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Global Full-f Gyrokinetic Simulations of Isotope Scaling in Ion Temperature Gradient Driven Turbulence

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The impact of the hydrogen isotope mass on the energy confinement, known as the isotope effect, has been universally observed in magnetized plasmas. Based on the experimental database of hydrogen (H) and deuterium (D) plasmas from multiple tokamak devices, the energy confinement time scales as $\tau_E \propto M^{0.2}$ in L-mode plasmas, where M is the average ion mass [1]. On the other hand, the correlation time and length of turbulent fluctuations are characterized by $l_c \sim \rho_{ts}$ and $t_c \sim a/c_s$, where ρ_{ts} and c_s are the ion gyroradius and ion sound speed of species s, respectively, and a is the minor radius [2]. A local diffusion theory with l_c and t_c gives the so-called gyro-Bohm diffusivity $\chi_{GB} = l_c^2/t_c = \rho_{ts}^2 c_s/a$, leading to the gyro-Bohm scaling $\tau_E \propto M^{-0.5}$ opposite to the experiment. Although the isotope effect significantly affects the energy confinement in ITER, the gap between the theoretical predictions and experiments is not fully resolved, and the isotope effect is an outstanding problem in fusion science.

Energy confinement is determined by turbulent transport induced by micro-instabilities such as the ion temperature gradient driven (ITG) mode and the trapped electron mode (TEM). The isotope effect on TEM turbulence was explained by the collisional stabilization of TEMs, causing nonlinear changes in zonal flows, and by the non-adiabatic parallel electron dynamics. However, the isotope effect on ITG turbulence remains an open problem, despite its observation in many ITG dominant experiments. To understand the isotope effect on ITG turbulence, we investigate how the isotope effect depends on the normalized gyroradius $\rho^* = \rho_{ts}/a$ and on the heating sources.

Most theoretical studies of the isotope effect were based on the local δf flux-tube gyrokinetic model, which describes turbulent transport under fixed temperature gradients at the local limit $\rho^* \rightarrow 0$. In such a local model, the different ρ^* in H and D plasmas cannot be distinguished, and the plasma size scaling becomes inherently the gyro-Bohm scaling $\tau_E \propto M^{-0.5}$. However, ρ^* scan experiments showed the Bohm scaling $\tau_E \propto M^0$ or worse [3]. The Bohm like scaling has also been confirmed in global gyrokinetic simulations [4]. Therefore, the ρ^* scaling might contribute a significant part of the isotope effect.

Regarding the dependency of the isotope effect on the heating sources, ion heated L-mode experiments with neutral beam injection (NBI) on DIII-D showed almost no isotope effect [5], but a clear isotope effect was observed in electron heated L-mode experiments with electron cyclotron resonance heating on ASDEX Upgrade [6]. These experiments were dominated by ITG turbulence, and when NBI was added, the isotope effect depended on the ion to electron heating ratio. To understand the impact of different heating sources and the resulting coupling between the ion and electron heat transport channels, more comprehensive global full-f gyrokinetic models are needed.

In this work [7], isotope scan numerical experiments with ion and electron heating conditions were conducted using the Gyrokinetic Toroidal 5D full-f Eulerian code GT5D [8]. The energy confinement time in the ion heated numerical experiments was almost independent of isotope mass, and close to Bohm scaling $\tau_E \propto M^0$. The normalized collisionless ion gyrokinetic equations for H and D plasmas become identical at the same ρ^*, and collisions weakly affect ITG turbulence. Therefore, the energy confinement is determined mainly by the ρ^* scaling, which becomes Bohm like because of bursty non-local transport [4]. On the other hand, the electron heated numerical experiments showed a clear isotope effect, $\tau_E \propto M^{0.15}$. In this case, in addition to the ρ^* scaling, the isotope mass dependency of the collisional energy transfer from electrons to ions contributed to the total isotope mass scaling by enhancing the ion heat transport channel. Systematic electron heating power scans for the H and D plasmas showed similar ion and electron temperature profiles at an H to D heating power ratio of ~1.4. These results qualitatively agree with the isotope mass scalings in L-mode experiments with various ion and electron heating conditions [5].

Although the isotope mass dependencies in both scaling laws were improved from gyro-Bohm scaling, they are governed by different mechanisms, ρ^* scaling and collisional energy transfer. In future burning plasmas in larger devices, electron heating is expected to dominate, and the latter mechanism may lead to less energy transfer from electrons to ions, and thus, better total energy confinement. On the other hand, if Bohm scaling is sustained in large devices as shown in fixed-flux gyrokinetic simulations [4], the former mechanism may improve the energy confinement.

References

[1] ITER Physics Basis,. Nucl. Fusion 39, 2175 (1999).
[2] G. McKee et al., Nucl. Fusion 41, 1235 (2001).
[3] C. C. Petty et al., Phys. Plasmas 2, 2342 (1995).
[4] Y. Idomura et al., Phys. Plasmas 21, 020706 (2014).
[5] D. Schissel et al., Nucl. Fusion 29, 185 (1989).
[6] P. Schneider et al., Nucl. Fusion 57, 066003 (2017).
[7] Y. Idomura, Phys. Plasmas 26, 120703 (2019).
[8] Y. Idomura, J. Comput. Phys. 313, 511 (2016).