Exploring phase space turbulence in magnetic fusion plasmas

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Abstract. Plasma turbulence accompanied with fluctuations of the distribution function and the electromagnetic fields develops on the phase space composed of the configuration space and the velocity space. Detailed structures of the distribution function in magnetic fusion plasmas are investigated by means of gyrokinetic simulations performed on massively parallel supercomputers. The gyrokinetic simulations of drift wave turbulence have demonstrated entropy transfer in the phase space, zonal flow enhancement by helical fields and the resultant transport reduction. The state-of-the-art high performance computing is utilized for a multi-scale turbulence simulation covering ion- and electron-scales and for a global-scale simulation of turbulent transport in a sub-ITER sized plasma.

1. Introduction

Plasma turbulent transport is one of the most important issues in the magnetic fusion research, and the most challenging target in numerical simulations of fusion plasmas. While fusion plasma confinement has reached the break-even condition or beyond, comprehension of particle and heat transport, of which levels are anomalously higher than estimates of collisional transport, is still demanded for a more reliable prediction of future experiments [1]. Direct numerical simulations of plasma turbulence are expected to provide physics-based understandings on the transport properties.

Magnetic fusion plasma with a high temperature of several keV is almost collisionless and beyond applicability of the conventional fluid approximation. In order to overcome the limitation, and to reveal the turbulent transport mechanisms in fusion plasmas, gyrokinetic simulations have been developed [2], where time-evolutions of distribution functions are solved on the phase space. The new approach extends a concept of turbulence onto the velocity space. Indeed, drift wave turbulence simulations manifest cascades of fluctuations of the distribution function $f$ not only in the configuration (real) space but also in the velocity space [3, 4, 5]. Deformation of the distribution function in the kinetic plasma turbulence leads to development of fine-scale structures of $f$ through collisionless particle motions preserving the phase-space volume, where production of the entropy variable defined by a quadratic integral of a perturbed part of $f$ balances with the turbulent transport [6]. Then, the fine structures of $f$ are mixed in the phase space, which is a unique feature of collisionless or weakly collisional plasma turbulence. A similarity to a mixing process in the neutral fluid turbulence is discussed in this article.
In recent studies of plasma turbulent transport, zonal flows, which are radially sheared plasma flows with poloidal and toroidal symmetry and are driven by the electric \((E \times B)\) drift motions of ions and electrons, have attracted many researcher’s attention [7]. The zonal flows self-generated by turbulence play a crucial role in regulating turbulence and in reducing transport. A collisionless response function of zonal flow to a source term gives the kernel for the zonal flow evolution, and consists of two parts; A short time scale response is related to a geodesic acoustic mode (GAM) oscillation [8], while a long time scale response provides a residual zonal flow component [9]. The GAM oscillation is accompanied with reversal of the electrostatic potential, and suffers from the collisionless (Landau) damping. The Landau damping of plasma waves, including the GAM oscillation, is associated with the aforementioned collisionless mixing process of the distribution function in the velocity space. The residual part of the response function, which influences an efficiency of zonal flow generation, is related to an unmixed (or coherent) structure of the distribution function. Therefore, exploration of phase-space structures of \(f\) is expected to provide a key idea for achieving a better plasma confinement.

The gyrokinetic simulation of plasma turbulent transport has been widely utilized as a powerful tool for evaluating anomalous transport fluxes in fusion plasmas. Successful comparisons with current experiments demonstrate a potential for predicting future experiments. Although fully predictive simulations for future devices demand a leap in the physical and numerical modelings as well as in high performance computing (HPC), recent developments in the both fields, computational plasma physics and the HPC, are enhancing the capability toward the burning plasma simulation.

In the present article, we shortly review our kinetic simulations of phase space turbulence in magnetic fusion plasmas, and introduce the state-of-the-art peta-scale gyrokinetic simulations performed on the K computer [10]. The paper is organized as follows. The gyrokinetic equations are summarized in the next section. In section 3, generation of fine structures of the distribution function in the velocity space is discussed. Section 4 deals with simulations of zonal flows and turbulence controlled by confinement fields. Recent gyrokinetic simulation results obtained by the use of the K computer will be shown in section 5. A summary is given in the last section.

2. Gyrokinetic equations

The anomalous transport in magnetic fusion plasmas is attributed to turbulence induced by drift waves of which frequencies are much lower than the ion cyclotron (gyro-) frequency. Parallel and perpendicular wavelengths of drift waves are characterized by the device size and the thermal gyroradius, respectively. As the Vlasov or Boltzmann equation for a one-body distribution function involves multiple spatio-temporal scales, such as the Debye length, the plasma frequency, the gyrofrequency \((\Omega)\), etc, a reduced set of formulae is quite useful to describe the drift wave turbulence with low frequencies \((\omega \ll \Omega)\).

Nonlinear gyrokinetic equations are originally derived by taking a gyrophase average of the Vlasov equation and by applying a recursive formulation [11] under the gyrokinetic ordering of

\[
\frac{\omega}{\Omega} \sim \frac{k_{||}}{k_{\perp}} \sim \frac{v_{D}}{v_{t}} \sim \frac{\rho}{L} \sim \frac{\delta n}{n_{0}} \sim \epsilon
\]

with a smallness parameter \(\epsilon\), where \(k_{||}, k_{\perp}, v_{D}, v_{t}, \rho, L, \delta n, \) and \(n_{0}\) are the parallel and perpendicular wavenumbers, a guiding-center drift velocity, a thermal speed, a thermal gyroradius \((= v_{t}/\Omega)\), a typical scale-length of equilibrium, a perturbed density, and an averaged density, respectively. In an electrostatic limit, it is written as

\[
\left[ \frac{\partial}{\partial t} + v_{||} \cdot \nabla + v_{d} \cdot \nabla - \frac{\mu}{m_{s}} (b \cdot \nabla B) \frac{\partial}{\partial v_{||}} \right] \delta f_{s} + \frac{c}{B_{0}} b \cdot \nabla \Phi \times \nabla \delta f_{s} = (v_{s} - v_{d} - v_{||} b) \cdot \frac{e_{s} \nabla \Phi}{T_{s}} F_{Ms} + C
\]
where $F_{Ms}$ and $\delta f_s (= f_s - F_{Ms})$ mean the equilibrium Maxwellian and perturbed parts of a gyrocenter distribution function $f_s$ for $s$ species. Here, the independent variables of the velocity space coordinates are a velocity component parallel to the confinement field ($v_\parallel$) and a magnetic moment ($\mu$). The magnetic and diamagnetic drift velocities are denoted by $v_d$ and $v_*$, respectively. The electrostatic potential acting on the gyrocenter is represented by $\Phi$. Also, $c$, $m_s$, $e_s$, $T_s$, $B_0$, and $C$ mean the speed of light, mass and charge of a particle, temperature, the confinement field strength, and a collision term, respectively. A unit vector parallel to the confinement field is given by $b$. The $\delta f$ formulation is useful for a local simulation of turbulence and transport.

A Hamiltonian formulation of the gyrokinetic equation in a collisionless limit is also obtained by means the Lie transform to the gyrocenter coordinates [12],

$$\frac{Df_s}{Dt} = \frac{\partial f_s}{\partial t} + \{f_s, H_s\} = 0$$

where $H_s$ means a perturbed Hamiltonian independent of the gyrophase. The Poisson brackets are denoted by $\{,\}$. Equation (3) is rewritten in a conservation form as the Hamiltonian flow is incompressible, and preserves the phase volume. It is a great advantage in a global-scale turbulence simulation which solves evolution of the total distribution function (that is, so-called full-$f$ approach).

In the local limit, the $\delta f$ gyrokinetic equation derived from the recursive method coincides with that obtained from the Hamiltonian formulation [13]. In the both cases, the electromagnetic fluctuations are calculated from the Poisson’s and Ampère’s laws of which source terms include velocity-space integrals of the distribution function.

3. Phase space turbulence and transport

To emphasize a basic property of the phase space turbulence in a magnetized plasma, that is, turbulent mixing of the distribution function in the velocity space, we briefly review results of a simple two-dimensional gyrokinetic simulation of ion temperature gradient (ITG) turbulence [3, 4]. Model setting in the real space with a uniform magnetic field is schematically shown in Fig. 1. The velocity space dimension is further reduced by assuming the Maxwellian distribution for the perpendicular velocity space, and Eq. (2) is integrated over the $\mu$ space. We solve the reduced gyrokinetic equation for ions while assuming the adiabatic electron response ($\delta n_e/n_0 = e\phi/T_e$) in the electrostatic limit. In the simulations presented in this section, zonal flow components are neglected so that interactions of turbulent eddies and generation of fine structures of the distribution function are clearly captured in a fully developed turbulence.

The ITG modes are destabilized when the ion temperature gradient exceeds a critical value, and drive the ion heat transport perpendicular to the magnetic field (that is, in the $x$ direction in Fig. 1). A snapshot of the electrostatic potential fluctuation at $t = 600L_n/v_{ti}$ is plotted in Fig. 2, where the instability growth has been saturated and the statistically steady turbulence is sustained. Here, $L_n$ means the density gradient scale length, and $v_{ti}$ is the ion thermal speed. The positive and negative contours of $\phi$ are, respectively, represented by thick and thin solid curves. The largest eddy mainly drives the ion heat transport, while smaller scale fluctuations are generated in the turbulence. While the collision frequency in the present simulation is fixed to zero, a statistically steady transport is observed in the ITG turbulence. This fact is associated with the mixing of distribution function in the phase space.

In the collisionless (or in a weakly collisional) plasma turbulence, fluctuations develop not only in the real but also in the velocity space. Each panel in Fig. 3 shows velocity-space structures of the ion distribution function for the linearly most unstable mode, where complex-valued amplitudes of $\delta f_k$ are normalized by the electrostatic potential $\phi_k$, and the real and imaginary parts are plotted by green and blue lines, respectively. Right after saturation of the
Figure 1. Model setting for ion temperature gradient turbulence simulation with a uniform magnetic field and density and temperature gradients.

Figure 2. Contour plot of electrostatic potential found in ion temperature gradient turbulence simulation, where thick and thin lines represent positive and negative values, respectively.

linear instability growth, at $t = 200L_n/v_{ti}$, one finds a smooth profile of $\delta f_k$ which reflects the eigenfunction of the ITG mode. As the time advances, fine-scale fluctuations develop in the velocity space. While 8,192 grid points are used for the $v_\parallel$ coordinates, the finest scale length in the velocity space reaches the grid size at $t \sim 600L_n/v_{ti}$. Then, the numerical simulation is stopped. The obtained result manifests spontaneous and continuous generation of fine structures of $\delta f$ which is attributed to the advection term, $v_\parallel \cdot \nabla \delta f$, coupled with the turbulent stretching of $\delta f$ in the real space (namely, effective increase of the parallel wavenumber) [4].

Generation of the fine structures of $\delta f$ is related to the turbulent transport through an entropy balance. From the gyrokinetic equation for the perturbed distribution function, Eq. (2), with a help of the quasi-neutrality condition and the adiabatic electron response, one derives a balance equation,

$$\frac{d}{dt} (\delta S_n + \delta_{n,1} W) = J_{n-1/2} - J_{n+1/2} + \delta_{n,2} \frac{L_n}{L_T} Q_i - 2\nu n \delta S_n ,$$

where

$$\delta S_n = \sum_k \delta S_{k,n} = \sum_k \frac{1}{2} n! |\hat{f}_{k,n}|^2$$

$$J_{n-1/2} = \Theta k_y n! \text{Im} \left( \hat{f}_{k,n-1} \hat{f}^*_{k,n} \right) ,$$

and $\delta_{n,m} = 1$ for $n = m$ but $\delta_{n,m} = 0$ for $n \neq m$. The electrostatic potential energy and the ion heat flux are denoted by $W$ and $Q_i$, respectively. Also, $L_T$ is the temperature gradient scale length, and $\Theta = \theta L_n/\rho_i$ with the inclination angle ($\theta \ll 1$) of the magnetic field. Here, $\hat{f}_{k,n}$ ($n = 0, 1, 2, ...$) are defined by coefficients of the Fourier and Hermite-polynomial expansion of the perturbed distribution function,

$$\delta f_k(v_\parallel) = \sum_{n=0}^{\infty} \hat{f}_{k,n} H_n(v_\parallel) F_M(v_\parallel) .$$
The model collision term is given by the Lenard-Bernstein operator,

$$ C(\delta f) = \nu \frac{\partial}{\partial v_{||}} \left[ \frac{\partial}{\partial v_{||}} + \frac{v_{||}^2}{v_T^2} \right] \delta f(v_{||}) $$

(8)

with the collision frequency \( \nu \).

Summation of Eq. (4) for \( n \) provides a total balance equation of an entropy variable, \( \delta S \),

$$ \frac{d}{dt}(\delta S + W) = \frac{L_n}{L_T} Q_i + D, $$

(9)

where

$$ \delta S = \sum_{n}^{\infty} \delta S_n \quad \text{and} \quad D = -\sum_{n}^{\infty} 2\nu n \delta S_n. $$

(10)

When the ITG instability growth is saturated and the turbulent flows are statistically steady, \( dW/dt \approx 0 \) and \( Q_i \) is approximately constant. In the collisionless turbulence shown above, therefore, the growth of fine structures of \( \delta f \), leading to increase of \( \delta S \), balances with the transport, that is,

$$ \frac{d}{dt} \delta S \approx \frac{L_n}{L_T} Q_i. $$

(11)

This is a quasi-steady state of collisionless turbulence. In case with finite collisionality (\( \nu \neq 0 \)), fine structures of \( \delta f \) developed in the velocity space are dissipated by ion-ion collisions, and the increase of \( \delta S \) is saturated at a finite level. Then, a statistically steady state of weakly collisional turbulence is realized where

$$ \frac{L_n}{L_T} Q_i + D \approx 0. $$

(12)

A spectral theory of velocity-space fluctuations has been developed for the statistically steady state of the weakly collisional turbulence [4]. In the steady turbulence with finite collisionality, the left hand side of Eq. (4) vanishes. For \( n \geq 3 \), thus, difference of the entropy transfer functions, \( J_{n-1/2} - J_{n+1/2} \), balances with the collisional dissipation. However, if \( \nu L_n/v_{ti} \ll 1 \), the dissipation term plays a role only for large values of \( n \), namely, it is localized in the high-\( n \) regime. Thus, an intermediate region, which is free from the entropy production by the transport or the collisional dissipation, appears where the transfer function \( J_{n-1/2} \) is nearly constant and independent of \( n \). Figure 5 depicts the entropy production, transfer, and dissipation processes in the \( n \)-space. The obtained results suggest a similarity to the passive scalar transport in a neutral fluid turbulence with a large Prandtl number [4], and exhibit an unique picture of the plasma turbulence which develops in the phase space.

4. Zonal flows and turbulence control

The velocity-space mixing of the distribution function also plays a significant role in dynamics of the zonal flow which is considered to regulate the ITG turbulence in toroidal fusion plasmas. Evolution of a zonal flow is given by a turbulent (nonlinear) source term as well as short- and long-time response kernels which are derived from the linear gyrokinetic equation [9]. The short-time response describes the GAM oscillation of which collisionless Landau damping creates fine striation structures of \( \delta f \) due to passing particles. A coherent structure of \( \delta f \) associated with the neoclassical polarization shielding is produced due to trapped particles in the long-time response of zonal flows [14] which determines the residual level after the GAM damping [9]. It is expected that the higher residual level of zonal flows contributes to the more effective generation, and leads to the lower turbulent transport. Thus, it is preferable to find a magnetic configuration in which the zonal flow generation is enhanced and induces a better confinement. One of the
examples is shaping of a poloidal cross section of a tokamak [15]. A non-axisymmetric toroidal confinement provides us more degrees of freedom in optimization for the zonal flow response. Here, we discuss the zonal flow response in a helical confinement system, that is, the Large Helical Device (LHD) [16].

In the non-axisymmetric systems, helical-ripple-trapped particles making a radial drift motion provide additional shielding of zonal flow potential [17, 18]. A gyrokinetic simulation of the zonal flow response in a helical system clearly captures a velocity-space structure of $\delta f$ associated with the zonal flow potential shielding. A snapshot of the ion distribution function for a zonal flow component is shown in Figure 5 where a color contour shows the real part of $\delta f$. Vertical striation patterns are generated during the Landau damping of GAM due to particle motions passing through the toroidal and helical ripples of the confinement field strength. In a trapped region marked by a white dashed oval, one finds a negative part of $\delta f$ (colored by blue) which is caused by the radial drift motion of trapped particles and is responsible to shielding of the zonal flow potential. Thus, the higher zonal flow response is found in helical configurations with the slower radial drift velocity.

The above theoretical and numerical studies of zonal flows provide an important implication to the helical plasma confinement. If the field configuration could be optimized so as to lower the radial drift motion responsible for the neoclassical ripple transport, it simultaneously improves the anomalous transport though the zonal flow enhancement [19]. Gyrokinetic simulations of the ITG turbulence in helical systems, by means of the GKV code [14], confirm that the self-generated zonal flows enhanced in an optimized configuration with the slower radial drift lead to reduction of the ion heat flux [20], which is qualitatively consistent with experiments. More recently, the gyrokinetic simulations have been extended for direct comparisons with the LHD experiments [21, 22], showing a quantitative agreement on the ion heat transport flux [23]. The above simulations are carried out by means of a local flux tube model, and the obtained results...
are utilized for development of an anomalous transport model that takes into account the effect of turbulence regulation by zonal flows [24]. It is a practical outcome of exploring the phase space turbulence which involves not only large scale structures but also small scale fluctuations of the velocity distribution function.

5. Peta-scale simulation of fusion plasma turbulence

Phase space turbulence simulations shown in the previous sections demand large computational costs. For example, over $5 \times 10^{10}$ grid points (that is, $128 \times 128 \times 768 \times 128 \times 48$ in the $(x, y, z, v, \mu)$ coordinates) are employed for numerically resolving the ITG turbulence fluctuations on the five-dimensional phase space of a non-axisymmetric system [20], and more than 100 hours of computational time were spent using 256 nodes of the Earth Simulator [25] (which was a huge vector-parallel machine with the peak performance of $4 \times 10^{13}$ (40 tera) flops). Thanks to the recent development of supercomputer technology, gyrokinetic simulations with the similar resolution are able to be more frequently executed on current systems with the peak speed of several hundreds tera flops. For more comprehensive understandings of plasma turbulence, nevertheless, peta-flops scale simulations are highly demanded. In the followings we discuss the two examples of peta-scale turbulent transport simulations performed on the K computer.

5.1. Ion- and electron-scale turbulences

In burning fusion plasmas, electron heat transport is a critical issue, because alpha particles produced by D-T reactions mainly interact with electrons. But, it is still an open issue in which scale of turbulence drives the anomalous electron heat flux. Typical wavenumber and frequency of the electron-scale turbulence are, respectively, characterized by the electron gyroradius and transit time which are smaller than those in the ion-scale turbulence by a factor of \(v_{ti}/v_{te}\) (that is, \(\sqrt{m_e/m_i}\) for \(T_e = T_i\)). Thus, the anomalous electron heat transport is intrinsically a multi-scale problem where one needs to consider the ion- and electron-scale turbulences simultaneously. Smallness of the mass ratio, \(m_e/m_i\), requires the peta scale computing, since the computational cost is proportional to \((m_i/m_e)^{3/2}\), e.g. \((m_i/m_e)^{3/2} \sim 8 \times 10^4\) for a hydrogen plasma.

A multi-scale plasma turbulence simulation using the gyrokinetic simulation code, GKV [14, 26], has been carried out on the K computer, where the electron and ion temperature gradient modes are simultaneously destabilized by the temperature gradients. A color contour of the electrostatic potential fluctuation is shown in Figure 6 where a small panel shown on the right is a magnified plot at the center of the simulation box. In the main panel, one finds growth of the ITG mode with the wavelength of 15 ~ 20\(\rho_i\). As shown in the magnified plot, fine scale turbulent fluctuations are embedded in the ITG mode perturbations. Because of the faster
electron motions than ions, the electron temperature gradient (ETG) mode primarily grows in the early phase of the simulation, driving the electron heat transport. Then, the ITG modes are excited with longer spatio-temporal scales, and their growths are saturated by the self-generated zonal flows. Once the ion-scale turbulence dominates, the electron scale turbulence is regulated, and the electron heat is mainly carried by the ion-scale fluctuations. More detailed results of the multi-scale turbulent transport simulation will be published elsewhere.

The highly optimized GKV code enables us to perform the multi-scale simulation of the ion and electron scale transport with the real mass ratio \( \frac{m_i}{m_e} = 1836 \). Several optimization techniques have been employed, such as a process mapping suitable to the topology of inter-node connections, overlapping of communications with computations, and so on [27]. Finally, the parallelization efficiency of 99.99994% is achieved on \( \sim 600 \) k processor cores of the K computer, which implies further potential of gyrokinetic simulations to elucidate the anomalous transport in fusion plasmas with multi-scale and multi-physics turbulence.

5.2. Global-scale simulation of plasma turbulent transport

The gyrokinetic turbulence simulations discussed above deal with local transport phenomena where the simulation domain perpendicular to the confinement field is scaled with the thermal ion gyroradius \( \rho_i \), and is assumed to be much smaller than the equilibrium scales. This assumption may be validated for large-sized devices, such as ITER where the ratio of the minor radius of a torus \( a \) to \( \rho_i \) is about \( a/\rho_i \gtrsim 600 \). However, it is necessary to take account of a global radial domain, if formation or relaxation of the equilibrium profiles are focused on, or if the scale separation of fluctuations and background quantities is non-trivial. The GT5D code [28], solving the full-\( f \) gyrokinetic equation, like Eq. (3), with finite collisionality and energy source and sink terms, has been developed and applied to the ion scale turbulent transport problems in tokamaks [29]. Recent results from the GT5D simulations have demonstrated a plasma size scaling of the ion heat transport, momentum transport and toroidal rotation, intermittent transport events, and a role of source and sink models [30, 31, 32, 33].
As expected, the GT5D simulations demand huge computational costs, and have been performed by utilizing 100 tera flops systems or beyond [34]. So far, the ITG turbulent transport for a plasma size of $a/\rho_i \leq 450$, which is relevant to the present day tokamaks, has been simulated by the GT5D code [33]. However, it is still not enough for predicting performance of ITER of which plasma volume is more than ten times larger than that of the current experiments. Thus, it demands the use of a peta-scale machine, like the K computer. The GT5D code is highly optimized also for the K computer by applying a hybrid parallel model and communication-overlap techniques [35], where an excellent strong scaling is confirmed even with a sustained computational performance of $\sim 10 \%$. The achieved parallelization efficiency is 99.99989 $\%$ for $\sim 600$ k cores of the K computer, which enables the ion-scale turbulence simulations for a sub-ITER scale plasma of $a/\rho_i = 600$.

A snapshot of the electrostatic potential found in the ITG turbulence simulation for the case of $a/\rho_i = 450$ is shown in Figure 7, where one clearly finds the turbulent fluctuations scaled by the ion thermal gyroradius. It means that the fusion plasma confinement itself is a multi-scale problem of the macro-scale profile relaxation and the micro-scale turbulent transport. It is also observed that non-local transport events influence a global confinement of ion thermal energy. Detailed results on the statistical property of turbulent transport and the size scaling, including the case of $a/\rho_i = 600$, will be reported elsewhere.

6. Summary

Phase space turbulence and transport in magnetic fusion plasmas has been investigated by means of gyrokinetic simulations where time-evolutions of a one-body distribution function coupled with fluctuations of electromagnetic fields are solved numerically. In this article the recent progress is briefly reviewed where we focus on mixing processes in the phase space and on multi-scale plasma turbulence.

Generation of fine velocity-space structures of the perturbed distribution function $\delta f$ is characterized by increase of a quadratic integral (the entropy variable) of which transfer from

Figure 7. Color contour of electrostatic potential of ion temperature gradient turbulence in a sub-ITER scale plasma with $a/\rho_i = 450$. 
the macro to micro velocity scales balances with the cross-filed transport driven by the drift wave turbulence. Velocity-space structures of $\delta f$ are also influential to zonal flows which regulate the ion temperature gradient turbulence. The zonal flow response is controlled by the helical confinement field which determines the radial drift motion of trapped particles. This is confirmed by the gyrokinetic simulations resolving the velocity-space structure of $\delta f$ for a zonal flow component. gyrokinetic turbulence simulations have verified the transport reduction due to zonal flow enhancement controlled by the helical field, and contribute to development of a reduced transport model.

The recent progress of high performance computing enables us to utilize peta-scale systems, such as the K computer. A multi-scale gyrokinetic simulation clarifies a whole spectrum of turbulent fluctuations in the case where the ion- and electron-scale turbulences are simultaneously excited. Also, a global gyrokinetic simulation has been extended to resolve the turbulent transport problem in a sub-ITER scale plasma where non-local transport events are identified.

Production and control of a burning plasma is a critical issue in the ITER experiment, where prediction of the plasma confinement performance is an important subject in plasma physics. But, there are still some open issues associated with the turbulent transport, such as the isotopic effect, the impurity transport, and so on. Understandings of the unresolved issues are believed to be brought by future developments of gyrokinetic turbulence simulations with a help of the state-of-the-art of the high performance computing.

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