Isotope and Plasma Size Scaling in Ion Temperature Gradient Driven Turbulence

Yasuhiro Idomura

Japan Atomic Energy Agency, Wakashiba 178-4, Kashiwa, Chiba 277-0871, Japan

Introduction

The impact of the hydrogen isotope mass on the energy confinement 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 $\tau_L \propto M^{0.2} P_{in}^{-0.73}$ in L-mode plasmas, where M is the average ion mass and P_{in} is heating power [1]. On the other hand, the conventional local diffusion theory gives the gyro-Bohm diffusivity, leading to the isotope mass scaling $\tau_{GB} \propto M\rho^{*-3} \sim M^{-0.5}$ opposite to the experiment. The gap between theory and experiment has been addressed in former works. The isotope effect on trapped electron mode (TEM) turbulence was explained by the collisional stabilization of TEMs [2], causing nonlinear changes in zonal flows [3], and by the non-adiabatic parallel electron dynamics [4]. However, the isotope effect on ion temperature gradient driven (ITG) turbulence has not been reproduced except for very limited cases, where ITG turbulence is stabilized by electromagnetic effects and the $E \times B$ flow shear stabilization has a large impact [5]. Therefore, 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 ρ^* and on the heating sources. Most theoretical studies of the isotope effect are based on the local gyrokinetic model, which inherently gives the gyro-Bohm scaling, provided that a non-local effect such as $E \times B$ flow shear is not taken into account. However, ρ^* scan experiments on L-mode plasmas showed the Bohm scaling $\tau_B \propto M\rho^{*-2} \sim M^0$. The Bohm like scaling has also been confirmed in global gyrokinetic models [6, 7]. Therefore, the ρ^* scaling might contribute a significant part of the isotope effect. Regarding the heating sources, ion heated L-mode experiments with neutral beam injection on DIII-D showed almost no isotope effect [8], but a clear isotope effect was observed in electron heated L-mode experiments with electron cyclotron resonance heating on ASDEX Upgrade (AUG) [9]. These experiments were dominated by ITG turbulence, and the isotope effect depended on the ion to electron heating ratio. In this work [10], we address the isotope effect in L-mode like plasmas from a series of global full-f gyrokinetic simulations with different ion species, plasma sizes, heating sources, and heating powers.

Simulation model

The electrostatic ITG-TEM turbulence is simulated by the Gyrokinetic Toroidal 5D full-f Eulerian code GT5D [11], in which a global full-f model with gyrokinetic ions and hybrid kinetic electrons is computed. Multi-species collision is modeled by the linear Fokker-Planck collision operator and the zeroth-order equipartition operator, which gives the collisional energy transfer from electrons to ions $P_{e\to s} \propto (m_e/m_s)(T_e - T_s)$. Auxiliary heating is imposed by on-axis heating ($r/a < 0.4$) at a fixed heating power $P_{in,s}$ with no particle and momentum input. An L-mode like no slip boundary condition with fixed edge density and temperature is imposed by a Krook operator at the plasma surface ($r/a > 1$), where the gyro-center distribution is relaxed to the boundary condition at a rate of $\sim 0.1 v_{tD}/a$. Numerical experiments are conducted over an energy confinement time scale to satisfy a power balance condition, where quasi-steady plasma profiles and resulting energy confinement times are self-consistently determined. H and D plasmas with $a/\rho_{tH} = 210$ and $a/\rho_{tD} = 150$ are respectively computed in $1/6$ wedge torus configurations on 5D grids, $(N_R, N_\zeta, N_Z, N_{v\parallel}, N_{v\perp}) = (240, 48, 240, 96, 20)$ and $(160, 32, 160, 96, 20)$. Here, (R, ζ, Z) is the cylindrical coordinates, and $(v_\parallel, v_\perp)$ are the velocities parallel and perpendicular to the magnetic field, r is the radial coordinate, a is the minor radius, and m_s, T_s, v_{ts}, and ρ_{ts} are the mass, the temperature, the thermal velocity, and the gyroradius of species s.

Ion heated numerical experiments

Ion heated numerical experiments are conducted for the Cyclone case using adiabatic electrons. To determine the scalings with respect to ρ^* and M, we compare the results of H and D plasmas with the same a and similar ρ^*, $(\hat{M}, \hat{a}) = (1,1), (2,1)$, and $(2, 1.5)$, where $\hat{M} = m_s/m_H$, $\hat{a} = a/a_0$, $a_0 = 150\rho_{tD}$, and the magnetic field and q profile are fixed. Figure 1(a) plots the ion energy confinement time τ_i against the ion energy flux Q_i. The heating powers for $(\hat{M}, \hat{a}) = (1,1), (2,1)$ and $(\hat{M}, \hat{a}) = (2, 1.5)$ are respectively varied as $P_{in,i} = 2, 4, 6, 8$MW and $P_{in,i} = 4, 6, 8, 11$MW, and the power balance condition $Q_i \sim P_{in,i}$ is established in all cases. The energy confinement is degraded by increasing the heating power, and the exponents of the heating power scaling laws are similar for all isotope masses and plasma sizes. From the results of $(\hat{M}, \hat{a}) = (1,1)$ and $(2,1)$, the confinement scaling is estimated as $\tau_{i,ion} \propto Q_i^{-0.56} M^{-0.06}$, which is close to Bohm scaling. When the heat flux is normalized in gyro-Bohm units ($\Delta x = \rho_{ts}$ and $\Delta t = a/v_{ts}$), the D and H plasmas at similar ρ^*, $(\hat{M}, \hat{a}) = (1,1)$ and $(2,1)$, show similar transport properties. In gyro-Bohm units, the normalized collisionless gyrokinetic equations for the D and H plasmas are identical at the same ρ^*. In addition, in the collisionless parameter regime, the collisionality dependency of the ITG turbulence is very weak, except for marginally stable plasmas. Therefore, in the ion heating condition, the ITG turbulence is independent of isotope mass

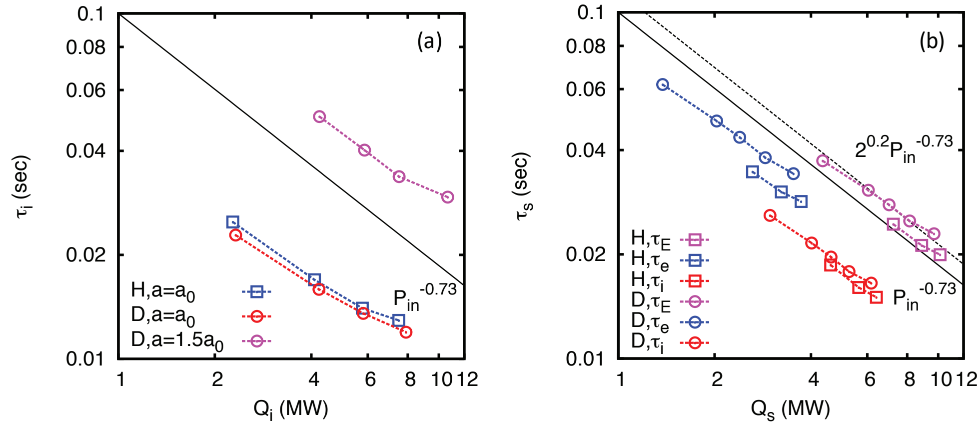

Figure 1: *Power scans of (a) ion and (b) electron heated numerical experiments. The energy confinement time* τ_s *is plotted against the corresponding energy flux* Q_s*. The solid and dotted lines show the confinement scaling in L-mode plasmas* $\tau_L \propto M^{0.2}P_{in}^{-0.73}$ *[1].*

and determined mainly by ρ^*. In the former ρ^* scaling study [7], Bohm scaling was found to be produced by bursty non-local transport caused by avalanches. The slightly negative isotope effect in $\tau_{i,ion}$ is attributed to gyro-Bohm dependency of the neoclassical transport. The Bohm like scaling with almost no isotope mass dependency is consistent with the ion heated L-mode experiments on DIII-D [8].

Electron heated numerical experiments

Electron heated numerical experiments are performed using the hybrid kinetic electron model, where the initial condition is changed based on the density and temperature profiles and the temperature ratio in the AUG experiment [9]. In the hybrid kinetic electron model, the mass ratio is reduced to $m_D/m_e = 100$, while the electron collision frequency is given by the real electron mass, because the electron-ion collisions significantly affect the collisional stabilization of TEMs and the collisional energy exchange between the electrons and ions. Figure 1(b) respectively plots the electron, ion, and total energy confinement times, τ_e, τ_i, and τ_E, as functions of their corresponding energy fluxes, Q_e, Q_i, and $Q_{tot} = Q_e + Q_i$. The heating powers of the H and D plasmas are varied as $P_{in,e} = 6, 8, 10$MW and $P_{in,e} = 4, 6, 7, 8, 10$MW respectively, and the power balance condition $Q_{tot} \sim P_{in,e}$ is approximately satisfied. Under the ITG turbulence dominated conditions, the ratio of energy fluxes varies for $Q_i/Q_e = 1.7 \sim 2.2$, and τ_e is larger than τ_i. The exponents of the power degradation of τ_e and τ_i are similar in the H and D plasmas. The power degradation of τ_e is indirectly determined by the ion heat transport channel (via the collisional energy transfer). The confinement scaling laws in the electron heated numerical experiments are estimated as $\tau_{e,ele} \propto Q_e^{-0.64}M^{0.21}$, $\tau_{i,ele} \propto Q_i^{-0.63}M^{0.09}$, and $\tau_{E,ele} \propto Q_{tot}^{-0.62}M^{0.15}$. These results clearly indicate the isotope effect, especially on τ_e. Owing to the isotope effect, the turbulent ion and electron heat diffusivities in the reference cases are worse than Bohm scaling.

Summary

The isotope effect on ITG turbulence was addressed using the global full-f gyrokinetic model. The energy confinement time in the ion heated numerical experiments was almost independent of isotope mass, and scaled as $\tau_{i,ion} \propto Q_i^{-0.56} M^{-0.06}$, close to Bohm scaling. The normalized collisionless gyrokinetic equations for the H and D plasmas are equivalent at the same ρ^*, and the ion energy confinement in the ITG turbulence was determined mainly by the ρ^* scaling, which becomes Bohm like because of bursty non-local transport [7]. On the other hand, the electron heated numerical experiments showed a clear isotope effect, $\tau_{E,ele} \propto Q_{tot}^{-0.62} M^{0.15}$, where, 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. These results qualitatively agree with the isotope mass scalings in L-mode experiments. 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 which are characterized by smaller ρ^* and collisionality, electron heating is dominant, and the latter mechanism may lead to less energy transfer from electrons to ions, and thus, better total energy confinement. If Bohm scaling is sustained up to smaller ρ^* as shown in fixed-flux gyrokinetic simulations [7], the former mechanism may also improve the energy confinement. However, if the ρ^* scaling shows transition to gyro-Bohm scaling as predicted in fixed-gradient gyrokinetic simulations [6], this effect may be lost, leading to worse energy confinement.

Acknowledgement

This work was supported by the MEXT Japan (Program for Promoting Researches on the Supercomputer Fugaku "Exploration of Burning Plasma Confinement Physics”). This research used K computer (hp190190), Fugaku (hp210178), JFRS1, and JAEA-ICEX.

References

[1] ITER Physics Basis. *Nuclear Fusion*, Vol. 39, No. 12, pp. 2175–2249, dec 1999.
[2] I. Pusztai, et al. *Phys. Plasmas*, Vol. 18, No. 12, p. 122501, 2011.
[3] M Nakata, et al. *Phys. Rev. Lett.*, Vol. 118, p. 165002, Apr 2017.
[4] E. A. Belli, et al. *Phys. Plasmas*, Vol. 26, No. 8, p. 082305, 2019.
[5] J. Garcia, et al. *Nuclear Fusion*, Vol. 57, No. 1, p. 014007, dec 2016.
[6] Z. Lin, et al. *Phys. Rev. Lett.*, Vol. 88, p. 195004, Apr 2002.
[7] Y. Idomura and M. Nakata. *Physics of Plasmas*, Vol. 21, No. 2, p. 020706, 2014.
[8] D.P. Schissel, et al. *Nuclear Fusion*, Vol. 29, No. 2, pp. 185–197, feb 1989.
[9] P. A. Schneider, et al. *Nuclear Fusion*, Vol. 57, No. 6, p. 066003, 2017.
[10] Y. Idomura. *Physics of Plasmas*, Vol. 26, No. 12, p. 120703, 2019.
[11] Y. Idomura. *J. Comput. Phys.*, Vol. 313, pp. 511 – 531, 2016.