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Theoretical Prediction of the Isotopic Effect of Turbulent Transport

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We briefly review a few theoretical attempts to explain isotopic dependence of tokamak anomalous transport in the past. Then, we introduce more recent effort in the context of ExB zonal flows driven by turbulence.

1. Introduction

Isotopic dependence is one of key unsolved issues in magnetic confinement research. Deuterium (D) plasmas have been observed to be better confined than hydrogen (H) plasmas over many years of tokamak research as reviewed in [1,2]. Addition of Tritium has made confinement even better in TFTR[3] and in JET[4]. Furthermore, success of ITER relies on expected enhancement of H-mode access and confinement as experiments proceed with working gas in the order of H, He, DD, and DT.

In this manuscript, we discuss possible nonlinear theoretical mechanisms behind isotopic dependence of tokamak confinement.

2. Partial Survey of Theories on Isotopic Dependence

There have been many theoretical attempts to explain the isotopic dependence of confinement in the past. It is not possible to give a thorough review here, and the author can only cover a few of them. Some proposed mechanisms are based on assumptions which can only be satisfied at the plasma edge. For dissipative drift wave turbulence, the isotopic dependence may exist through non-adiabatic electron dynamics which depend on $k_{\parallel}$ and magnetic shear[5]. This needs to be further confirmed with global simulations with results which are independent of simulation box size and shape. There has also been work on the isotopic dependence of the energy content of the H-mode pedestal region[6]. More recent work seems to report, however, the absence of this trend[7]. For the current-driven ballooning mode(CDBM)[8], the isotopic dependence comes from the Alfvén speed. That model uses electron dynamics which are hydrodynamic, rather than near-adiabatic (or Boltzmann response).

Gyro-Bohm scaling has an isotopic dependence which is opposite to experimental observations. From local calculations of ITG instabilities without an explicit consideration of nonlinearly self-generated zonal flows, one usually obtains a Gyro-Bohm scaling, for instance[9]. Furthermore, quasi-local nonlinear gyrokinetic simulations of tokamak core turbulence for parameters from actual experiments have reported trends close to Gyro-Bohm scaling[10].

3. Isotopic Dependence of Zonal Flows

Almost all previous theoretical attempts based on models which are free from other significant inconsistencies with experimental results have not succeeded in obtaining the isotopic dependence observed in experiments. One commonality of those attempts is that ExB zonal flows driven by turbulence has not been explicitly included. There’s a theoretical work related to zonal flows in stellarator geometry[11]. The effect considered in that work disappears in tokamak geometry which is axisymmetric. Isotopic dependence of stellarator plasma confinement was observed to be weaker than that of tokamak plasmas.

While the well-known Rosenbluth-Hinton residual zonal flows with radial scale greater than the magnetically trapped ion radial width ρ_{bi} have no isotopic dependence [12], a recent study[13] finds that shorter radial scale (shorter than ρ_{bi}) but larger than the magnetically trapped electron radial width ρ_{be} residual zonal flows exhibit isotopic dependence. These finer scale zonal flows in deuterium (D) plasmas can be stronger than those of hydrogen (H) plasmas, and possibly lead to lower turbulence and transport and better confinement in qualitative agreement with experimental results.

Based on analytic calculations utilizing neoclassical and classical polarization densities which appear in modern bounce-kinetic[14] and modern gyrokinetic theories[15,16], a useful connection formula covering a wide range of radial scales of ZFs from ρ_{bi} down to ρ_e scale has been obtained in [17]. The residual zonal flow level R_{ZF} from a calculation including both ion and electron dynamics can be written as,

$$R_{ZF} = \frac{\tau\chi_{cl,i}+\chi_{cl,e}}{\tau\chi_{cl,i}+\chi_{cl,e}+\tau\chi_{nc,i}+\chi_{nc,e}} \qquad (1)$$

where $\chi_{cl,i(e)} = 1 - \Gamma_0\left(q_r^2\rho_{i(e)}^2\right)$. The generalized connection formula for neoclassical shielding can be written as

$$\chi_{nc,i(e)} = \left\{ \frac{1}{1.63\epsilon^{3/2} q_r^2 \rho_{\theta i(e)}^2} + \left[1 + \frac{\sqrt{8\epsilon}}{\pi}\Gamma'_{tr} + \left(1 - \frac{\sqrt{8\epsilon}}{\pi}\right)\Gamma'_p\right]\frac{1}{1 + q_r^2\rho_{i(e)}^2} + \sqrt{\frac{\pi^3}{2}}\, q_r\rho_i \left[1 + \frac{\sqrt{8\epsilon}}{\pi}\Gamma_{tr} + \left(1 - \frac{\sqrt{8\epsilon}}{\pi}\right)\Gamma_p\right]\frac{q_r^2\rho_{i(e)}^2}{1 + q_r^2\rho_{i(e)}^2}\right\}^{-1} \quad (2)$$

with $\rho_{\theta i(e)} = \rho_{i(e)}\, B/B_\theta$, and other notations defined in [17].

In [17], the coefficient 1.63 was 1.83. This has been recently revised using the same bounce-kinetic approach[18], but without using the usual deeply trapped or strongly circulating approximations employed in [17]. This formula exhibits a desired isotopic dependence as explained in [13].

Since the zonal flows reduce turbulence and transport, one can characterize this effect by a zonal-flow-induced turbulence reduction factor R_{turb}[19,20] which appears as

$$\chi = R_{turb}\chi_0 \quad (3)$$

where χ_0 is a hypothetical value of the thermal diffusivity χ in the absence of zonal flows. While there's no first-principle-based analytic formula for R_{turb} with a wide validity regime, a useful theory-based fitting formula from a series of numerical simulations has appeared from a recent work[21].

4. Conclusion

There has been a recent experimental work[22] which shows a decrease in fluctuation structures at the edge which are long-range correlated in toroidal direction as working gas is changed from D to H.(we recall that zonal flows are toroidally symmetric). Accompanying increase in transport from D to H plasmas was higher for TEXTOR tokamak, than TJ-Ⅱ stellarator. Extending this kind of research to core fluctuation measurements which include the Heavy Ion Beam Probe measurements of zonal flows[23] could be highly rewarding. On theoretical front, dedicated nonlinear gyrokinetic simulations with a high resolution in velocity space (to properly treat the residual zonal flows) which include shorter wavelength fluctuations down to the electron banana width scales can be illuminating.

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References

[1] M.Bessenrodt-Weberpals et al: Nucl. Fusion **33** (1993) 1205.
[2] F. Wagner and U. Stroth: Plasma Phys. Control. Fusion **35** (1993) 1321.
[3] R. J. Hawryluk: Rev. Mod. Phys. **70** (1998) 537.
[4] J. Jacquinot and JET Team: Nucl. Fusion **38** (1998) 1263.
[5] B. D. Scott: Phys. Fluids B **4** (1992) 2468.
[6] J. G. Cordey et al: Nucl. Fusion **39** (1999) 301
[7] H. Urano et al: presented at the 24th IAEA fusion energy conference (2012).
H. Urano. et al: Nucl. Fusion **48** (2008) 045008
[8] K. Itoh el al: Plasma Phys. Control. Fusion. **36** (1994) 279
[9] J. Q. Dong, W. Horton and W. Dorland: Phys. Plasmas **1** (1994) 3635
[10] C. Estrada-Mila et al: Phys. Plasmas **12** (2005) 022305
[11] T.-H Watanabe et al: Nucl. Fusion **51** (2011) 123003
[12] M. N. Rosenbluth and F. L. Hinton: Phys. Rev. Lett. **80** (1998) 724
[13] T. S. Hahm, Lu Wang, W. X. Wang, E. S. Yoon and F.X. Duthoit: Nucl. Fusion **53** (2013) 072002
[14] B. H. Fong and T. S. Hahm: Phys. Plasmas **6** (1999) 188
[15] T. S. Hahm: Phys. Fluids 31 (1988) 2670
[16] T. S. Hahm: Phys. Plasmas 3 (1996) 4658
[17] L. Wang and T. S. Hahm: Phys. Plasmas 16 (2009) 062309
[18] F. X. Duthoit, A. J. Brizard and T. S. Hahm: Submitted to Phys. Plasmas (2014)
[19] P. H. Diamond et al: Plasma Phys. Control. Fusion 47 (2005) R35
[20] K. Itoh et al: Phys. Plasmas 13 (2006) 055502
[21] T. –H Watanabe et al: 24th IAEA fusion energy conference (2012)
[22] Y. Xu et al: Phys. Rev. Lett. **110** (2013) 265005
[23] A. Fujisawa et al: Phys. Rev. Lett. **93** (2004) 165002