edge. In turn, the isotope effect on P_{L-H} is likely to propagate to the isotope effect measured on the power threshold for type III to type I ELMs, $P_{\text{typeI-typeIII}} \sim 1/A$, and to the strong isotope effect on thermal energy confinement time measured in type I ELMy H-modes, $\tau_{\text{th}} \sim A^{0.4}$. This is in contradiction of the gyro-Bohm scaling, which would predict $\tau_{\text{th}} \sim A^{-0.2}$. On the other hand, in deuterium plasmas the dimensionless confinement time follows the gyro-Bohm scaling, $B \tau \sim \rho^{*-3}$ [44], in agreement with experimental results from several other tokamaks, including JET-C, see e.g. [2] and references therein. As previously shown in JET-C, and in contrast to JT-60U findings, in JET-ILW the isotope effect is found at the pedestal and it propagates through the plasma core via constant critical temperature gradient in conditions where ions and electrons are strongly coupled and/or the ion heat transport is stiff. On the other hand, it is possible that in plasmas with weak ion-electron coupling the ion transport could be different and, consequently,

Overall, a favourable isotope effect on confinement and P_{L-H} is observed in tokamak experiments, which projects favourably to a future reactor that will operate in deuterium-tritium mixtures. The isotope dependence observed in experiment is in contradiction of the gyro-Bohm scaling, both in the L-mode and in the H-mode regime, while gyro-Bohm scaling of the thermal energy confinement is consistently confirmed in deuterium in H-mode experiments from many tokamaks. This discrepancy still presents a main challenge to the understanding of plasma turbulent transport and, despite many recent advances in theory, needs to be investigated further with extensive isotope studies across multiple tokamaks.

Indeed, recent numerical studies of an ITER modelling scenario, with non-linear gyrokinetic simulations, have shown that the core plasma micro-turbulence can depend on the isotope mass via multi-scale non-linear effects involving zonal flows, electromagnetic effects and ExB shear [23]. The local, gyro-Bohm scaling of plasma micro-turbulence is thus counteracted by the above effects, leading to isotope effects on heat transport on longer scale lengths [23], [45]. On the other hand, these theoretical analyses are highly relevant to the interpretation of isotope effects observed in high beta plasmas, such as the hot ion H-modes of TFTR or future hybrid deuterium-tritium plasmas in JET, where observation of these effects likely requires that ions are thermally decoupled from the electrons, unlike the JET experiments reported in this paper. Further theoretical work is required to understand the strong isotope effect measured at the pedestal of JET-ILW H-modes, or the isotope effect found in Ohmic and low beta JET-ILW L-modes.

Different results and interpretations of the isotope effects obtained across tokamak experiments, e.g. the contrasting results in H-mode from JT-60U and JET-C and JET-ILW discussed in Section 4, may be related to a variety of factors, such as different plasma heating methods, the role of T_i/T_e on ion-scale core turbulence, the impact of ExB flow shear

stabilization in the plasma core, high beta stabilization of ion-scale core turbulence, the impact of impurities. Such studies will be undertaken in JET in the upcoming isotope campaigns leading to deuterium-tritium experiments with the ITER-like wall, in support of ITER research.

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