Preliminary interpretation of the isotope effect on energy confinement in Ohmic discharges in JET-ILW

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The isotope effect on energy confinement is investigated in JET-ILW by comparing the electron and ion heat fluxes and diffusivities in hydrogen and deuterium Ohmic discharges. Main ion temperature profiles and gradients are obtained using neutral beam blips and analysing the H_α or D_α charge exchange spectra. Analysis of the heat fluxes between matched density pulses in H and D shows a decrease of the electron heat flux and an increase in the ion heat flux due to better electron-ion coupling in hydrogen. Alternatively, the ion heat flux is also scanned by increasing equipartition through the density instead of the isotope mass. This shows that at the same ion heat flux, $\nabla T_i/T_i$ is unchanged between H and D, which indicates that equipartition could largely explain the isotope effect in these low power, electron heated, discharges, consistent with results reported from ECRH heated L-modes in AUG [1]. However, the preliminary results presented here also show an inverse gyro-bohm dependence of the ion heat diffusivities. The relative importance of the two effects is still under investigation. A more fundamental observation is that the critical gradient for stiff profiles appears at larger $\nabla T/T$ for electrons than ions. This explains the change from electron to ion dominated heat fluxes at increased coupling. Implications such as the connections to the LOC-SOC transition and T_i/T_e ratios at higher heating power will be the subject of future modelling work.

Methodology

Heat transport analysis through power balance requires accurate temperature gradients and (T_e-T_i) in order to calculate the equipartition heat flux and heat diffusivities. This study focusses on a set of pulses with 2s stable density plateaus in deuterium and hydrogen at 2.6T/2.3MA.

- Ion temperatures are derived from D_α or H_α CXS using subtraction of background frames from before and after a NBI blip. Fig. 1 shows a fitted spectrum. The observed ion heating is small during the first 50ms of a NBI blip. Because sawtooth crashes are random with regard to the start of the blip, the following analysis has been done with sawtooth

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[*] See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nucl. Fusion Special issue: overview and summary reports from the 26th FEC (Kyoto, Japan, 17-22 Oct 2016)

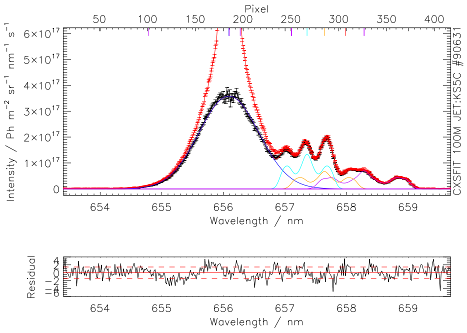
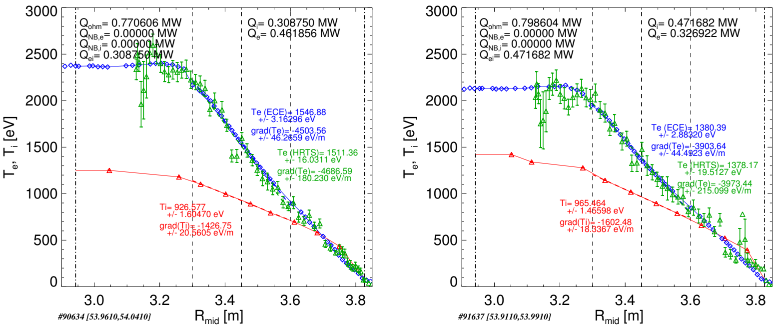


Figure 1: *Red: full D_α spectrum. Black: after background subtraction. Other colors show the fits to the charge exchange and beam emission spectrum.*



(a) Deuterium.

(b) Hydrogen.

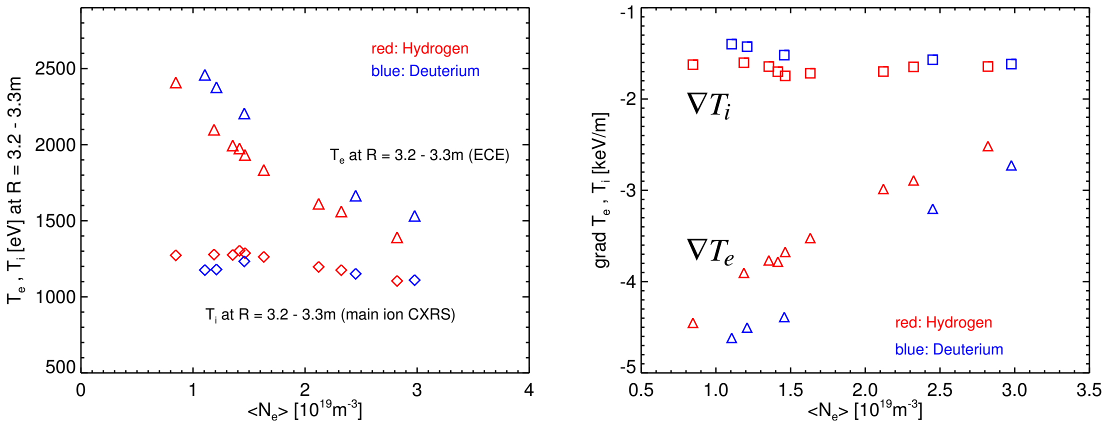
Figure 2: *Linear fits to the $T_{e,i}$ profiles at R=3.3-3.6m to obtain the temperature gradients.* $< n_e > \approx 2\ 10^{19} m^{-3}$.

averaged data. Using only the first frame of the NBI blip (5-10 ms of heating) made no qualitative difference for the results presented here. Two reversals of the intrinsic rotation are observed as function of density, reported in [4]. The ion temperature data used here has been shifted out with a rigid 6 cm, based on a suspected radial mismatch with T$_i$ profiles measured from an opposing periscope in a different set of pulses. It is to be noted that the modeled neutron rate (entirely thermal) in these discharges is very senstive to T$_i$ and near perfect agreement is reached with the measured neutron rate.

- The electron temperature and gradients from ECE have been used, mapped using an equilibrium incorporating a recently improved toroidal field measurement [3]. This gives very good consistency with high resolution Thomson scattering in these pulses (see fig.2) if the latter is shifted out with a rigid 2.5 cm.

- A linear fit is used to extract the temperatures and their gradients between R=3.3m and 3.6m. An example is shown in fig. 2 for a deuterium and hydrogen pulse at matched density. The results presented here should be regarded as preliminary until an investigation into the radial alignment of the profiles is concluded. Note that as long as the radial uncertainty on the profiles is such that the gradients are not affected, then the main systematic uncertainty in this work will be in the heat fluxes for the higher density pulses and not affect the main conclusions.

- The ion heat flux is calculated by integrating the equipartition power to the ions up to R=3.45m. The electron heat flux is the difference between the ohmic power within the radius of interest (based on neo-classical resistivity) minus the equipartition power.



(a) Core ion and electron temperatures.

(b) Ion and electron temperatures gradients at R=3.45m.

Figure 4: *Overview of electron and ion temperatures as function of density for H and D.*

Energy confinement in hydrogen and deuterium

Fig. 3 shows the thermal energy confinement time for the density scans in hydrogen and deuterium. Energy confinement is ≈ 10% lower ($\propto$ $M^{0.1-0.2}$) in hydrogen. The LOC-SOC transition appears at the same density. The drop in energy confinement comes from a drop in electron temperature that is not fully compensated by an increase in ion temperature going from deuterium to hydrogen. This is illustrated in fig. 4(a) which shows the core electron and ion temperatures for these pulses. The decrease in (T_e-T_i) as function of density and when comparing deuterium to hydrogen is indicative of the better electron-ion coupling ($P_{e-i} \propto \frac{Z^2}{M}\frac{n^2}{T_e^{1.5}}(T_e - T_i)$).

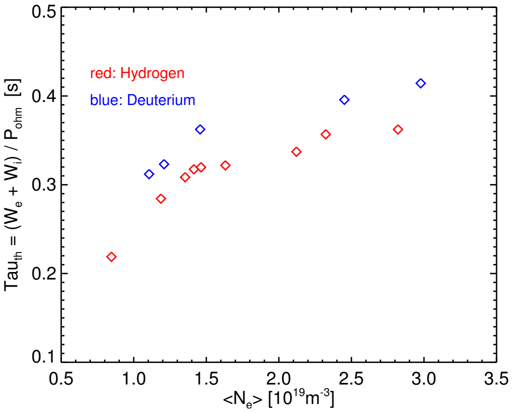
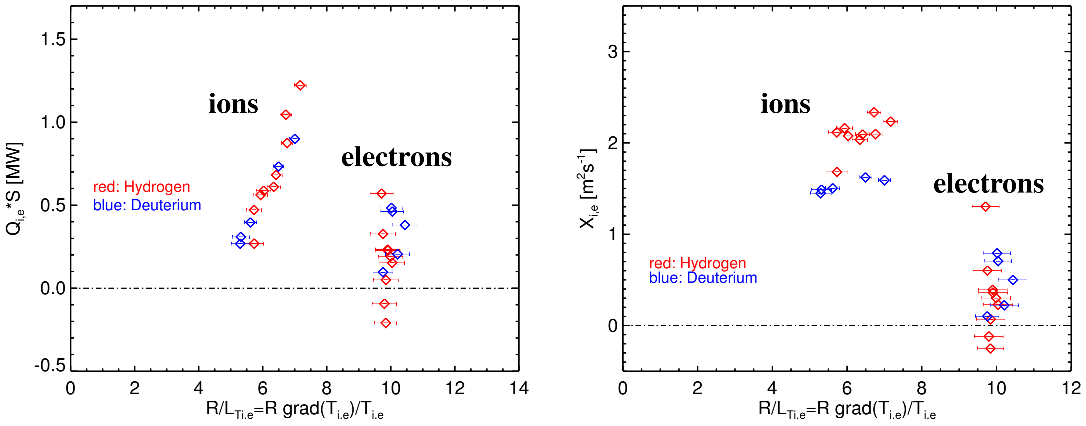


Figure 3: *Thermal energy confinement as function of density for the hydrogen and deuterium discharges.*

Electron and ion heat transport

Improved e-i coupling will cause a decrease in global confinement in discharges for which the species that is dominantly being heated has the lowest heat diffusivity, consistent with the work reported in [1]. The analysis of the heat fluxes and diffusivities shows that this is indeed the case for these ohmic discharges and also shows that the heat flux switches from electron dominated to strongly dominated by the ion channel above the LOC-SOC transition. However, both the ion temperature and its gradient respond only very weakly to this increased heat flux (fig. 4(b)). The electron profiles show strong differences in T_e and its gradient (fig. 4), but $\nabla T_e / T_e$ remains constant (fig. 5). If we interpret this in terms of a critical gradient model



(a) Ion (data on the left) and electron (data on the right) heat fluxes.

(b) Ion (data on the left) and electron (data on the right) heat diffusivities.

Figure 5: *Electron and ion heat fluxes and diffusivities as function of normalized temperature gradients.*

based on normalised gradients [2], then we observe a difference in the critical gradients between electrons and ions (fig. 5(a)) causing higher ion heat diffusivities in this regime with low overall heat fluxes. Preliminary heat transport modelling using a model of the form [2] (excluding gyro-bohm dependence in χ_i) with different ion and electrons critical gradients is able to qualitatively reproduce the isotope effect and LOC-SOC transition in these discharges. It should be noted that the decrease of T_e/T_i as the density is increased is expected to be stabilizing for ITG turbulence and therefore the interpretation in terms of stiffness could be more complex than only a difference between the ion and electron critical gradients. Additionally, we observe a $\propto \sqrt{2}$ difference between the hydrogen and deuterium ion heat diffusivities at the same normalised temperature gradient (fig. 5(b)), which would indicate an intrinsic mass dependence that is the inverse of the gyro-bohm scaling. This is not yet conclusive and should be confirmed in discharges at higher power (L-mode) with overlap in both density and ion heat flux [5]. Modelling has started to quantify the relative importance of equipartition and a potential intrinsic mass effect on χ_i in these discharges. The different critical gradients for ions and electrons could also have implications at higher power in terms of defining the conditions leading to larger T_i/T_e

References

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