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Physics of Isotope Effect on Turbulent Transport in LHD Plasmas
LHDプラズマの乱流輸送に生ずる同位体効果の物理

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A possible isotope effect on turbulent transport in the Large Helical Device (LHD) plasma is discussed. Zonal flow response enhancement by an equilibrium-scale radial electric field is predicted by the gyrokinetic theory and simulation. Coupling of the neoclassical transport, the zonal flow enhancement, and the turbulence regulation brings the ion-mass dependence of the turbulent transport in the LHD plasma. The isotope effect on turbulent transport is expected to appear as a more favorable ion mass dependence of the transport than the conventional gyro-Bohm scaling.

1. Introduction

Isotope effects on turbulent transport in magnetically confined fusion plasmas are important but still remain to be resolved for reliable prediction of plasma performance in fusion reactors [1]. The conventional gyro-Bohm scaling,

$$\chi \propto \rho^2 v_t / L \propto \sqrt{m} T_i^{3/2} \Big/ LB^2 \,, \qquad (1)$$

suggests that the transport coefficient increases in proportion to the square root of the ion atomic mass number for the same ion temperature T_i (where ρ, v_t, L, m, and B denote the ion thermal gyroradius, the thermal speed, the equilibrium scale-length, the ion mass, and the magnetic field strength, respectively). Equation (1) implies that the confinement may degrade in the deuterium discharge with respect to the hydrogen plasma. However, the various tokamak experiments report a more favorable ion mass scaling of the energy confinement time than the gyro-Bohm one and the lower power threshold of the H-mode transition.

The isotope effect on the plasma transport is one of the main issues in non-axisymmetric systems, such as the Large Helical Device (LHD) [2]. The LHD deuterium experiment project aims “to clarify the mass dependence (isotope effect) in the plasma confinement, leading to establishment of a model for the burning experiment using deuterium and tritium” [3].

The theoretical understanding on the isotope effects is still not mature, while the gyrokinetic simulation of the plasma turbulent transport made a tremendous progress in the last two decades. The conventional local transport model leads to the gyro-Bohm scaling by construction, even with a numerical coefficient for Eq. (1) involving dependences on various plasma parameters.

In the transport analysis of tokamak plasmas, thus, a sheared poloidal ***E*** x ***B*** rotation is incorporated causing an additional ion mass dependence of the turbulent transport to the gyro-Bohm through difference of the Mach number.

In contrast, in non-axisymmetric systems, an equilibrium-scale radial electric field (E_r) is generated by the neoclassical transport, and improves the collisionless orbits of helical ripple trapped particles. Recent theory and simulations of zonal flows in helical systems have opened a new route to possibly suggest the isotope effects on the plasma turbulent transport, where the zonal flow response turns out to be enhanced by the equilibrium scale E_r. [4-6].

In this article, we briefly describe possible physics mechanisms of the isotope effect on the turbulent transport expected in the deuterium experiments in LHD.

2. Theory of Zonal Flow Enhancement in Helical Systems

Zonal flows with the constant electrostatic potential on flux surfaces in a torus are generated by the Reynolds stress of turbulence, and regulate the turbulent transport. Effective generation of the zonal flow is thought to be a key for lowering the anomalous transport. In helical systems, the zonal flow generation is enhanced by optimization of the confinement field structure with slower radial drift of helical-ripple trapped particles [7-8]. The theoretical prediction is verified by gyrokinetic simulations of the ion temperature gradient (ITG) turbulence [9].

The idea of the zonal flow enhancement is extended to helical configurations with the equilibrium radial electric field E_r which is generated by the neoclassical transport. Improvement of the collisionless particle orbits by E_r leads to enhancement of the zonal flow response kernel, where the residual zonal flow [10] amplitude increases as the poloidal Mach number (M_p) of the $\boldsymbol{E} \times \boldsymbol{B}$ rotation [4,5].

The neoclassical transport analysis for the hydrogen and deuterium plasmas in LHD shows that magnitude of the equilibrium-scale E_r is insensitive to the ion mass. It means that the poloidal flow with higher M_p is expected for larger ion mass, if the same ion temperature is achieved. Therefore, the M_p-dependence of the zonal flow enhancement is translated into the ion-mass dependence. This could be an origin of the isotope effects on the turbulent transport in LHD plasmas.

3. Simulation of Zonal Flow Enhancement in LHD

The zonal flow enhancement by E_r has recently been confirmed by means of the gyrokinetic simulations using GKV code [6]. The residual zonal flow amplitudes given by the GKV simulation for a model LHD configuration with the inward-shifted magnetic axis position are summarized in Fig. 1 as a function of M_p. The dashed line indicates the theoretical prediction of the residual zonal flow level in the long wavelength limit in the radial direction (k_r=0). A quantitatively good agreement is found between the theory and simulation. One finds that the residual zonal flow amplitude rapidly increases in the M_p-range relevant to the LHD

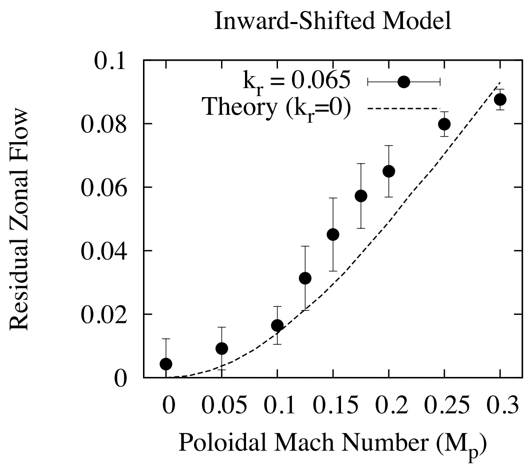

Fig.1. Poloidal Mach number dependence of the residual zonal flow obtained by gyrokinetic simulation for the LHD model configuration with the inward-shifted magnetic axis position [6].

experiments. For example, the residual level is amplified more than two times when M_p is changed from 0.1 to 0.15. Thus, the increase of the ion mass from the hydrogen to the deuterium results in the stronger response of zonal flows to a source given by the turbulence. The nonlinear gyrokinetic simulations of the ITG turbulence for the LHD model configuration with E_r also suggest effective zonal flow generation in case with finite M_p [6].

4. Summary

In this article, we have described a possible isotope effect on turbulent transport expected in the deuterium experiment in LHD. The zonal flow response enhancement by the equilibrium-scale radial electric field is confirmed by both the gyrokientic theory and simulation. Coupling of the neoclassical transport, the zonal flow enhancement, and the resultant turbulent regulation, thus, is expected to bring the ion-mass dependence of the turbulent transport in helical systems with more favorable isotope scaling than the gyro-Bohm one.

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References

[1] ITER Physics Expert Group: Nucl. Fusion **39** (1999) 2175.

[2] O. Motojima et al, Nucl. Fusion **43** (2003) 1674.

[3] Y. Takeiri, S-P4-1 in this conference.

[4] H. Sugama, and T.-H. Watanabe, Phys. Plasmas **16** (2009) 056101.

[5] H. Sugama, T.-H. Watanabe, and M. Nunami, Contrib. Plasma Phys. **50** (2010) 571.

[6] T.-H. Watanabe, H. Sugama, and M. Nunami, to appear in Nucl. Fusion (2011).

[7] H. Sugama, and T.-H. Watanabe, Phys. Rev. Lett. **94** (2005) 115001.

[8] H. Sugama, and T.-H. Watanabe, Phys. Plasmas **13** (2006) 012501.

[9] T.-H. Watanabe, H. Sugama, and S. Ferrando-Margalet, Phys. Rev. Lett. **100** (2008) 195002.

[10] M. N. Rosenbluth and F. L. Hinton, Phys. Rev. Lett. **80** (1998) 724.