A new synergy effect between neoclassical and turbulent particle transport in ion temperature gradient driven turbulence

Yasuhiro Idomura[1]

[1] Center for Computational Science and e-systems, Japan Atomic Energy Agency

e-mail : idomura.yasuhiro@jaea.go.jp

The theoretical understanding of impurity transport is of critical importance for predicting the performance of burning plasmas in ITER, which will consist of multiple ion species including various intrinsic and seeded impurities such as helium ash, beryllium in the plasma facing component, neon and argon injected for the divertor control, and tungsten from the divertor wall.

In experiment, impurity transport is often observed to be anomalous. Theoretically, impurity transport has been discussed based on the frameworks of neoclassical and turbulent transports. The former was established in the standard neoclassical theory [1], while the latter has been studied based on quasilinear transport models and local δf gyrokinetic simulations [2]. In particular, the transport of tungsten, which is characterized by a high Mach number and poloidally asymmetric density distributions, has been actively investigated, and these two frameworks were respectively extended to the neoclassical theory with poloidally asymmetric density distributions [3] and local δf gyrokinetic simulations of turbulent impurity transport including the Coriolis and centrifugal effects [2]. Here, these two frameworks have been developed independently by assuming a complete scale separation between turbulent and neoclassical transports based on the transport ordering, in which they are considered to be additive.

However, a concern on the validity of this traditional assumption was raised in recent studies based on the so-called full-f gyrokinetic model, in which both turbulent and neoclassical transports are self-consistently treated in a single first principles model. In the conventional scale separation approach, poloidally asymmetric density distributions are determined only by an equilibrium distribution modified by the centrifugal effects in rotating tokamaks. However, it was shown that turbulent fluctuations can also generate poloidally asymmetric E×B flows called convective cells and related poloidally asymmetric density distributions. In the presence of turbulence driven poloidally asymmetric density distributions, neoclassical and turbulent transports are not additive and a synergy effect between them appears [4].

Another important consequence of the conventional scale separation approach is that the ambipolar condition is exactly satisfied in the frameworks of neoclassical and turbulent transports independently. On the other hand, in the full-f gyrokinetic model, the ambipolar condition is derived for the total particle flux including both neoclassical and turbulent transports. This removes an important constraint which prohibits an interaction between neoclassical and turbulent transports, and may introduce another synergy effect. However, the above full-f gyrokinetic simulations were using adiabatic electrons, and the synergy effect through the ambipolar condition has not been investigated.

In this work [5], this new synergy effect between neoclassical and turbulent particle transports is investigated in ion temperature gradient driven (ITG) turbulence using the Gyrokinetic Toroidal 5D full-f Eulerian code GT5D [6] including kinetic electrons, bulk ions, and low to medium Z tracer impurities, where Z is the charge number. It is found that in addition to turbulent particle transport, enhanced neoclassical particle transport due to the new synergy effect through the ambipolar condition makes a significant contribution to particle transport of bulk and impurity ions. Bursty excitation of the ITG mode generates non-ambipolar turbulent particle fluxes of electrons and bulk ions, leading to a fast growth of the radial electric field following the ambipolar condition. The divergence of E×B flows in toroidal plasmas compresses up-down asymmetric density perturbations, which are subject to transport induced by the magnetic drift. The enhanced neoclassical particle transport depends on the ion mass because the magnitude of up-down asymmetric density perturbation is determined by a competition between the E×B compression effect and the return current given by the parallel streaming motion. It should be noted that electron makes a minor contribution to the neoclassical particle transport of ions in the standard neoclassical theory. However, kinetic electrons are essential for simulating the non-ambipolar turbulent particle flux, which is the origin of the enhanced neoclassical transport.

A unique feature of the synergy effect is that this mechanism selectively enhances only particle transport. This kind of selective particle transport mechanism has various implications. If one considers the radial electric field induced by other mechanisms such as MHD modes and magnetic perturbations, this mechanism may explain selective particle transport phenomena such as I-mode plasmas [7] and density pump-out. The new synergy effect sheds a new light on this interesting topic.

References

[1] S. Hirshman and D. Sigmar, Nucl. Fusion 21, 1079 (1981).
[2] C. Angioni et al., Nucl. Fusion 54, 083028 (2014).
[3] E. Belli et al., Plasma Phys. Control. Fusion 56, 124002 (2014).
[4] D. Esteve et al., Nucl. Fusion 58, 036013 (2018).
[5] Y. Idomura et al., Phys. Plasmas 28, 012501 (2021).
[6] Y. Idomura, J. Comput. Phys. 313, 511 (2016).
[7] D. Whyte et al., Nucl. Fusion 50, 105005 (2010).