Isotope effect on transport in L-mode plasmas in DIII-D

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This paper explores the effect of isotopes on transport in L-mode plasmas. Majority deuterium and deuterium/hydrogen plasma shots with nearly identical engineering parameters (B_T, I_P, β, and P_{inj}) are compared and TRANSP [1–3] profiles for thermal diffusivity χ_i show a decrease with the addition of the lower isotope mass. However, the usual isotope effect on confinement time is confirmed, as τ_E is diminished appreciably with the addition of hydrogen. A scan of different rotation values Ω_0 is performed using TGYRO [4], where the NEO neoclassical [5] and TGLF turbulent [6] models are used.

I. INTRODUCTION

The effects of varying isotope on transport in tokamak plasmas are not well understood, with experimental scaling results often disagreeing or even contradicting the theoretical predictions that confinement should decrease with heavier isotopes. Conventional tokamak plasmas, like those in DIII-D, have been shown [7, 8] to follow gyro-Bohm scaling for the electrons and either gyro-Bohm, Bohm, or Goldston scaling for the ions in L-mode, depending on the type of auxiliary heating used. Bohm, gyro-Bohm, and Goldston scaling, respectively, are given by:

$$\tau_B \sim \frac{a^2}{D_B}$$
$$\tau_{gB} \sim \tau_B \frac{1}{\rho^*} F(\beta, \nu_*)$$
$$\tau_G \sim I_p n^0 B_T^0 P_{tot}^{-1/2}$$

where $D_B \sim \frac{(\delta x)^2}{\delta t} \sim \frac{1}{16}\frac{ck_BT}{eB}$ is the Bohm diffusion, $\rho^* = \frac{\rho}{a}$ is the normalized gyro-radius, and ν_* is the effective collision frequency. Theoretically, an increase in isotope mass would lead to larger values of $\rho*$ and be detrimental to the confinement time. Experimentally, however, increasing isotope mass leads to a reduction in turbulent transport and the energy confinement time goes like $\tau_E \sim \sqrt{A_i}$, which is in clear violation of these predicted scaling laws. Though the cause of this is still very much an area of current research, zonal flows and their interactions with turbulent transport are suspected to be some of the main culprits behind this discrepancy.

II. TURBULENT TRANSPORT

Transport that exceeds the neoclassical prediction is assumed to be due to turbulence. Zonal flows, including both low frequency ZFs and those at the geodesic acoustic mode (GAM) frequency, are thought to mitigate turbulent transport [9, 10]. They may also have a dependence on species mix. In experiment, increasing isotope mass has led to an increase in long-range correlation amplitude [11], which could be evidence of an increase in zonal flow. This relationship has been seen for both helical and tokamak plasmas [12]. Gyrokinetic simulations have also shown a positive relationship between isotope mass and zonal flows [13] when non-linear electromagnetic effects are considered.

III. EXPERIMENT

A Frontier Science experiment that took place at DIII-D last year comprised two days, whose objective was to observe the effects of ten different fast ion distribution functions on ion cyclotron emission (ICE) and compressional Alfvèn eigenmodes (CAEs). These distribution function variations were created by modifying the neutral beams heating the plasma in the following ways: co/counter-injection, on/off-axis injection, and deuterium/hydrogen as the species. Hydrogen was puffed in the first day and injected via neutral beam on the second. The magnetic field was also varied from $B_T = 1.0 - 2.1$ T.

The varying species mix between shots allows for a comparison between mainly deuterium and deuterium-hydrogen plasmas. The two selected shots for analysis had $B_T \approx 1.7$ T, as seen in Fig 1. The n_D and n_H profiles are shown in Fig. 2. The second shot involved co-injecting, off-axis beams running in hydrogen, and reached a mean ratio of $\frac{n_H}{n_H+n_D} \approx 0.406$.

The hydrogen density was determined at the core and near the scrape-off layer ($\rho \sim 2.3$ m). For the core, deuterium blips (~ 10 ms) were injected and the exponential decay in neutron emission was fit to determine n_D [14]. This ratio was then used to determine a value for n_H by assuming that the plasma was quasineutral and had a low Z_{eff}. The ratio of hydrogen $\frac{n_H}{n_H+n_D}$ was determined at the edge through careful main-ion CER analysis. The full n_H profile in Fig. 2 was determined in the OMFIT-profiles module [15] by applying these ratios to core and edge values of n_e, n_D, and n_C, and then fitting the two resulting regions of data.

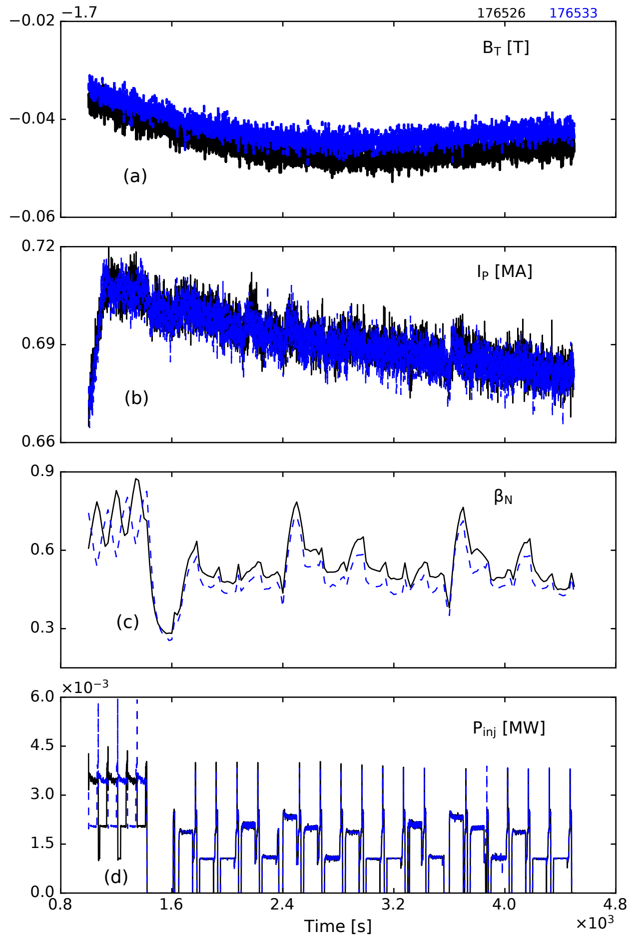

FIG. 1. The majority deuterium (#176526, black) and mixed species (#176533, blue) shots exhibit similar a) magnetic field strengths, b) poloidal currents, c) β_N, and d) injected powers.

A. TRANSP calculations

The following analysis focused on a time window of 40 ms during a 2.3 MW co-injecting neutral beam pulse, centered about 2.45 s. Subsequent TRANSP analysis shows disagreement between calculated and experiment neutron rates in the mixed species shot, but the χ_e profiles were similar and the effects of varying isotopes may be more clear. Further work might include similar analysis centered about a lower-powered 1.074 MW beam pulse at 2.45s that had better neutron rate agreement, but where the χ_e profiles differ significantly and may affect transport.

In TRANSP, a fixed hydrogen density profile was assumed, leaving n_D, n_e, and n_C to be flexible enough to satisfy quasineutrality conditions. As the shots had similar engineering parameters (as seen in Fig. 1), τ_E, χ_e, and χ_i can be compared directly. The resulting calculated confinement time (Fig.3) decreased with the addi-

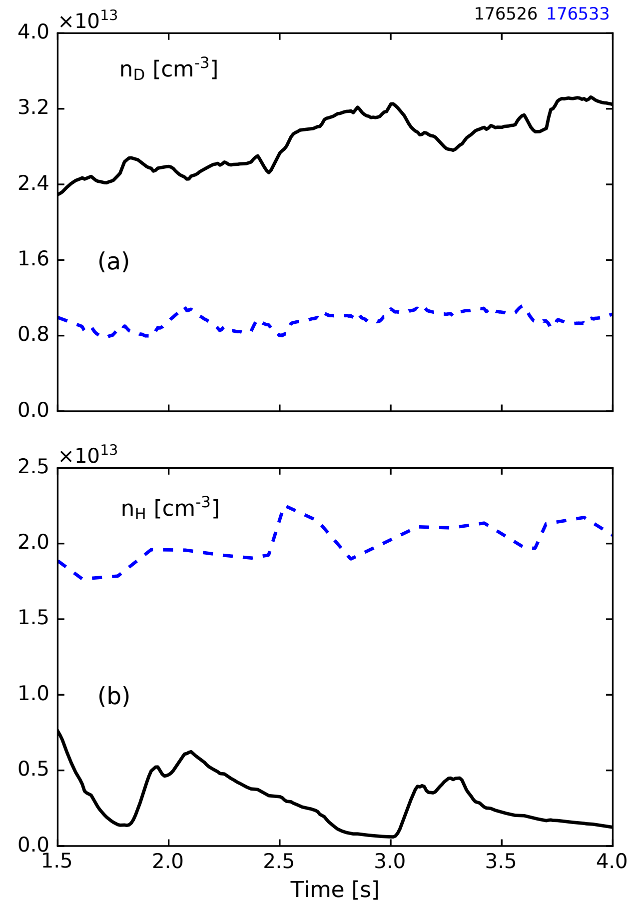

FIG. 2. a) Deuterium and b) hydrogen density profiles for the majority deuterium (again, #176526, black) and mixed species (#176533, blue) shots.

tion of the lighter species. The ion thermal diffusivity (c) grew for the shot with lower isotope mass, and peaked most around $\rho \sim 0.45 - 0.60$.

B. TGYRO analysis

Further transport analysis was performed with the TGYRO code, which runs both the NEO and TGLF codes to predict neoclassical and turbulent transport, respectively. The profiles output by TRANSP were used as inputs for TGYRO. The carbon, nitrogen, and fast ion populations were neglected, and only the effects of thermal deuterium and hydrogen studied. TGYRO then assessed the amount of transport measured from the experiment and iteratively determined the gradient necessary to produce the input profiles. In this analysis, only the energy flux was considered, and only T_i was evolved. Future work could involve any of the following: studying particle, momentum, and/or power transport; evolution by any or a combination of T_i, T_e, density, E_r, pedestal.

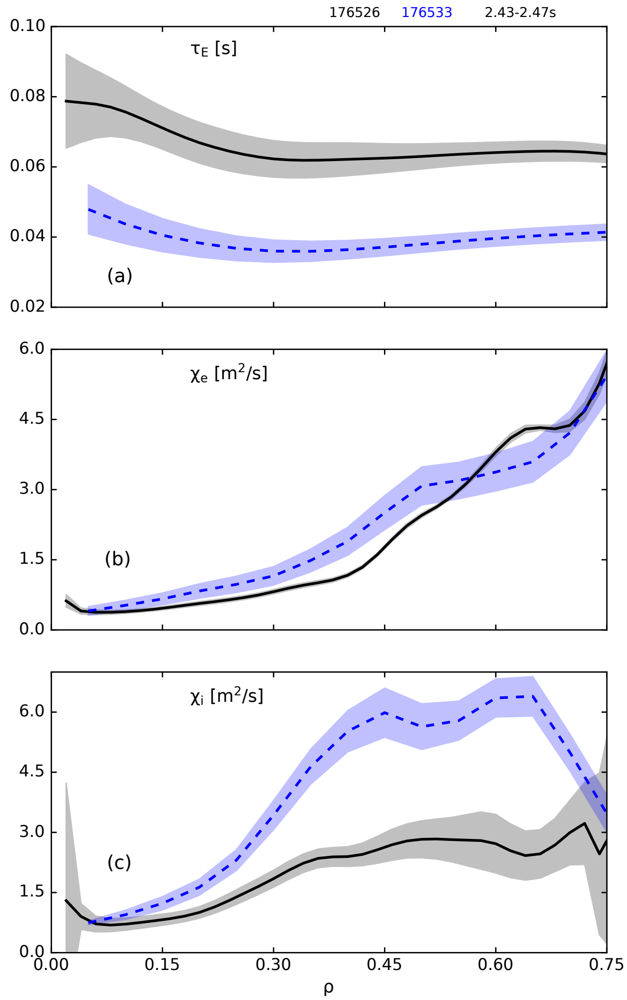

FIG. 3. TRANSP outputs for a) electron and b) ion thermal diffusivities, as well as c) global confinement time. The addition of the lighter isotope species lowered τ_E and increased χ_i.

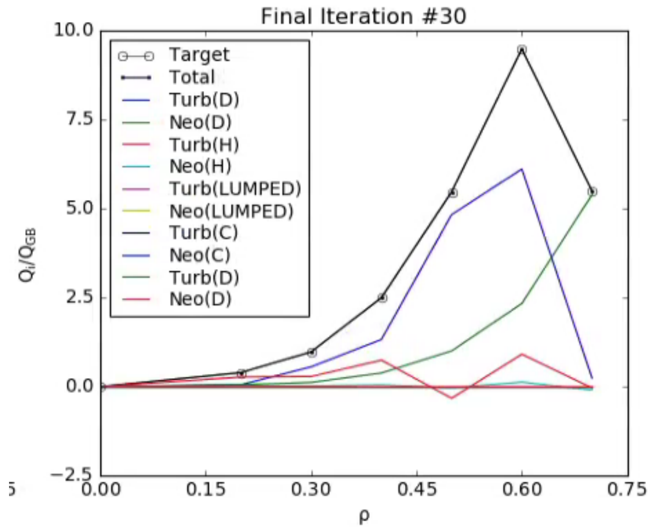

FIG. 4. TGYRO heat flux matching for majority deuterium case. Turbulent transport for deuterium is dominant, followed by neoclassical deuterium until $\rho \sim 0.6$, where this is reversed.

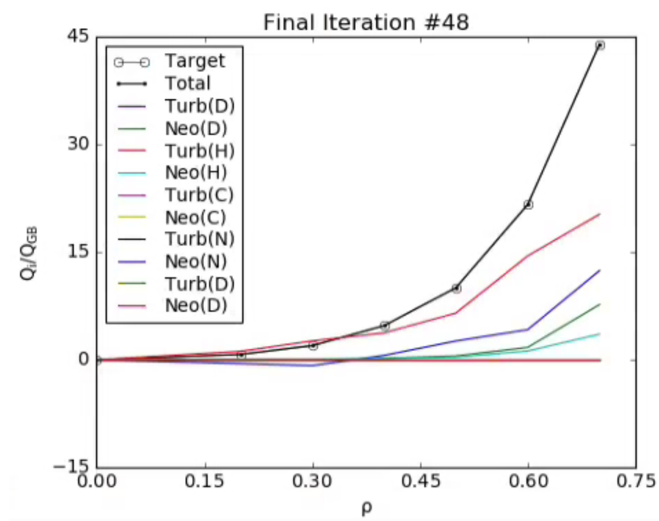

FIG. 5. TGYRO heat flux matching for mixed species case. Turbulent transport for hydrogen dominant, followed by turbulent deuterium and then neoclassical deuterium.

The first step was to look simply at the input profiles as they were and match the heat fluxes from experiment. For both cases, it was evident that turbulent transport affected the ion heat flux the most. Neoclassical transport of deuterium became noticeable at larger radii, $\rho \gtrsim 0.6$. Interestingly, the mixed species case had a much larger contribution from the turbulent transport of hydrogen than for deuterium for all radii.

Input profiles can be scaled within TGYRO, in order to mimic the effects of higher or lower rotation, similar but less or more dense plasmas, etc. Rotation was varied in this case, as mean $E \times B$ flows are thought to have an negative effect on zonal flows. Figures 6 and 7 depict the resulting profiles and scale lengths for various rotation scalings, where the rotation profile was scaled by factors 0.1, 0.5, 2, and 5. An interesting result is that T_i doesn't change nearly as much for the mixed species case, whereas the heavier isotope case shows a much larger change in T_i and scale length. However, it is important to note that the fluxes for the majority deuterium case exceed that of experiment, which may point to a computational error taking place rather than a physical effect in the plasma.

IV. CONCLUSIONS AND FUTURE WORK

The addition of a lighter isotope decreased confinement time, confirming the isotope effect for the L-mode

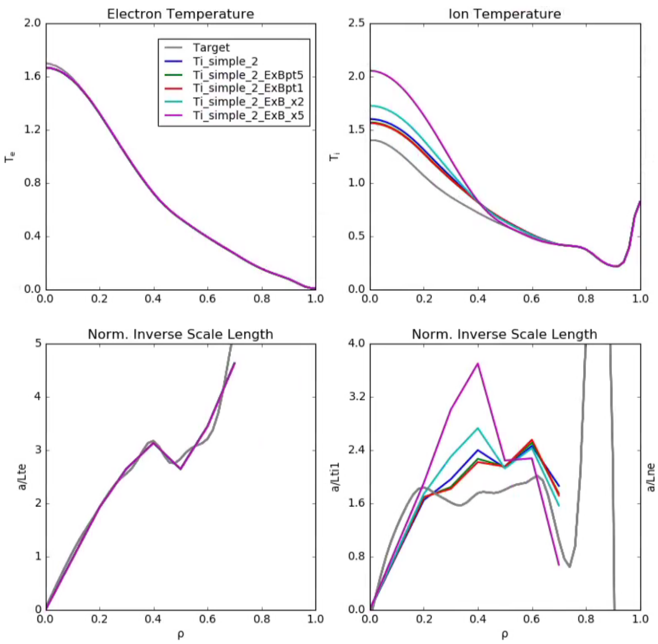

FIG. 6. TGYRO $E \times B$ scan for majority deuterium case.

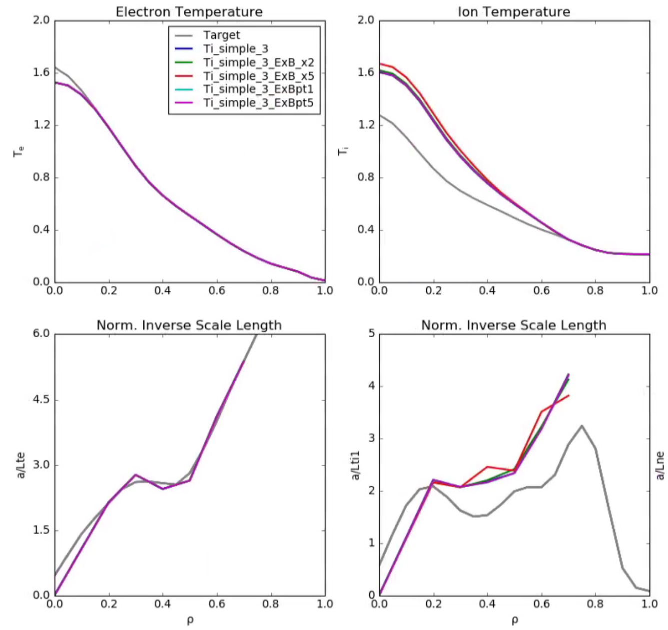

FIG. 7. $E \times B$ scan for mixed species case.

plasmas used in this experiment. However, the ion heat diffusivity decreased. $E \times B$ scans showed that increased shear greatly affected the ion temperature needed to observe the same output flux from experiment in the deuterium case, whereas the T_i was much less affected in the mixed species case.

There remains a large amount of data from this experiment, and future work might include performing similar analyis using TRANSP and TGYRO on a wider range of mixed shots; investigating low-frequency signals, possibly through BES and magnetics data; a much more thorough TGYRO analysis of transport of energy, particles, momentum, and power through evolution of more profiles than simply T_i; including the effects of (thermal) helium in the plasma. The effects of having a deuterium vs. hydrogen beam as a heating source in TGYRO might also warrant further consideration, as the analysis above was for a deuterium beam.

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