

## Isotope Effect on Pedestal Structure in DIII-D

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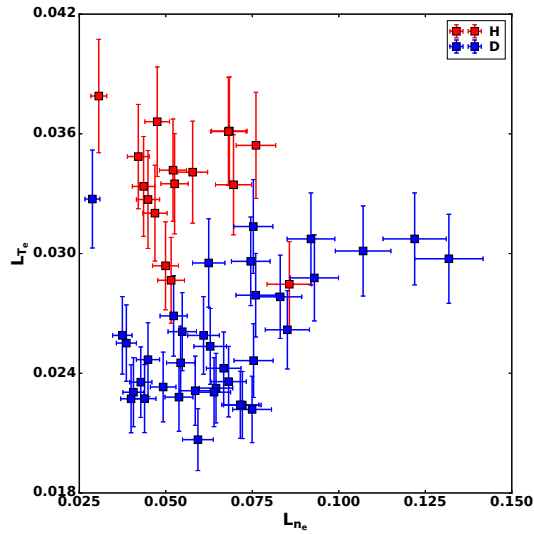
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Heavier hydrogenic isotopes have better confinement times and performance especially in the H-mode confinement regime. This effect manifests in significantly higher L-H transition power ( $P_{L \rightarrow H}^H \gtrsim 2P_{L \rightarrow H}^D$ ) and lower pressure pedestals in hydrogen compared to deuterium. The isotope effect primarily comes from the edge pedestal region [1] where steep gradients interact with edge fueling and MHD peeling-ballooning stability. Many studies have investigated the isotope effect on heat transport on several machines such as ASDEX [2] and DIII-D [3]. However, the isotope effect on particle transport is more difficult to quantify due to the presence of an edge source term from fueling or divertor neutral particles ionizing inside the separatrix. Understanding the isotope effects on our models is critically important to predicting ITER PFPO 1 hydrogen operations. Extrapolating to future tokamaks such as ITER is even more difficult because their Scrape Off-Layers (SOL) are hot and dense enough to eliminate fueling inside the separatrix.



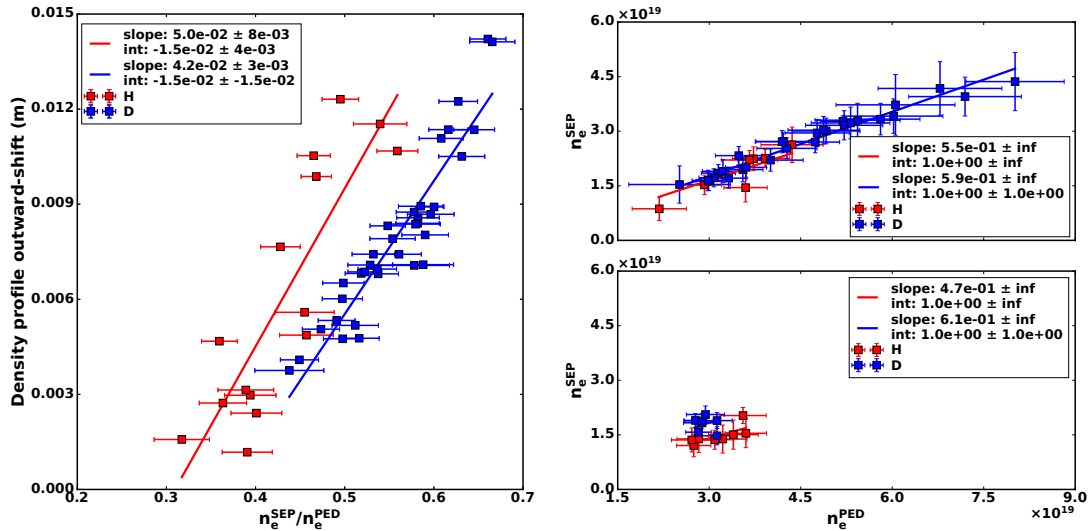
**Fig. 1** Temperature gradient scale length vs. density gradient scale length for hydrogen (red) and deuterium (blue). Scale lengths are measured in meters along the vertical Thomson Scattering chord.

In this study we examine whether there exist systematic pedestal structure differences between hydrogen and deuterium in stationary ( $>500$ ms) H-modes on DIII-D and investigate whether those differences are more likely caused by fueling or transport. We use a dataset of hydrogen and deuterium, which consists of 36 deuterium discharges and 16 hydrogen discharges from an experiment attempting to recreate the core and edge conditions of the deuterium experiment. All discharges are lower single null with similar triangularity, a range of collisionalities ( $\nu^* \sim 0.1 - 5$ ),  $I_p / B_T$ , and input powers ranging from 3-8MW varying the Electron Cyclotron Heating (ECH) and Neutral Beam Injection (NBI) mixture. In this analysis, stability changes from shaping are relatively minor; however, it is clear that particle transport is different in ECH+NBI discharges compared to NBI only discharges.

To examine the effects of transport, we examine the normalized edge electron density and temperature gradients ( $L_x = x / \nabla x$ ) and the ratio of these gradients  $\eta_e \equiv L_{n_e} / L_{T_e}$  averaged over the steep gradient region ( $0.95 \lesssim \psi_n < 1.0$ ). Simulation work on DIII-D has shown that  $\eta_e$  exhibits a critical threshold behavior where Electron Temperature Gradient (ETG) microturbulence increases significantly when  $\eta_e \gtrsim 1.4$  [4]. The average gradients and resulting scale lengths are approximated using the height and width of an edge hyperbolic tangent fit to the Thomson Scattering averaged over a stationary state ( $>500$ ms). Figure 1 shows the temperature

and density gradient scale lengths for both isotopes. There is a clear separation by isotope in the temperature channel while the range in  $L_{n_e}$  for each isotope overlap. The larger edge temperature gradients scale lengths shown for hydrogen in figure 1 are a consequence of the increased heat transport in hydrogen. These scale lengths are larger despite the average heating power in the hydrogen discharges being  $\sim 20\%$  higher to maintain a stable H-mode. However, the density gradient scale lengths overlap. This indicates that the isotope effect affects the particle and heat transport channels separately and while there is clearly increased heat transport, much more investigation is required to understand the particle transport.

Direct quantification of the edge source term is difficult. Empirically, more fueling increases the separatrix density, while increasing the pedestal density less and increasing the ratio of separatrix density over pedestal density ( $n_e^{SEP}/n_e^{PED}$ ) [5]. The data show that the density pedestal (steep gradient region) is "shifting" outwards with respect to the temperature pedestal and this behaviour has been observed on DIII-D, JET, and ASDEX [6]. This rise in  $n_e^{SEP}$  also decreases ballooning stability, while the shift increases  $\eta_e$  and moves the bootstrap current outwards affecting the peeling stability [6]; however, these effects are outside the scope of this conference paper.



**Fig. 2** (left) profile shift (steepest point of each profile as defined by the tanh-symmetry point:  $n_e^{SYM} - T_e^{SYM}$ ) vs.  $n_e^{SEP}/n_e^{PED}$ . (right)  $n_e^{SEP}$  vs.  $n_e^{PED}$  for NBI only (top row) and ECH+NBI (bottom row).

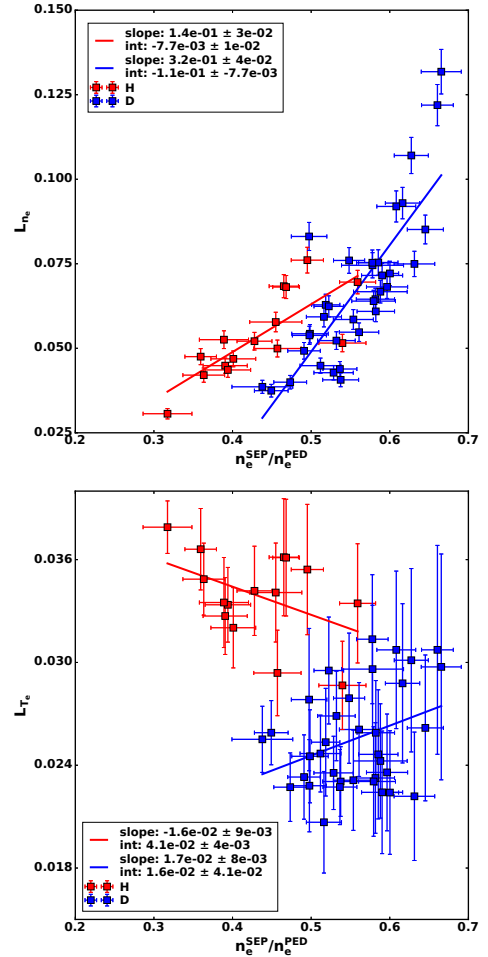
Figure 2 (left) shows the profile shift as a function of the ratio  $n_e^{SEP}/n_e^{PED}$ . The slope of the shift is similar for each isotope most likely since the profiles are following the same functional form of a hyperbolic tangent function. The x-intercept indicates a systematic difference where hydrogen pedestals tend to have lower  $n_e^{SEP}/n_e^{PED}$  compared to deuterium. The range of the hydrogen data also extends to lower  $n_e^{SEP}/n_e^{PED}$  and the range of deuterium increases past hydrogen. Hydrogen neutrals have a  $\sqrt{2}$  faster velocity and this increased penetration could be contributing to the slight decrease in the ratio of  $n_e^{SEP}/n_e^{PED}$ . However the decrease is on the order of 12% and cannot fully explain the isotope effect.

Figure 2 (right) examines the isotope difference for  $n_e^{SEP}/n_e^{PED}$  separating the data by heating power. The NBI-only discharges (top row) indicate a similar ratio although the range of hydrogen data is limited in pedestal height. For discharges with NBI+ECH heating (bottom) the slopes

are within error; however, there is significant scatter and this dataset only consists of a small range of  $n_e^{SEP}$  and  $n_e^{PED}$ . Future work will investigate whether ECH pumpout is altered by the isotope effect. Overall the data are suggestive of a small dependence on fueling as the primary contributor to the pedestal structure difference from the isotope effect.

We also examine the effects of the ratio of  $n_e^{SEP}/n_e^{PED}$  on the gradient scale lengths. Figure 3(top) shows that the density scale length responds differently between isotopes. Hydrogen tends to have narrower (lower  $L_{ne}$ ) pedestals that widen more slowly with increased  $n_e^{SEP}/n_e^{PED}$  than deuterium pedestals indicated by the decreased slope. By demonstrating earlier that fueling is not especially different between the isotopes, this is most likely a result of a change in particle transport. However, increased particle diffusivity would smooth out and widen the hydrogen pedestals; therefore, this might demonstrate a difference in a convective pinch term between the isotopes.

Figure 3 (bottom) shows that hydrogen  $L_{Te}$  decreases as the ratio of  $n_e^{SEP}/n_e^{PED}$  is increased while for deuterium  $L_{Te}$  increases. However, this effect is less significant than it appears at face value. The separatrix temperature in DIII-D is generally fixed between 70-100eV due to power balance using the two-point SOL [7]. However, our dataset currently uses an automated hyperbolic tangent fitting algorithm and the separatrix temperature and pedestal temperature each vary by a factor of 5 while the ratio of  $T_e^{SEP}/T_e^{PED}$  only varies between 0.26-0.32. Overall the magnitude of  $L_{Te}$  only varies by a factor of two from the highest hydrogen discharge to the lowest deuterium discharge and is caused by the increased heat transport in hydrogen mentioned previously. What may be interesting for future detailed analysis is inspecting the discharges with similar  $L_{Te}$  at higher at  $n_e^{SEP}/n_e^{PED} = 0.5$ .

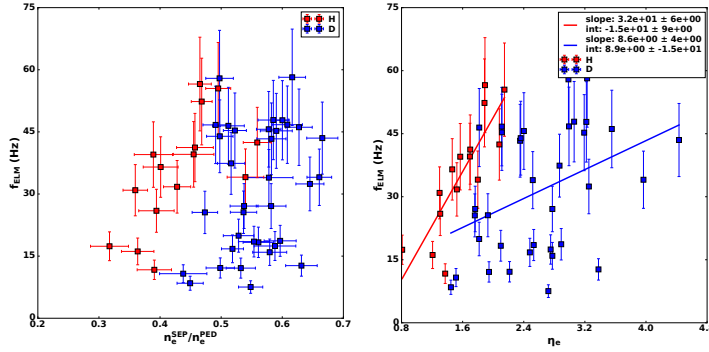


**Fig. 3** (top)  $L_{ne}$  vs.  $n_e^{SEP}/n_e^{PED}$ . (bottom)  $L_{Te}$  vs.  $n_e^{SEP}/n_e^{PED}$ .

Another method of analyzing the isotope effect on transport vs. fueling is to examine the ELM dynamics. Type-I ELMs are defined by increasing frequency with increasing injected power and this is true within our dataset. Figure 4 (left) shows there is not much of a correlation between ELM frequency and  $n_e^{SEP}/n_e^{PED}$  other than the difference in  $n_e^{SEP}/n_e^{PED}$  between hydrogen and deuterium previously described. The ELM frequency does not have any clear dependence on  $T_e$ ,  $\nabla T_e$ ,  $n_e$ , or  $\nabla n_e$ .

ELM frequency is also known to change with respect to the location of the pedestal on the peeling-ballooning stability diagram. Preliminary work has shown that hydrogen discharges are more often ballooning (pressure) limited rather than peeling (current) limited. This is true especially in comparison to deuterium discharges at matched injected power and  $q_{95}$  because the

increased heat transport means that lower pressure gradients will drive less bootstrap current. Figure 4 (right) shows ELM frequency vs.  $\eta_e$  and the steeper slope of hydrogen might represent a limit of ballooning ELMs, while the scatter in deuterium could be explained by being located at different positions on the peeling ballooning stability diagram with larger slower ELMs. Future work in this area will investigate the role of  $T_e/T_i$  for driving the transport and ELM frequency for ECH+NBI vs. NBI-only heated plasmas in hydrogen and deuterium.



**Fig. 4** (left) ELM frequency vs.  $n_e^{SEP}/n_e^{PED}$  and (right) ELM frequency vs.  $\eta_e$ .

convective pinch between the isotopes, and there are almost no changes in  $L_{Te}$ . For ELMs, other than the shift to lower  $n_e^{SEP}/n_e^{PED}$  for hydrogen, there is no difference in the frequency; yet there is a clear dependence on  $\eta_e$ . All of these factors suggest that hydrogen pedestal structure is more strongly influenced by transport with a small contribution from fueling.

Future work will use the calibrated Lyman- $\alpha$  LLAMA diagnostic [8] to infer neutral ionization profiles and quantify the fueling of deuterium and hydrogen discharges on DIII-D. We will also make use of the turbulence diagnostics to examine hydrogen and deuterium pedestal density and temperature height matches to measure the dominant type of microturbulence. Combining this information with the profiles will allow a direct comparison of the isotope effect on fueling versus transport in setting the pedestal.

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