A gyrokinetic Vlasov code on high performance architectures towards multi-scale turbulence simulation in magnetic fusion plasma

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Drift wave micro-turbulence at ion or electron scale has been extensively studied to understand the transport property over the years. It has shown that the ion temperature gradient (ITG) driven turbulence with the zonal flow dynamics seems be responsible for the ion heat transport with neoclassical level in Tokamaks. However, high electron transport observed in experiments could not be successfully explained through the conventional electron temperature gradient (ETG) driven turbulence theory. While various alternative mechanisms including trapped electron mode (TEM) have been proposed, the multi-scale micro-turbulence covering ion and electron scales may also provide a new fluctuation source and the transport channel in plasmas. Linearly, a short wavelength ITG instability may be excited with non-adiabatic kinetic electron response [1]. To simulate the nonlinear evolution of such a multi-scale ITG-ETG turbulence involving both kinetic ion and electron dynamics on first principles, a new gyrokinetic Vlasov code on high performance architectures is developed aiming to use more than several thousands of CPUs. At the first stage of the large-scale gyrokinetic simulation, the code performance is benchmarked through the calculations of the short wavelength ITG mode comparing with the theoretical results.

In this work, we present the current status of our code, a C^{++} /Fortran-03 written code, which is parallelized to use up to $\mathcal{O}(10^3)$ CPUs - using finite differences for the gyro-kinetic Vlasov equation and a Fourier solver for Poisson's equation. As a Fourier solver, we apply p3dfft [2], which supports pencil-decomposition (2D data decomposition in x-y) of the domain. The Vlasov solver itself is decomposed in all directions but needs to be synchronized via `MPI_reduce` and `MPI_Bcast` for the Poisson part solver. Overall we achieve a scaling efficiency of about 60% for 1024 CPUs, however further increase in scalability is limited by the Fourier solver, which – as all parallelized Fourier solvers – rely on the slow `MPI_Alltoallv` call for data transpositions. To increase the scalability further, we replace the Fourier solver by a hp-FEM (Finite Element) solver, which is numerically more expensive, but – if Krylov subspace methods are used to solve the underlying matrix – more scalable than Fourier methods[3]. The multi-scale ITG-ETG turbulence simulations with reduced ion-electron mass ratio are in progress.

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20th International Toki Conference (ITC-20)
on The Next Twenty Years in Plasma and Fusion Science
December 7 - 10, 2010, Ceratopia Toki, Toki-City, Gifu, Japan

Remote collaboration system based on the monitoring of large scale simulation “SIMON” : A new approach enhancing collaborator

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Large scale simulation using super-computer, which requires long CPU time and produces large amount of data, has been introduced as a third pillar in various fields in science and technology. Such simulations are expected to bring scientific discoveries through elucidation of various complex phenomena, which are hardly studied by using conventional theoretical and experimental approaches. To assist such simulation studies in which many collaborators working at geographically different places participate, we developed a unique remote collaboration system, referred to as SIMON (SImulation MONitoring System) [1,2].

This system utilizes a *client-server control* introducing the idea of *update processing*, which is contrary to that of widely used post processing. As a key ingredient, we developed the *trigger method* (Fig.1: Trigger), which transfers various requests for the update processing from the simulation (client) running on a super-computer to a workstation (server). The server that received requests from the simulation, such as data transfer, analysis and visualization, etc., (Fig.1: Data transfer, etc.) performs the corresponding tasks. The server delivers the latest results on web (Fig.1: dash line), so that the collaborators can monitor the results at any place in the world. We confirmed that the system works well and plays an important role as a common platform.

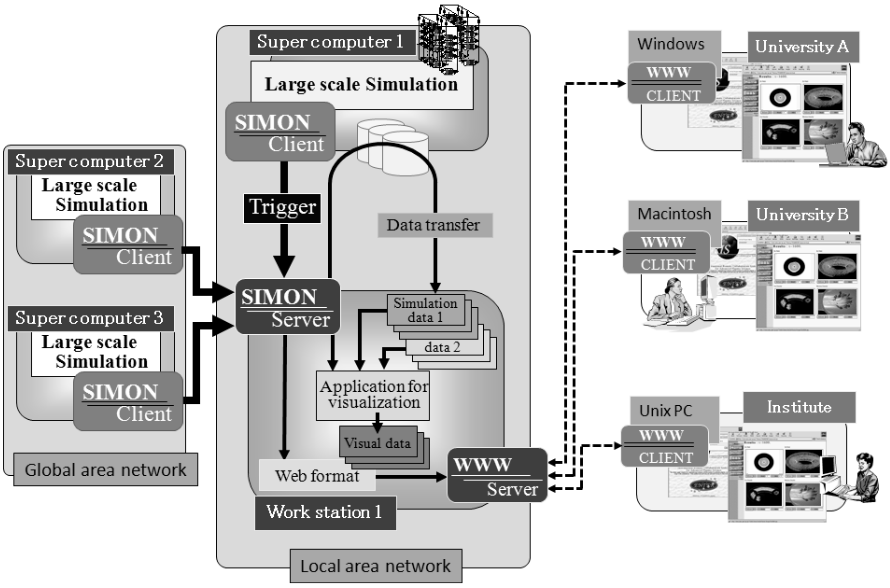

Fig.1 Schematic view of flowchart of various operations and functions in SIMON system

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20th International Toki Conference (ITC-20)
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Gyrofluid simulation of slab ITG turbulence in plasmas including pressure profile corrugation

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Coherent large-scale flows and structures such as the mean and zonal flows in drift wave turbulence play an important role not only in suppressing the ambient turbulence to form the transport barriers but also in arising various dynamic transport processes in fusion plasmas.[1] For example, it was found that small-scale zonal flow generated by electron temperature gradient (ETG) driven turbulence can stabilize the ion temperature gradient (ITG) turbulence through the nonlocal mode coupling and further induce an intermittency of ion heat transport [2]. Recently, a pressure profile corrugation is shown in the gyrokinetic simulations based on DIII-D experimental database [3, 4]. Such profile corrugation may be an indirect experimental evidence of the zonal flows in tokamak plasmas. It may be also produced nonlinearly by different scale turbulence through the zonal pressure generation.

In this work, we investigate the drift wave ITG instability in the presence of the pressure profile corrugation based on gyrofluid simulation. The influence of the profile corrugation on the evolution of the ITG turbulence and ion transport is discussed in a sheared slab geometry. Here, we assume that the pressure profile corrugation mainly modifies the driving force of ITG instability, so that the corrugation is given by the form of $\nabla p_{ex} \propto \cos(k_p x + \theta)$. Here θ is a phase factor. Linear stability analyses show that the profile corrugation may stabilize and destabilize the ITG mode depending on the wavelength number k_p and the phase factor θ. The stabilization is similar to the usual quasilinear flattening effect. But the destabilization may originate from the competition between the destabilization due to local steepening and the global flattening stabilization. Most interestingly, nonlinear simulation reveals an ion transport intermittency when the profile corrugation destabilizes the ITG mode. The underlying mechanism will be analyzed through the mode coupling incorporating with the zonal flow dynamics.

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Analysis of Relativistic Ponderomotive Force and Higher-Order Particle Motion in a Non-Uniform Laser Field Using the Noncanonical Lie Perturbation Method

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In recent years, ultra-short high-power lasers in the range of 10^{21} W/cm^2 have been developed and opened up various applications such as fast ignition-based laser fusion, compact accelerators and high-intensity X-ray/neutron sources. Recently, more innovative challenges aiming at higher intensities of $10^{23\text{-}26}$ W/cm^2, where not only electrons but also ions can exhibit relativistic characteristics have been proposed. Such ultra-high intensity lasers may belong to an entirely new regime where new scientific discoveries are expected [1]. In order to realize such higher intensities, a further reduction in the pulse width and/or the spot size is necessary. In such spatially localized laser fields, the *ponderomotive force* (light pressure) exists inevitably and plays an essential role [2].

Here, we analyze the relativistic particle motion in such non-uniform high intensity laser fields by using the noncanonical Lie perturbation theory [3]. This method is based on the perturbation theory of phase space Lagrangian and is efficient in studying the effects of higher-order perturbations such as the ponderomotive force. Note that it is difficult to investigate such effects precisely by applying the conventional averaging method to the equations of motion especially in the tightly focused nonlinear relativistic regime where the higher-order terms, such as the curvature of the laser field amplitude, play an important role. The noncanonical Lie perturbation method has been successfully introduced in the gyro-kinetic formalism in describing magnetically confined fusion plasmas [4] and also in the analysis of a relativistic beam orbit in a free-electron laser [5]. Motivated by these achievements, we extended this method to the analysis of particle motions irradiated by spatially localized high intensity lasers, assuming that the ratio between the excursion length of the fast time scale oscillatory particle motion and the scale length of the laser amplitude variation is small.

As a result, we successfully derived the relativistic ponderomotive force and the corresponding particle motion including higher harmonic oscillatory components. The particle motion in the direction of the laser propagation was found to show a secular motion characterized by growing oscillations exhibiting a cubic dependence on the laser amplitude. The second-order perturbation which corresponds to the curvature of the laser field amplitude will be also discussed.

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Numerical method for Eulerian gyro-kinetic Vlasov simulation based on the multi-moment scheme

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Nonlinear gyro-kinetic and drift-kinetic Vlasov simulations [1], which eliminate the higher-frequency phenomena than cyclotron one while keeping important kinetic effects, are considered to be an essential tool for the study of the turbulent transport driven by micro-scale instabilities. Although most of the global Vlasov simulation have adopted a Lagrangian (particle) approach due to the limitation of computational resources, an Eulerian (mesh) approach is superior in reducing numerical noise and extending to an open system. Recently, with the aid of rapid progress of high performance computing and advanced numerical schemes in CFD field, an Eulerian approach has been more available in Vlasov simulations.

In order to develop a reliable Eulerian Vlasov code from the view point of numerical properties, we have newly explored *the multi-moment scheme.* In this scheme, spatial derivatives are evaluated by the interpolation functions locally constructed by both point and cell-integrated values, which concept is similar to that of the Conservative Form of Interpolated Differential Operator (IDO-CF) scheme [2-3]. However, in the multi-moment scheme, not only a cell-integrated value $^0M = \int_{x_i}^{x_{i+1}} f dx$, but also the first and second order moments $^1M^x = \int_{x_i}^{x_{i+1}} (x - x_i) f dx$ and $^2M^x = \int_{x_i}^{x_{i+1}} (x - x_i)^2 f dx$, are used and time-integrated as independent variable, which drastically increases the numerical accuracy and resolution. Figure. 1 shows the theoretical (a) gain and (b) phase errors of various upwind schemes, i.e., the 1st-order upwind, 3rd-order upwind, IDO-CF and multi-moment schemes, respectively. It is found that the multi-moment scheme exhibits significantly smaller dissipations and phase errors even near Nyquist wave number as shown in Fig.1 (a) and (b), respectively. Futhermore, the above cell-integrated values are time-integrated in the flux forms, so that they are rigorously conserved. This property is essential for the long time scale Vlasov simulation. Thus, we found that the present scheme is superior in capturing small-scale structure without causing serious gain and phase error while keeping the conservation properties. Such a property is also confirmed through some benchmark tests.

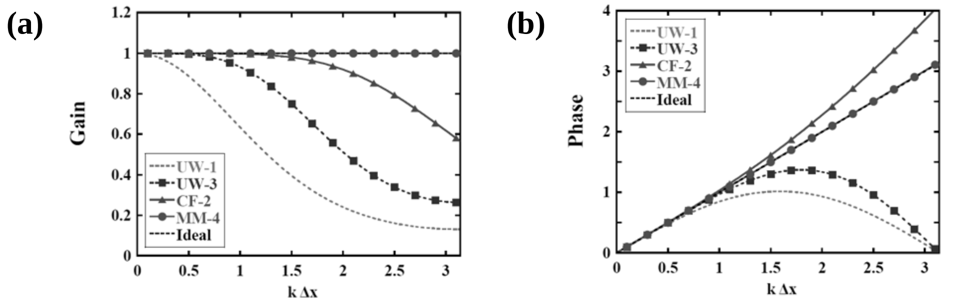

Fig. 1. Theoretical (a) gain and (b) phase errors of various upwind schemes

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Multi-scale turbulence interaction through cross-scale dynamo generation by micro-scale turbulent flow in plasmas

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Complexity of plasma turbulence does not only originate from the abundance of various linear and nonlinear instabilities including drift waves and MHD activities due to the complex geometry and non-homogeneity, but also results from highly nonlinear interaction among these electrostatic (ES) and electromagnetic (EM) fluctuations. In magnetic confinement fusion plasmas, recent experimental observations have shown some evidences such as the internal transport barriers (ITBs) along the low order rational q surfaces and MHD activities accompanying with suddenly occurring small-scale fluctuations. Such phenomena are speculated as a consequence of nonlinear interaction among macroscopic MHD activities and microscopic drift waves. Here we study the nonlinear interaction mechanisms of multi-scale multi-mode turbulence through direct gyrofluid simulation. A new interaction mechanism of cross-scale dynamo generation by micro-scale flow is identified through direct simulation and modelling analysis. The implication of the results in plasma control is discussed.

The interplay between EM MHD and ES micro-turbulence is directly simulated in a current sheet with $\psi_0 \propto \cosh^{-2}(x/\lambda)$ using gyrofluid model, in which resistive tearing mode and ion temperature gradient (ITG) instability are involved in a 2-dimensional narrow region [1]. A novel magnetic island seesaw oscillation pivoting around the singular surface is prominently observed accompanying with oscillatory zonal flows. To understand the underlying interaction mechanism, a minimal model [2], which incorporates reduced MHD and an individually evolving ES ITG eigenmode, is proposed to testify the response of the MHD fluctuation to the micro-turbulence. The modeling analyses, as a flexible test-bed, reproduce well the island dynamics as in direct simulations, highlighting (i) a dynamo current induced by micro-scale ES potential with opposed radial parity, (ii) an oscillating EM torque essential for the island seesaw due to radial odd-parity dynamo current, (iii) an island-dominated state with full reconnection, in which the magnetic tension force around the X-points tends to be too weak to prevent the island oscillation. It is inferred that the island seesaw dynamics may relax the mode locking to mitigate the major disruption, suggesting a promising state-of-the-art nonlinear approach for plasma control.

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