Research Plan of Complex Global Simulation Unit*)

Yasushi TODO, Hideaki MIURA, Mieko TOIDA, Ryuichi ISHIZAKI, Masahiko SATO, Hao WANG, Ryosuke SEKI, Jialei WANG, Malik IDOUAKASS, Panith ADULSIRISWAD, Naoki MIZUGUCHI, Takashi YAMAMOTO and Hideo SUGAMA

National Institute for Fusion Science, National Institutes of Natural Sciences, Toki 509-5292, Japan

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Global simulation, which takes into account the interactions between multiple hierarchies, is expected to be realized not only in the field of nuclear fusion research but also in other academic fields. However, such a complex global simulation is difficult to realize because the temporal and spatial scales of the microscopic hierarchy and those of the entire system are generally extremely different. The aim of the Complex Global Simulation Unit at the National Institute for Fusion Science is to develop simulation methods to address the abovementioned issue and to promote simulation research. This unit aims to develop 1) a global simulation of the whole magnetically-confined fusion plasma, including the core and peripheral plasma, based on the kinetic-magnetohydrodynamic hybrid simulation coupled with the gyrokinetic Poisson equation, and 2) a methodology with broad applicability for enabling simulations that closely reproduce real-world phenomena, transcending the strong limitations imposed by the capacity and capability of supercomputers. In addition, the unit aims to develop a method for coupling a particle-in-cell simulation and a global analysis of plasma waves. Furthermore, it aims to develop a multiphase (solid, liquid, gas, and plasma) simulation method for pellet injection into fusion plasmas.

Keywords: global simulation, kinetic-MHD hybrid simulation, data science, turbulence, particle-in-cell simulation

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1. Introduction

The behavior of a system composed of multiple hierarchies cannot be studied by only performing the simulations of individual hierarchies. It is essential to perform global simulations that account for the interactions between the hierarchies. Such complex global simulations are important research areas that are expected to be realized not only in the field of nuclear fusion research but also in other academic fields. However, these simulations are difficult to realize because systems and their microscopic hierarchies generally have extremely different temporal and spatial scales, and a supercomputer does not have sufficient capacity and capability to simulate the entire range of scales based on a single system of fundamental physical equations. The purpose of the Complex Global Simulation Unit at the National Institute for Fusion Science is to develop simulation methods to address the abovementioned issue and to promote simulation research.

The unit aims to develop 1) a global simulation of whole magnetic confinement fusion plasma, including the core and peripheral plasma, based on the kinetic-magnetohydrodynamic (MHD) hybrid simulation, and 2) a methodology with broad applicability to realize simulations that closely reproduce real-world phenomena, transcending the strong limitations imposed by the capacity and capability of supercomputers. Further, special attention will be given to modeling complex phenomena using coherent structures, self-similarity, and physics-based phenomenological model as well as numerical approaches, such as reduced-order modeling, and data science methods. In addition, the unit aims to develop a method for coupling a particle-in-cell (PIC) simulation and a global analysis of electromagnetic plasma waves. Further, it aims to develop a multiphase (solid, liquid, gas, and plasma) simulation method for pellet injection into fusion plasmas.

2. Global Simulation of Whole Magnetic Confinement Fusion Plasma

MHD is a theoretical framework that successfully explains the macroscopic behavior of laboratory, space, and astrophysical plasmas. MHD is a one-fluid plasma model coupled with the induction equation for a magnetic field. Ohm's law gives electric field as the vector product of fluid velocity and magnetic field. However, the adiabatic equation used as the pressure evolution equation in MHD is not valid for high-temperature collisionless plasma. The velocity distribution of particles in collisionless plasma deviates from Maxwell distribution because the collisional relaxation of the distribution to Maxwell distribution is slower than the evolution of the distribution caused by particle motion. The adiabatic equation assumes Maxwell distribution of particle velocities, which is not valid for colli-

author's e-mail: todo@nifs.ac.jp

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sionless plasma. Thus, MHD should be extended by considering the kinetic effects arising from particle dynamics for collisionless plasma.

A representative example that illustrates why MHD should be extended is energetic-particle-driven instabilities, such as Alfvén eigenmodes [1–6]. In magnetically-confined fusion plasmas, energetic particles are generally ions generated by neutral beam injection (NBI), ion-cyclotron-range-of-frequency (ICRF) wave heating, and fusion reactions. In addition, energetic particles can be electrons generated by an external current drive and heating or those generated during disruption of tokamak plasma. Kinetic-MHD hybrid simulations for energetic particles interacting with an MHD fluid are useful tools for understanding and predicting energetic-particle-driven MHD instabilities [7–17]. Most kinetic-MHD hybrid simulation models describe the bulk plasma as an MHD fluid and neglect the kinetic effects of thermal ions and electrons. A novel kinetic-MHD hybrid simulation model that accounts for the kinetic effects of thermal ions was recently proposed [18–20]. In this section, the model and the results of a kinetic-MHD hybrid simulation are discussed, and a research plan is proposed for the global simulation of whole magnetic confinement fusion plasma.

2.1 Kinetic-MHD hybrid simulation model

In the hybrid simulation of energetic particles interacting with an MHD fluid, bulk plasma is described by the nonlinear MHD equations, and the energetic particles are simulated using the gyrokinetic PIC method. The members of the unit have developed the MEGA code that includes the energetic-particle contribution in the MHD momentum equation as an energetic-particle current density consisting of magnetic gradient drift, magnetic curvature drift, and magnetization current [12]. Alternatively, the energetic-particle contribution can be expressed in the form of an energetic-particle pressure tensor. These two models are equivalent.

A novel hybrid simulation model was developed in which the gyrokinetic PIC method is applied to energetic particles and thermal ions to account for the kinetic effects of thermal ions [18–20]. Number density, parallel velocity, parallel pressure, and perpendicular pressure are simulated with the gyrokinetic PIC for both energetic particles and thermal ions. The model also incorporates Ohm's law which is extended with the electron pressure gradient term. The diamagnetic drift of the energetic particles and thermal ions is accounted for in the momentum equation.

2.2 Kinetic-MHD hybrid simulation results

Experiments on Alfvén eigenmodes destabilized by fast ions generated by NBI or ICRF wave heating have been conducted using current tokamak, helical, and spherical tokamak devices. In the DIII-D tokamak experiments, significant flattening of the fast-ion distribution associated with many Alfvén eigenmodes with low amplitudes has been observed [21]. A validation study of a DIII-D experiment was conducted by performing a simulation using the MEGA code [22–24]. In the validation study, realistic NBI as well as particle collisions and losses were implemented in the MEGA code. A novel method was developed to realize the simulation of the slowing-down time scale of fast ions [22]. This method consisted of alternately performing a kinetic-MHD hybrid simulation and a classical simulation, which neglects MHD fluctuations. Figure 1 shows the comparison of the fast-ion pressure profile obtained through the MEGA simulation and that through experiment [23]. In the MEGA simulation, interactions with multiple Alfvén eigenmodes cause flattening of the fast-ion pressure profile. The fast-ion pressure profile obtained through the MEGA simulation is consistent with experimental results within the experimental error bar. Profiles obtained from the simulated and experimental methods are largely flattened as compared to that obtained through the classical simulation, which includes beam ion injection and particle collisions but not MHD fluctuations. Figure 2 shows the comparison of the amplitude profile of the electron temperature fluctuation caused by the Alfvén eigenmode with the largest amplitude between the MEGA simulation and the experimental measurement. The two profiles are in good agreement including the absolute value of the amplitude. The simulated and experimental results for the frequency and phase distribution of the oscillations were also found to be in good agreement.

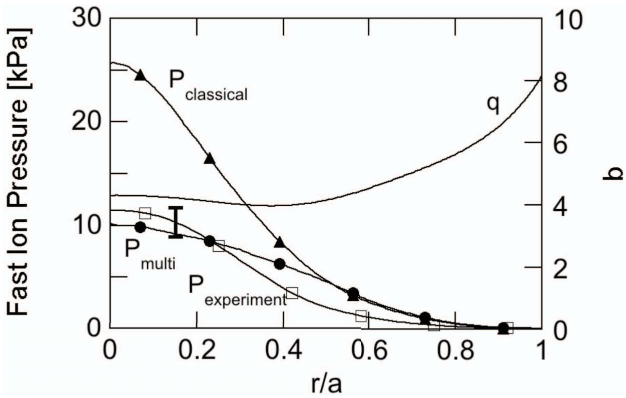

Fig. 1 Comparison of fast-ion pressure profiles obtained using the kinetic-MHD hybrid simulation (circles); using classical simulation (triangles), in which MHD fluctuations are neglected; and through experiment (squares) [23].

Geodesic acoustic modes (GAMs) are oscillating zonal flows in toroidal plasmas with poloidal and toroidal mode numbers $m/n = 0/0$ [25, 26]. Energetic particles that destabilize a GAM produce nonperturbative effects on the mode frequency and the spatial profile. This mode is called the energetic-particle-driven geodesic acoustic mode (EGAM) [27]. Kinetic-MHD hybrid simulations of EGAM in the Large Helical Device (LHD) were performed using a realistic three-dimensional (3D) equilibrium and a

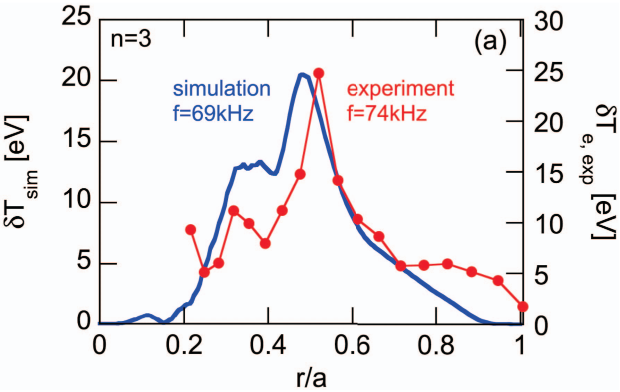

Fig. 2 Comparison of the profiles of electron temperature fluctuations induced by the Alfvén eigenmode with the largest amplitude obtained using the kinetic-MHD hybrid simulation (blue line) and through experiment (red line with circle) [23].

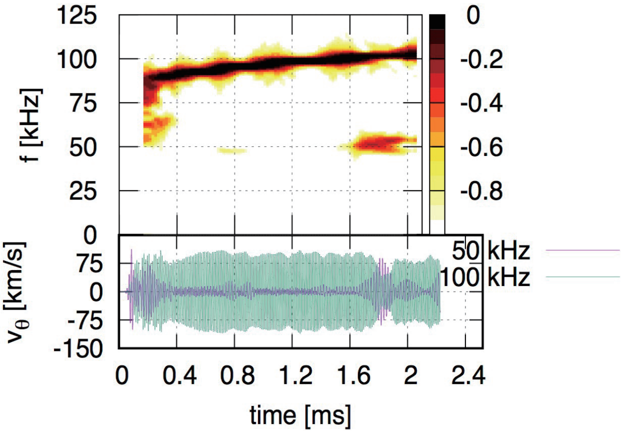

Fig. 3 Time evolution of the frequency spectrum of the poloidal MHD velocity (top) and the oscillation of the poloidal MHD velocity around 100 kHz and 50 kHz (bottom).

plasma profile based on the LHD shot No. 109031 [28]. An interesting phenomenon was observed in this experiment. The frequency of the primary EGAM chirped upward, followed by a sudden excitation of a secondary EGAM with a frequency half that of the primary EGAM. This phenomenon was successfully reproduced in MEGA simulations [29]. Figure 3 shows the frequency spectrum of the poloidal flow and the time evolution of the oscillations. In the simulation, when the frequency of the primary mode chirps up to 100 kHz, a secondary mode with a frequency of 50 kHz is suddenly excited. An analysis of the energetic particles destabilizing the EGAMs was performed to investigate the excitation mechanism of the secondary mode. The energetic particles were found to have orbital frequencies of 100 kHz. This result indicates that in addition to the fundamental resonance between particles with orbital frequencies of 100 kHz and the primary mode with a frequency of 100 kHz, there is a nonlinear resonance between these particles and the secondary mode with a frequency of

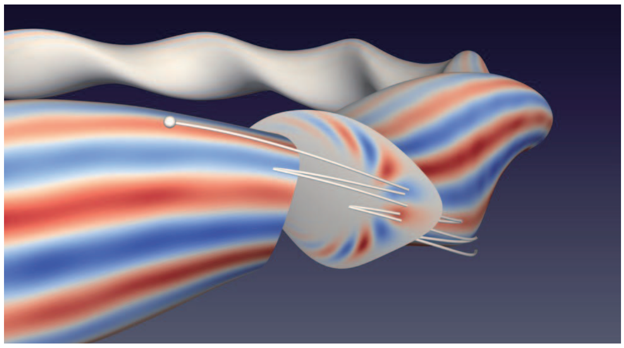

Fig. 4 Precession drift motion of a trapped ion and pressure perturbation of a resistive ballooning mode in LHD.

50 kHz. Energy is transferred from primary to secondary mode via the resonant particles, which resonate with both modes through fundamental and nonlinear resonances, respectively.

Current-driven MHD instabilities do not occur in helical plasmas without a net plasma current. The suppression of pressure-driven MHD instabilities, such as interchange modes and ballooning modes, is critical for realizing high-β plasmas, where β is the plasma pressure normalized by the magnetic pressure. LHD experiments have revealed that plasmas have more stability against MHD instabilities than what the MHD theory predicts [30, 31]. The kinetic effects of thermal ions on the linear stability of pressure-driven MHD instabilities were investigated using the MEGA code extended to account for kinetic thermal ions [19, 32, 33]. A detailed analysis revealed that the suppression effect of kinetic thermal ions arises from the precessional drift motion of ions trapped in the helical ripple in the poloidal and toroidal directions. Figure 4 shows that the poloidal precession drift motion enables ions to pass quickly through regions in which the mode structure of the instability has different phases. This behavior shows that the interaction between thermal ions and the pressure-driven MHD instability is so weak that the ion pressure is no longer the driving energy source for the instability.

Recurrent bursts of Alfvén eigenmodes are observed in tokamak and helical devices [34–37]. These Alfvén eigenmode bursts were reproduced successfully using a multiphase simulation based on the MEGA code [38–43]. Precession drift reversal and rapid transport of trapped energetic particles were observed in the MEGA simulation of an energetic-particle-driven instability in LHD [44]. The MEGA code can simulate energetic-particle-driven instabilities in stellarators with a helical magnetic axis, such as Heliotron J and CFQS [45–47]. MEGA simulations have been employed to elucidate the effects of energetic electrons on Alfvén eigenmodes in tokamak plasmas [48, 49].

2.3 Research plan for the global simulation of whole magnetic confinement fusion plasma

Burning plasmas are expected to be realized in future ITER experiments. In these plasmas, energetic alpha particles produced through fusion reaction play a key role in plasma heating. Energetic-particle-driven instabilities such as Alfvén eigenmodes that degrade the confinement of energetic alpha particles are important research topics for burning plasmas. These instabilities excite zonal flows and GAMs. As zonal flows suppress microturbulence, energetic-particle-driven instabilities may improve the performance of burning plasma. The interactions among energetic-particle-driven instabilities, zonal flows, and microturbulence are critical research topics for predicting the behavior of burning plasmas. Burning plasma performance can be considerably enhanced by the realization of "alpha channeling," which enables energy transfer from energetic alpha particles to thermal ions through interaction with plasma waves. Alfvén eigenmodes and EGAMs could be utilized for alpha channeling. The Complex Global Simulation Unit plans to perform kinetic-MHD hybrid simulations to study important research topics related to burning plasmas.

Gyrokinetic simulations should be performed to study microturbulence in magnetically-confined fusion plasmas [50–52]. Electrostatic field, which is an important factor in microturbulence, in the present version of the MEGA code is different from that obtained from the gyrokinetic Poisson equation [53]. Therefore, the gyrokinetic Poisson equation will be incorporated in the MEGA code, and the electrostatic field in the kinetic-MHD hybrid simulation will be replaced by that obtained from the equation. This modified gyrokinetic-MHD hybrid simulation will enable investigation of the interactions among energetic-particle-driven instabilities, zonal flows, and microturbulence. The interplay between MHD instabilities and microturbulence is also a critical research topic related to edge plasmas. The Complex Global Simulation Unit will develop a gyrokinetic-MHD hybrid simulation of whole magnetically-confined fusion plasma in which the core and edge plasmas are coupled. The simulation study will be conducted for a nonequilibrium open system in which the steady production of alpha particles through fusion reaction and the transport fluxes from the core to the edge plasma play key roles.

In addition, the unit will develop a method to couple PIC simulation with a global analysis of plasma waves. Furthermore, it will develop a multiphase (solid, liquid, gas, and plasma) simulation method for pellet injection into fusion plasmas. We performed a PIC simulation considering full ion and electron dynamics to investigate the nonlinear development of lower hybrid wave instabilities driven by energetic ions with a ring-like distribution in a velocity space perpendicular to the magnetic field [54–57]. These energetic ions are generated by NBI in fusion plasma and by a shock wave [58] in space plasma. Figure 5 shows the simulated magnetic fluctuations excited by energetic ions continuously injected into plasma with increasing density. Frequency chirping with the riser Ω_i appears near the lower hybrid resonance frequency ω_{LH}. This is similar to the frequency chirping observed for radiations at the plasma start-up phase of LHD experiments. In the geomagnetosphere, lower hybrid waves are considered to play an important role in ion energization, which can cause ion outflow from the Earth. We have demonstrated that energetic-ion injection can enhance ion acceleration through lower hybrid waves. To advance these studies, we need to develop a method to couple PIC simulations with global analysis of plasma waves and energy transfer.

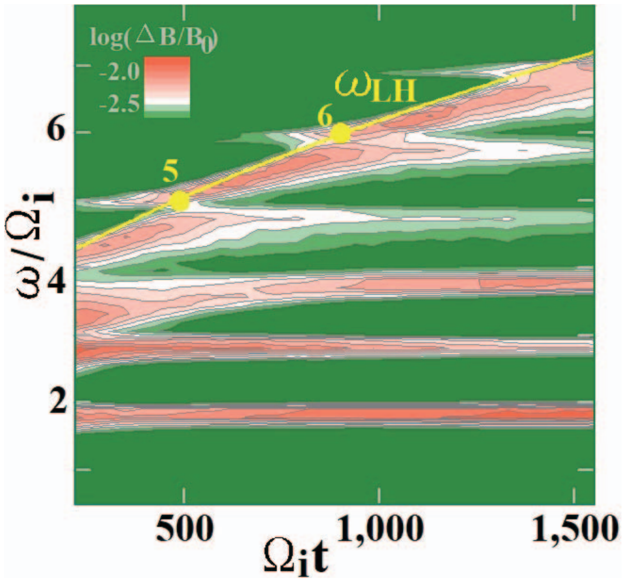

Fig. 5 Frequency chirping near the lower hybrid frequency of magnetic fluctuations excited by energetic ions continuously injected into plasma with increasing density [55].

Injecting small pellets of frozen hydrogen into torus plasmas is a proven fueling method [59]. When a pellet is injected into torus plasma, the ablation induces the formation of a high-density, low-temperature plasmoid due to the heat flux from the surrounding high-temperature plasma. LHD experiments were performed in which pellets were injected into a discharge without islands and into a discharge with an edge $m/n = 1/1$ island, where the o-point was located at the pellet injection point. The increase in the density inside the island was larger than that in the discharge without islands [60]. This result indicates a reduction in the inward pinch of particles in the presence of an island. MHD simulations have been performed to investigate the peak densities immediately after pellet injections. The MHD Infrastructure for Plasma Simulation (MIPS) code [61] was used, which was extended to include the pellet ablation [62]. The difference in the increase in density between the cases with and without islands was found to be induced by the gradient of the electron temperature

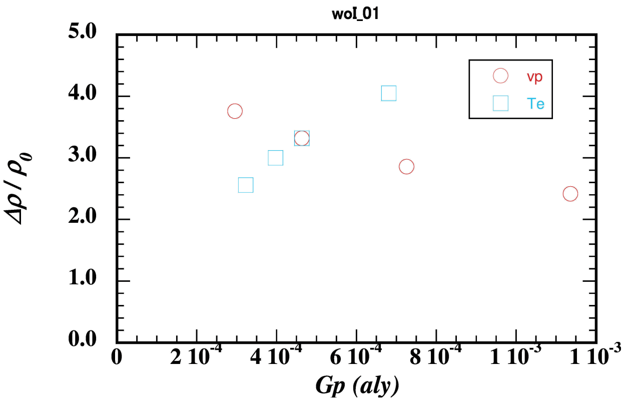

Fig. 6 The rate of increase of density $\Delta\rho/\rho_0$ as a function of the ablation rate G_p. From left to right, the squares indicate the electron temperatures in the bulk plasmas T_e = 1, 1.5, 2, and 4 keV and the circles indicate the injection speeds of the pellet v_p = 200, 500, 1000, and 2000 m/s.

driving the heat flux. Figure 6 shows the relation between the peak values of the ablation rate G_p and the rate of increase of density $\Delta\rho/\rho_0$ for different electron temperatures T_e in bulk plasma and the injection speeds v_p of the pellet. As T_e increases, there is an increase in G_p (because the pellet is exposed to a higher flux) and $\Delta\rho/\rho_0$. As a pellet with a higher v_p is injected deeper into the plasma and approaches the magnetic axis where the temperature is high, G_p increases. As the distribution of the density increase spreads in the direction of the major radius, the peak value of $\Delta\rho/\rho_0$ decreases. The ablation process for pellet injection into fusion plasmas is a typical multiphase physics phenomenon involving solid, liquid, gas, and plasma. To model this process, a simulation method will be developed by combining a solver for compressible and incompressible fluids [63] and the MIPS code.

3. Modeling for Simulation of a Complex Phenomenon

3.1 Purpose of and approaches in modeling

In this section, we provide an overview of the modeling methods for small-scale physics of turbulent phenomena described by partial differential equations (PDEs), such as the MHD, Hall-MHD, Navier-Stokes (NS), and Gross-Pitaevskii (GP) equations, including a discussion of microscopic and/or dissipative scales. Since it is difficult to provide a numerical resolution spanning a large scale to a small, microscopic or dissipative scale of turbulent phenomena simultaneously, we need to develop a methodology to reduce the size of numerical simulations and overcome the size and performance restrictions associated with using a supercomputer. In this case, we need to make our global simulation *smart*. Since only a limited number of scientists can access large-scale supercomputers, developing a methodology to reduce the size of a complex and global numerical simulation (a *smart global simulation*) will benefit numerous scientists without access to such computational resources.

The large-eddy simulation (LES) is an example of a previous attempt for overcoming the size and performance (resources) limitations of a supercomputer. In an LES, governing equations are low-pass filtered. Then the resulting grid-scale (GS) equations are solved together with a subgrid-scale (SGS) model, which is a phenomenological representation of influence of the SGS components on the GS components. (Further information on LES can be found in many textbooks, for example by Pope [64].) LES is used not only in hydrodynamic turbulence simulations but also in magnetohydrodynamic turbulence simulations [65]. We have developed an SGS model for Hall-MHD turbulence [66, 67] and have employed the SGS model for simulating the ballooning instability and turbulence in LHD, a heliotron-type nuclear fusion experimental device [68].

Although the LES approach successfully reduces computational size while reproducing the statistical nature of turbulence, the turbulence scaling range is generally narrow. Moreover, as a phenomenological model, an SGS model cannot reproduce dynamically correct behavior in GS. Thus the methodology should be further modified to incorporate the dynamical aspects of turbulence in SGS, which are clarified by means by DNS as in [69, 70], into GS.

Numerous numerical techniques can be employed to increase a numerical resolution that can be achieved using a supercomputer with limited capability. The compact finite difference (CFD) scheme is known to provide a higher resolution than the finite difference scheme [71]. Sixth-to-tenth-order CFD schemes have been employed in the simulations of the ballooning instability in LHD [72, 73]. A spectral-CFD hybrid scheme has been developed to exploit the high-resolution provided by CFD in turbulence simulations [74]. Another notable attempt of increasing numerical resolution is the use of the adaptive mesh refinement (AMR) method [75]. The AMR method has also been developed for simulating the Rayleigh-Taylor instability of MHD in plasma [76]. Despite these endeavors, traditional numerical techniques have not been sufficiently improved to overcome the limitations associated with a demand for high computational resources.

A few characteristics common to all turbulent phenomena should be considered in developing a novel methodology. As turbulence is characterized by a power-law scaling regime, self-similarity can be used to realize *smart* modeling. Dynamics at the dissipative and/or a microscopic scale can be reduced to a low-order dynamical system [77]. Next, we present studies and attempts on modeling performed in typical subjects.

3.2 Hierarchy of vortices in NS turbulence

The inertial subrange ($k^{-5/3}$ regime) in NS turbulence

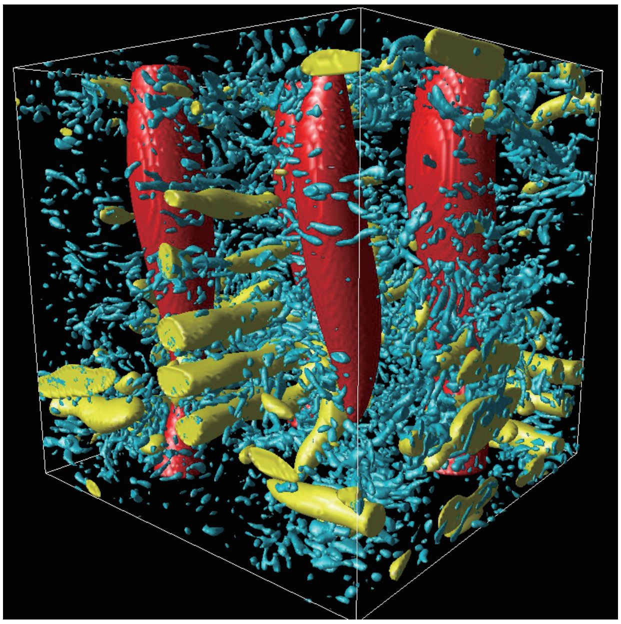

Fig. 7 Hierarchical vortex generation observed in the low-pass filtered enstrophy density.

covers an enormous 3D wavenumber space. Thus, effective modeling in this range is essential to realize a smart global simulation of NS turbulence. Fully-developed NS turbulence is often modeled as a collection of vortices with varying scales. Goto *et al.* [78] have reported a mechanism for generating a hierarchy of tubular vortices at each scale (Fig. 7). The mechanism involves the formation of antiparallel vortices at the k scale, subsequent formation of vortex sheets, and the generation of vortex tubes at the $2k$ scale. The authors have also shown that this hierarchy of vortices is closely related to limit-cycle-like behavior of turbulence generation, cascade, and dissipation (see Fig. 12 of Ref. [78]) and that their theory is applicable to wall turbulence as well [79, 80]. This understanding of turbulence provides important clues for modeling a wide range of inertial subrange of turbulence and for developing smart simulation models of NS as well as MHD turbulences.

3.3 Reduction to a low-dimensional dynamic system

In a dissipative PDE system, such as the NS and resistive MHD equations, a global attractor exists that can be expressed as a finite dimension (an independent mode) [77]. A trajectory of the dissipative system that approaches the global attractor exponentially can be modeled within the framework of the *inertial manifold*. This theory provides a basis for modeling PDEs as a low-dimensional dynamical system. Although the existence of the inertial manifold is difficult to prove strictly for the NS, MHD, Hall-MHD, or (hyper-diffusivity-imposed) GP equations, characteristics similar to those of an inertial manifold can be often found in numerical simulations.

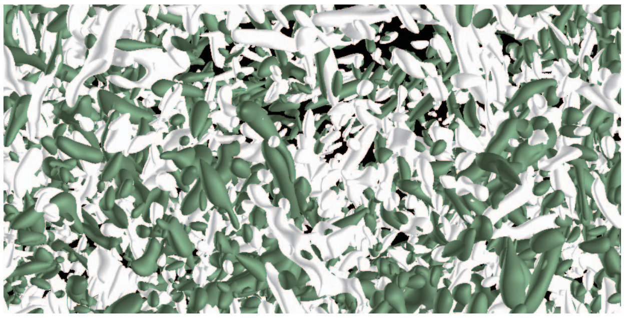

Fig. 8 Isosurface of the second invariants of the velocity gradient tensor (dark green) and the magnetic field gradient tensor (gray).

In a study based on the concept of the inertial manifold, machine learning was used to construct a low-dimensional system exhibiting turbulence in planar Couette flow at a low Reynolds number [81]. Recent improvements have made the machine learning algorithm more stable and efficient than the conventional algorithm [82]. This approach is expected to provide a connection between a model of the inertial subrange (self-similar hierarchy) regime and the dissipative/micro-physics regime.

3.4 Subion scale in Hall-MHD turbulence

Hall-MHD turbulence occurs over two scaling regimes, the MHD scale and the subion scale. While a self-similarity at the MHD scale has been studied extensively, a self-similarity at in the subion scale is not understood yet. An interaction between the MHD and subion scales is another subject to be studied more closely. Some influences of the subion scale on the MHD scale in Hall-MHD turbulence have been clarified by our earlier studies [83, 84]. Figure 8 shows coherent structures at the subion scale [83, 84].

One of the most severe numerical difficulties encountered in the Hall-MHD simulations is the need for high numerical resolution and a very small time-step width because of the occurrence of whistler waves and other dynamics at the subion scale. An SGS model at the subion scale has been developed to circumvent these difficulties [66, 67]. Though the SGS model performs as expected, we need to dynamically collect model data to realize *a smart simulation*. Furthermore, as discussed in the previous subsection, a method is needed to connect a model of sub-ion-scale physics to the MHD scale.

3.5 Quantum turbulence and quantum vortex

Quantum turbulence in superfluid liquid helium can be considered as the inviscid limit of NS turbulence. Quantum turbulence is also a key physical mechanism for understanding the heat transport properties of liquid helium used as a coolant for a superconducting device.

The same intrinsic difficulty is encountered in a GP

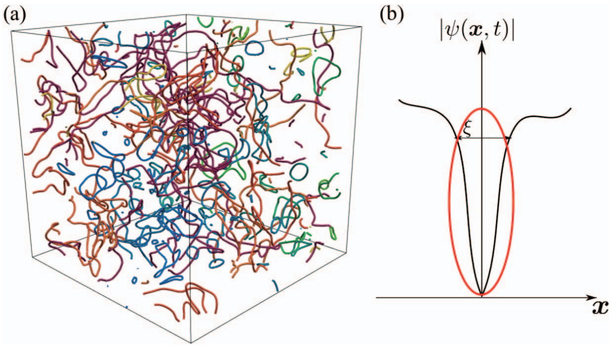

Fig. 9 (a) Vortex axes identified in a quantum turbulence simulation of the GP equation, and (b) the vortex core characterized by the healing length ξ from a vortex axis.

simulation on quantum vortex dynamics as in a Hall-MHD simulation: the wavenumber space consists of two scaling regimes, known as the strong turbulence (ST) and weak wave turbulence (WWT) regimes. The ST regime corresponds to the MHD scale and the WWT regime corresponds to the subion scale in Hall-MHD turbulence. Numerical simulations have been performed to study the scaling properties of the two regimes of GP turbulence [85,86]. However, the two scaling regimes in a GP turbulence simulation are limited for similar reasons as for Hall-MHD turbulence. This numerical difficulty could be considerably mitigated by developing a model of the WWT regime for a smart simulation.

An understanding of vortex dynamics is essential for studying heat transport properties in liquid helium. Figure 9 (a) presents the vortex axes, which are defined as $\psi(\mathbf{x}, t) = 0$, where ψ is a solution of the GP equation [87]. The region within the healing length ξ from the vortex axis (see Fig. 9 (b)) is called a vortex core. As the wavenumber regime $k > 1/\xi$ belongs to the WWT regime, a numerical model for the WWT regime should be developed so that the model can ease a stiffness of the GP equation without spoiling essential parts of quantum vortex dynamics. In other words, the WWT regime should be modeled along with the vortex dynamics.

3.6 Broader approaches for modeling

This study should be undertaken as a collaboration among researchers in many related research fields. The reduction of a PDE system to a low-dimensional dynamical system is closely related to approaches used in data science. The data science community is experienced in using various techniques for characterizing coherent structures and reduced-order modeling, such as proper orthogonal decomposition and dynamic mode decomposition (see Ref. [88], for example).

Data visualization is another research category that is relevant to the subject of this study. Kageyama *et al.* [89, 90] developed the four-dimensional street view (4DSV) to observe various complex phenomena, such as those shown in Figs. 7 and 8, from various angles, at various points in time and space, and by using various thresholds of isosurfaces.

A collaboration with the high-performance computing community is promising the enhancement of this study. For example, efficient numerical libraries, such as a 3D fast Fourier transform library [91] and a library to facilitate communication among computers of different architectures [92], are quite useful for numerical simulations discussed above.

4. Summary

Herein, we proposed a research plan for the Complex Global Simulation Unit along with the results of previous research studies. In addition, we propose the development of simulation methods for global simulation of multiple hierarchies as well as the validation and verification of the simulation in collaboration with experimental studies. We establish simulation problems based on original ideas with the aim of discovering novel phenomena to motivate and lead experimental research. Further, we promote interdisciplinary studies in collaboration with researchers in fields such as astrophysics, geophysics, turbulence, visualization, and computer science.

We will perform kinetic-MHD hybrid simulations to investigate important research topics related to burning plasmas, such as the interactions among energetic-particle-driven instabilities, zonal flows, and microturbulence, and alpha channeling, which enables energy transfer from energetic alpha particles to thermal ions through interactions with plasma waves. The interplay between MHD instabilities and microturbulence in edge plasmas will be also investigated. This simulation study will be performed for a nonequilibrium open system in which the steady production of alpha particles through fusion reaction and transport fluxes from the core to the edge plasma play key roles. The results may elucidate the physical process of edge pedestal formation. Furthermore, interdisciplinary studies will be conducted using kinetic-MHD hybrid simulations to investigate astrophysical problems, such as the interplay between cosmic rays and MHD waves and instabilities.

We consider that the development of our methodology enables simulations of high Reynolds number (i.e., small collisionality) turbulences to be performed at acceptable computational costs, maintaining the dynamics at small scales more effectively than other numerical approaches. Furthermore, the development is expected to enable the construction of a smart turbulence model through which turbulence simulations can be performed quickly with high predictability. The development is also expected to enhance our understanding of turbulence at wide separation scales relevant to plasma physics (the Hall-MHD equations for solar wind turbulence), fluid mechanics, atmospheric and oceanic sciences, and several engineering topics (NS equations for air, water, and several other fluid media), condensed matter physics (the GP equations for quantum fluids), and other turbulence phenomena described by a set of nonlinear PDEs.

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