Coupling full-f gyrokinetic studies to experimental measurements of the isotope effect for FT-2 tokamak plasmas

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Abstract:

The isotope effect is a well known but poorly understood contradiction between experimental and theoretical scaling expectations for tokamak plasma confinement and transport. We present the first direct evidence of the isotope effect on particle confinement in the FT-2 tokamak and investigate it via gyrokinetic simulations. Experimental measurements for comparable hydrogen and deuterium discharges show that the particle confinement time increases by 40 percent for the heavier isotope species. The isotope effect in particle flux is reproduced in global and local gyrokinetic simulations. Global simulations demonstrate a systemic reduction in particle fluxes across the radial range, showing a ratio of fluxes $\Gamma_H/\Gamma_D = 1.3$ at the edge and $\Gamma_H/\Gamma_D = 1.4$ at $r/a = 0.63$. Local simulations for the latter position agree qualitatively as they predict a flux ratio of $\Gamma_H/\Gamma_D = 1.6$. Besides the fluctuation level, smaller scales and a favorable shift in the cross-phase between the turbulent fluctuations are found to contribute to the isotope effect in the simulations.

1 Introduction

Generating fusion power depends highly on how well the scientific community can predict the performance of devices and plasma scenarios. Even though a respectable understanding on the influence of turbulence and flows on plasma confinement has been built over the years [1, 2], a distinct disagreement between experiments and theory remains on the isotope scaling of confinement.

Experiments have shown that both particle and energy confinement time increase when switching from hydrogen to deuterium dominated plasmas. The magnitude of this improvement varies depending on the operation mode at e.g. ASDEX [3]. This *isotope effect* challenges the fundamental theoretical concepts that would predict the opposite. Both classical and neoclassical transport are expected to increase with the ion Larmor radius ρ_i and the ion atomic mass number A ($\rho_i \sim \sqrt{A}$). The same applies to turbulent transport according to the gyro-Bohm scaling. Gyrokinetic simulations are able to produce favorable deviations from the gyro-Bohm scaling of transport, indicating that the effect depends on the temperature ratio of electrons and ions $\tau = T_e/T_i$ and electron-ion collisions [4, 5].

In this publication, we continue the investigation of the isotope effect in turbulent transport in the FT-2 tokamak L-mode regimes, where intense zonal flow oscillations have also been observed [9]. We present the first evidence of improved particle confinement for deuterium plasmas in the tokamak. No corresponding improvement in energy confinement is found. We are able to replicate the effect in particle transport in both global and local gyrokinetic simulations via ELMFIRE and GENE codes. The nonlinear investigations highlight the importance of the cross-phase and the scale of the turbulent fluctuations besides the actual fluctuation level. The differences between the local and global simulations are also discussed.

2 Numerical tools and Setup

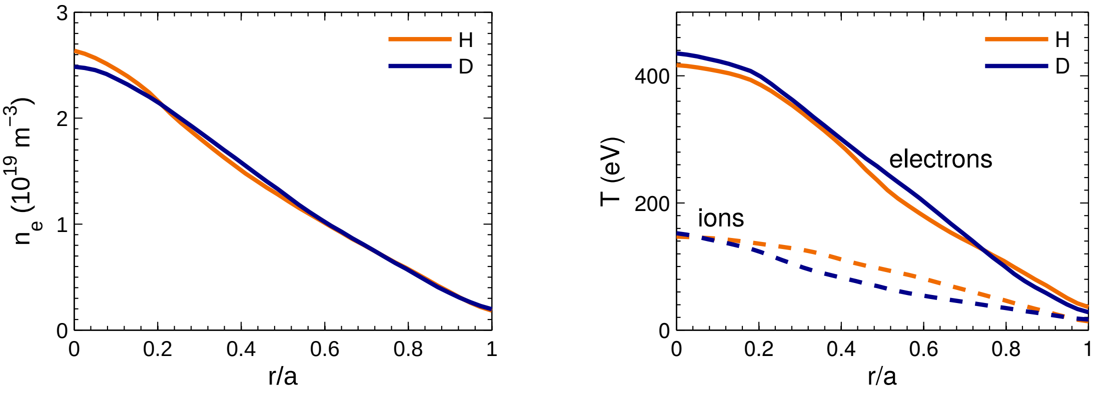
ELMFIRE is a particle-in-cell application of the gyrokinetic theory. The code evolves the full distribution of two gyrokinetic ion species and drift-kinetic electrons in a global toroidal geometry with circular and concentric flux surfaces. Collisions are modeled according to a binary Monte Carlo operator. ELMFIRE thus simulates self-consistently the evolution of the electrostatic equilibrium and fluctuations. Even though the computation geometry can cover the plasma from the magnetic axis to the scrape-off layer, the latter region is excluded from current calculations to reduce computational complexity. An in-depth overview of the code is available in Refs. [10, 11, 12]. Kinetic electron implementation and electric field interpolation schemes are described in more detail in Refs. [13, 14].

GENE (Gyrokinetic Electromagnetic Numerical Experiment) is a simulation code based on an Eulerian approach and the δf method. It solves the electromagnetic gyrokinetic equations for the perturbed particle distribution of an arbitrary number of particle species in a local or global simulation geometry. A more detailed description of the code is available via Refs. [15, 16, 17].

We investigate comparable hydrogen and deuterium discharges in the FT-2 tokamak. It is a large aspect ratio tokamak (major radius $R = 55$ cm, minor radius $a = 7.9$ m) with a limiter configuration and a circular cross-section. The specific plasma discharges have otherwise comparable parameters but different main fuel isotopes, i.e. hydrogen and deuterium. Temperature and density profiles 1 have been interpolated from experimental measurements by the ASTRA transport code [18]. Although higher densities can be achieved at FT-2, the density was kept low to have a wider plasma region accessible for the upper hybrid resonance backscattering (UHR BS) diagnostics [**?**, **?**].

Measurements have determined the main impurity ion species to be oxygen, here simulated as the partially ionized O^{+6}. Based on loop voltage measurements, the effective charge was determined as $Z_{\mathrm{eff}} = 2.3$ and $Z_{\mathrm{eff}} = 2.8$ for the hydrogen and deuterium parameters, respectively. Toroidal magnetic field was set at $B_t = 2.27$ T and $B_t = 2.22$

T on axis and total plasma current at $I_p = 20.5$ kA and $I_p = 19.4$ kA for hydrogen and deuterium, respectively. The current profiles lead to very similar profiles for the safety factor q_s as determined by ASTRA.



(a) Density profiles (b) Temperature profiles

FIG. 1: a) Density and b) temperature profiles as interpolated by ASTRA for $t = 27$ ms in the discharges. The profiles are used as input for ELMFIRE and GENE calculations.

3 Experimental results on isotope effect in confinement

The global particle confinement time τ_p is larger for deuterium by a factor of 1.4 compared to the corresponding hydrogen plasma. To estimate the confinement time, the particle balance is written as

$$\tau_p = \frac{\langle n_e \rangle}{\Phi - d\langle n_e \rangle / dt}, \tag{1}$$

where $\langle n_e \rangle$ is the line averaged electron density and Φ the particle source. The time derivative of the averaged density is zero for the interval $t = 26 - 30$ ms. For equal densities the relationship between the confinement time and the source simplifies to $\tau_p \propto \Phi$. The source, in turn, is proportional to the ionization rate and neutral particle density determined by recycling and fueling. In the temperature range typical for the tokamak plasma edge, the ionization rate is proportional to the H_β or D_β radiation rate. Therefore the particle source could be characterized by the H_β and D_β radiation source which is proportional to the neutral particle density.

The H_β and D_β line intensities for $t = 26 - 30$ ms indicate $\tau_{p,D} \approx 1.4\tau_{p,H}$. The volume integrated line intensities were measured in the toroidal section with the fueling pump and in the toroidally opposite section to control for the effect of extra neutral density caused by fueling. In both cross-sections the line radiation is more intense in hydrogen than in deuterium, signaling a higher particle source for the lighter isotope and thus larger particle flux through the separatrix for the lighter isotope.

In contrast to particle transport, there is no favourable isotope effect in energy confinement for these parameters at the FT-2 tokamak. From the power balance we can write the energy confinement time τ_E as

$$\tau_E = \frac{W}{P_{in} - dW/dt}, \tag{2}$$

with W being the energy content of the plasma and P_{in} the input power. For the steady state phase of these Ohmic discharges, the derivative of the energy content vanishes while P_{in} is given by the Ohmic heating power as $P_{\rm oh} = U_{\rm L} I_p$ from the loop voltage $U_{\rm L}$ and total plasma current I_P. Since the energy content and the heating power are approximately the same for the hydrogen and deuterium plasmas being compared, the energy confinement time is also equal ($\tau_E \approx 1$ ms) and there is no isotope effect.

4 Simulation results on isotope effect

The electron flux Γ_e is larger for hydrogen compared to deuterium across the plasma volume in the ELMFIRE simulations. The ratio of the mean fluxes decreases from 1.6 at $r/a = 0.3$ to 1.3 at the very edge (Fig. 2). Local GENE simulations at $r/a = 0.63$ also predict a particle flux ratio of 1.6. Given that the density profiles are very similar, the same ratio is seen in the diffusion coefficient, indicating improved particle confinement as observed in the experiments.

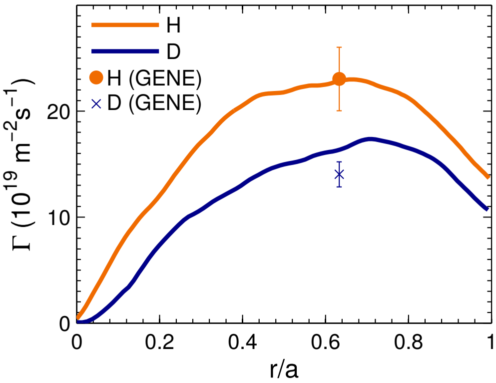


FIG. 2: Particle flux is larger for the deuterium case in both global ELMFIRE (solid lines) and local GENE (markers) simulations. The values are time averages in the saturated turbulent state of the simulations.

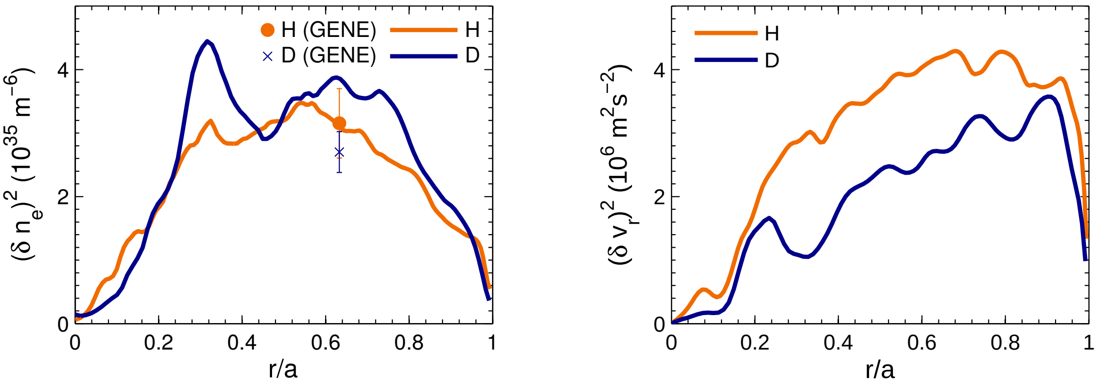
Neither simulation code shows an equal ratio in the density fluctuation level as in the particle fluxes. Instead, the values for deuterium are even larger at $r/a = 0.3$ and $r/a = 0.6 - 0.8$ in ELMFIRE calculations when averaged over the flux surface. In local GENE results, the density fluctuation level is 10% smaller in deuterium. We estimate the turbulent contribution to the fluxes in ELMFIRE calculations by utilizing the potential, density, and temperature values from the 3D spatial grid. This allows us to assess the significance of fluctuation amplitudes and cross-phases. Assuming that the radial $E \times B$ drift v_r is responsible for the turbulent transport, we calculate the turbulent particle flux Γ_T as

$$\Gamma_T(r) = \langle \delta n \delta v_r \rangle \tag{3}$$

The fluctuations are calculated on each grid point relative to the flux surface averaged values after sampling the density and velocity from markers to the grid. Calculating the Fourier transform of the δv_r and δn as V and N, respectively, the cross-phase at wavenumber k is then obtained as

$$\alpha_k = \arg\langle[V^*(k)N(k)\rangle], \tag{4}$$

where * denotes complex conjugate and $\langle\cdot\rangle$ averaging over samples, i.e. different time instances and toroidal positions.



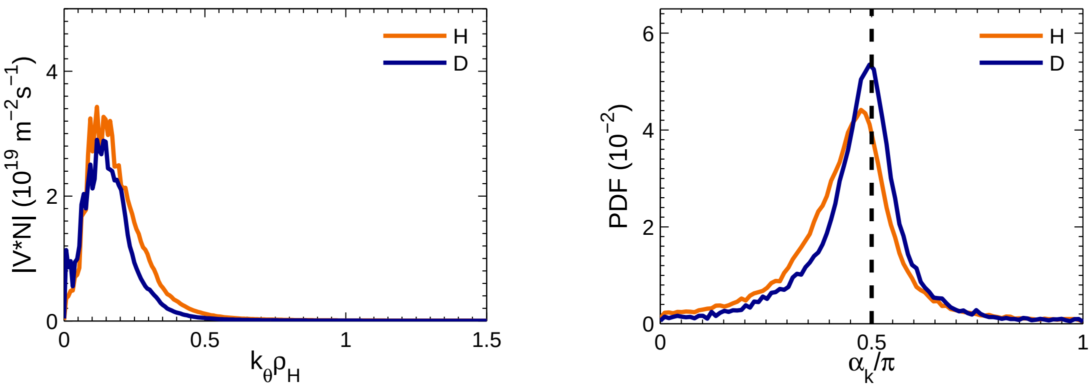
(a) Density fluctuations

(b) Radial velocity fluctuations

FIG. 3: a) Density fluctuation level is larger for deuterium around $r/a = 0.3$ *and in the interval* $r/a = 0.6 - 0.8$ *in the ELMFIRE simulations due to zonal flow activity. b) Radial velocity fluctuation level is systematically larger for hydrogen in ELMFIRE simulations.*

Most importantly, the turbulent particle flux calculated according to Eq. (3) reproduces the isotope effect seen in the flux sampled directly from the particle markers in ELMFIRE. For hydrogen, the turbulent flux is The difference in the fluxes between the discharges can thus be attributed to turbulence and explained in the context of the fluctuation levels. Even though the density and potential fluctuations are larger for the deuterium case in some regions for ELMFIRE results, the radial velocity oscillations δv_r are smaller across the plasma volume (Fig. 3).

The isotope effect is visible in the fluctuation spectra of ELMFIRE simulations. Large scale density fluctuations are more intensive in deuterium, as underlined by a distinct peak around poloidal mode number $m = 1$. The surplus fluctuations in the deuterium case in the region $r/a = 0.6 - 0.8$ are caused by the $m = 1$ sideband of the GAM. A hefty stationary zonal flow exists around $r/a = 0.3$ which leads to the suppression of the



(a) Cross-spectra in k_θ (b) Cross-phase between δn and δv_r

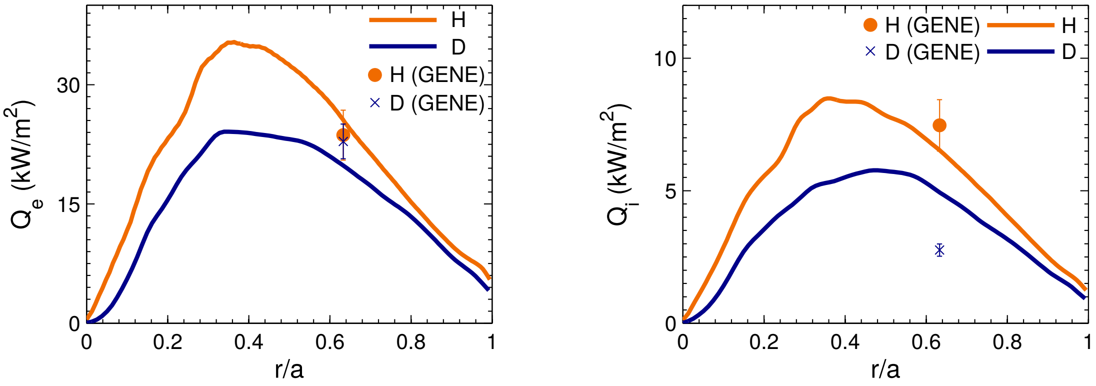
FIG. 4: a) Cross-spectra of turbulent density and velocity fluctuations in the wavenumber space show similar amplitudes and a slight shift between the spectral peaks for ELMFIRE simulations. b) The corresponding cross-phase distribution peaks closer to $\pi/2$ *for the deuterium. Here the distribution is shown for* $k_\theta \rho_i = 0.1 - 0.3$.

radial velocity fluctuations there. At the outer midplane, the density fluctuation levels are practically equal and more consistent with the GENE results.

The cross-spectra between density fluctuations and radial velocity fluctuations for ELMFIRE simulations peak at small spatial scales (Fig. 4(a)). The spectra have comparable maximum values in the wavenumber space, but the hydrogen spectra has a wider distribution. The hydrogen case has a greater contribution from large-wavenumber potential fluctuations. This translate into more substantial turbulent velocity fluctuations, even though the potential fluctuation level is comparable.

The average electron response is more adiabatic in the deuterium case of ELMFIRE simulations. The mean cross-phase α_k between the fluctuations is closer to $\pi/2$ for deuterium, although the cross-phase distributions are very similar (Fig 4). The mean cross-phase is only 7% larger for deuterium, but due to nonlinear $\Gamma \propto \cos(\alpha_k)$ dependency, this would already translate to a 50% reduction in fluxes.

ELMFIRE simulations predict an isotope effect in the energy fluxes on both channels (Fig. 5). The effect is more pronounced in the core: flux ratio $Q_{e,H}/Q_{e,D}$ is 1.4 at $r/a = 0.4$ and 1.2 at $r/a = 0.9$. The diffusive electron energy flux shows no isotope effect at the edge, indicating that the reduction in the particle flux also translates into a reduction in energy flux in the deuterium case. The greater diffusive flux is supported by larger electron temperature fluctuations and radial $E \times B$ drift from $r/a = 0.75$ inwards in the hydrogen scenario. For example at $r/a = 0.63$ the fluctuation level is 7% lower for the lighter isotope. The fluxes are comparable in the initial burst of transport in both cases, but the deuterium values are reduced more drastically as the nonlinear effects kick in.



(a) Electron energy flux

(b) Ion energy flux

FIG. 5: Energy fluxes for a) electron and b) ion channel show disagreement between ELMFIRE and GENE, but the sum of ion and electron energy fluxes is equal in local and global simulations.

5 Summary and discussion

In this publication, we report the first experimental observation of the isotope effect in the FT-2 tokamak. When keeping the other parameters similar but switching the main fuel isotope from hydrogen to deuterium, the particle confinement time increases approximately by a factor of 1.4, similarly to recent experiments at the ISTTOK tokamak [**?**]. No improvement in the energy confinement time is observed. ASTRA analysis also shows negligible differences in the total energy transport of the discharges.

Gyrokinetic simulations are able to reproduce the isotope effect in particle transport despite only a small difference in the density fluctuation levels. The observations are in contradiction with the gyro-Bohm scaling. The discharges are simulated with the gyrokinetic full-f code ELMFIRE, including kinetic electrons and a global full-torus geometry. In the nonlinear calculations, the particle flux is higher for the hydrogen parameters across the plasma volume. Both the strength of the isotope effect and its extent agree with measurements of Ohmic ASDEX discharges at low densities [3]. Local gyrokinetic calculations are conducted with the δf code GENE at $r/a = 0.63$. The local simulations also reproduce the isotope effect in the particle flux.

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