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Isotope effects in ion temperature gradient driven turbulence
イオン温度勾配駆動乱流における同位体効果送

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Isotope effects on the electrostatic ion temperature gradient driven (ITG) turbulence with adiabatic electrons are investigated by numerical experiments using the global full-f gyrokinetic Eulerian code GT5D. By comparing isotope and plasma size scans, transport scalings with respect to the isotope mass M and the normalized gyro-radius ρ^* are estimated from the ion energy confinement time τ_{ion} of L-mode like plasmas. It is found that hydrogen and deuterium plasmas at the same ρ^* and the ion temperature show the similar transport properties, when the ion heat diffusivity and the heat flux are normalized in gyroBohm units. The transport scaling obtained from GT5D is close to the Bohm scaling, which gives the isotope scaling of $\tau_{ion} \propto M$, which is too weak to explain strong confinement degradation in hydrogen plasmas.

1. Introduction

The influence of isotope effects on turbulent transport is one of critical issue in predicting the performance of ITER. So far, this issue has been studied in many tokamak experiments, and the following global energy confinement scalings are obtained for L- and (ELMy) H-mode plasmas, respectively, [1]

$$B_T \tau_L \propto M^{1.67} \rho^{*-1.85}, \quad (1)$$

$$B_T \tau_H \propto M^{1.96} \rho^{*-2.7}, \quad (2)$$

where B_T is the toroidal field, M is the isotope mass, and ρ^* is the normalized gyro-radius. According to these transport scalings, deuterium plasmas are expected to have better confinement than hydrogen plasmas at a given temperature and B_T. In fact, recent dedicated isotope experiments on JT-60U showed that the ion heat flux necessary for hydrogen to sustain the same ion temperature profile was two times larger than that required for deuterium [2]. This dependency is opposite to conventional transport theories such as the gyro-Bohm scaling, which predicts better confinement for hydrogen plasmas. Therefore, a physical mechanism behind the isotope effect is still an outstanding issue. In addition, the isotope math M also affects $\rho^* \propto M^{0.5}$, and it is very complicated to distinguish the isotope scaling and the plasma size scaling. The latter effect was studied in ion temperature gradient driven (ITG) turbulence, and Bohm like scaling in L-mode plasmas was explained by bursty non-local transport leading to stiff temperature profiles [3,4]. In order to see these points clearly, we perform numerical experiments of ITG turbulence using the global full-*f* gyrokinetic Eulerian code GT5D [5], where M and ρ^* are changed independently.

2. Calculation model

GT5D is based on the modern gyrokinetic theory, in which the gyrokinetic equation is simply given as

$$\frac{\partial f}{\partial t} + \{f, H\} = C(f) + S, \quad (3)$$

where f is a full-f ion distribution function, { , } and H are the Poisson bracket operator and the Hamiltonian in the gyro-center coordinates, C is a linear Fokker-Planck collision operator, and S is a source term, which involves fixed on-axis heating, and a sink term implemented by a Krook type operator. The sink term imposes a L-mode like boundary condition, i.e., no-slip boundary condition and fixed edge temperature on average. Turbulent fluctuations are determined by solving the gyrokinetic Poisson equation with linearized ion polarization density.

In this work, we consider electrostatic ITG turbulence with gyrokinetic ions and adiabatic electrons in a circular concentric tokamak configuration with R/a=2.79 and $q(r)$ = 0.85 + 2.18 $(r/a)^2$, which has Cyclone like parameters [6] at mid minor radius. Here, a is the minor radius, and $q(r)$ is the safety factor profile. A reference case is a deuterium plasma with ρ^{*-1}=225, which is compared against a hydrogen case with ρ^{*-1}=212 and a ρ^* scan (B_T scan) case with deuterium, ρ^{*-1}=150. In the numerical experiment, we estimate quasi-steady temperature profiles and the corresponding energy confinement time.

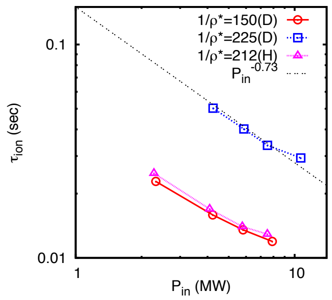

Fig.1 Power scan of ITG turbulence simulations with (M,ρ^{*-1}) = (2,150), (2,225), (1,212).

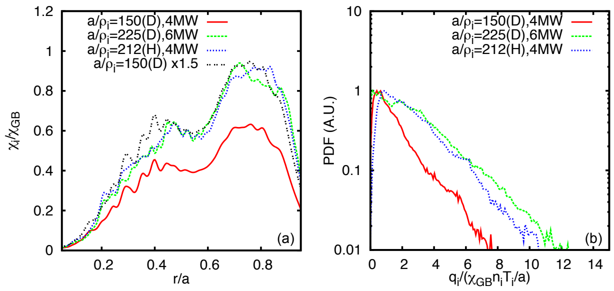

Fig.2 (a) radial profiles of the ion heat diffusivity and (b) PDFs of the ion heat flux at r/a~0.5. Both data are normalized in gyroBohm units.

3. Simulation results

In order to make quantitative comparisons at the similar temperature, systematic power scans were performed for these three cases in Fig.1. Although ion temperature profiles in the plasma core are stiff and the temperature gradient is constrained near a nonlinear critical gradient, those in the outer region are less stiff and the central ion temperature increases with the heating power P_{in} [3]. Accordingly, all three cases show the so-called power degradation of global energy confinement, and the heating power scaling is close to that for L-mode plasmas, $\tau_E \propto P_{in}^{-0.73}$. In the power scan, the reference case at P_{in}=6MW, the hydrogen case at P_{in}=4MW, and the ρ^* scan case at P_{in}=4MW give the similar ion temperature profiles, and these plasmas are compared in detail below.

In all three cases, turbulent correlation length and time are respectively given as L_c~$5\rho_i$ and τ_c~$2a/c_s$, which suggest gyroBohm like scaling. However, in Fig.2, the transport levels clearly show a Bohm like feature. The ρ^* scan of deuterium plasmas between (M,ρ^{*-1}) = (2,150) and (2,225) exhibits Bohm like scaling due to bursty non-local transport, which is driven at transient super critical states, produced by a local power balance condition [4]. By increasing plasma size and heating power, the frequency and amplitude of intermittent bursty events are increased and tails of probability distribution functions (PDFs) of the ion heat flux are extended in Fig.2 (b). Interestingly, the hydrogen case with (M,ρ^{*-1}) = (1,212) shows the similar transport properties as the reference case with (M,ρ^{*-1}) = (2,225), and gives much higher transport levels than the deuterium plasma with (M,ρ^{*-1}) = (2,150), when the ion heat diffusivity and the heat flux are normalized in gyroBohm units. Therefore, the present isotope scan is expected to have the similar parameter dependency as the Bohm scaling,

$$B_T\tau_B \propto M\rho^{*-2}, \tag{4}$$

which predicts similar global energy confinement between hydrogen and deuterium plasmas. It should be noted that a better confinement in gyroBohm units does not necessarily mean a better global energy confinement time. In fact, in Fig.1, the hydrogen case with (M,ρ^{*-1}) = (1,212) and the ρ^* scan case with (M,ρ^{*-1}) = (2,150) gives the similar ion energy confinement time over broad heating power regime. From ion confinement times in three selected plasmas, exponents of M and ρ^* are estimated as

$$B_T\tau_{ITG} \propto M^{1.05}\rho^{*-2.29}, \tag{5}$$

which is very close to the Bohm scaling.

4. Summary

Isotope effects on the electrostatic ITG turbulence with adiabatic electrons are investigated by using GT5D. The numerical results give a Bohm like scaling. Although the ρ^* dependence of this scaling gives reasonably good agreement with the L-mode scaling, its isotope dependence $\propto M$ is too weak to explain the experiment $\propto M^{1.67}$, and drastic confinement degradation between deuterium and hydrogen experiments is still an open question. This issue will be addressed in future works.

Acknowledgments

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