3. Numerical Simulation Reactor Research Project

Numerical Simulations of MHD properties in LHD plasmas

Highlight

Numerical scheme for 3D global flow consistent with 1D experimental data and effects on MHD dynamics of interchange mode

We study the nonlinear interaction between the global flow and the interchange modes using three-dimensional (3D) numerical simulations. In the Large Helical Device (LHD) experiments, partial collapses of the electron temperature profile due to the interchange modes are observed in some discharges. In the collapses, the mode rotation stops during the mode growth and the nonlinear collapse [1]. The mode frequency is dominated by the background flow frequency [2]. Thus, we numerically analyze the effects of the flow on the nonlinear evolution of the interchange mode. For this purpose, we have developed a numerical scheme to calculate the flow profile consistent with the experimental data firstly. In LHD, one-dimensional radial profiles of the poloidal and toroidal components of the flow are observed only in the outer side of the torus [3]. By applying the scheme to the data, we can obtain the 3D profile of the global flow in the entire plasma region. Figure 1 shows the 3D profile of the stream lines corresponding to the experimental data. This figure indicates that the flow value in the inner side that is not observed experimentally is larger than that observed in the outer side. Then, the stabilizing effects of the flow on the MHD dynamics is studied with the MIPS code [5]. In the present study we utilize a static and strongly unstable equilibrium calculated by the HINT code [6]. The global flow is incorporated in the initial perturbation. As the results, in the change of the absolute value of the flow, the flow stabilizes the interchange mode weakly up to a certain value, while destabilizes the plasma beyond the value through the excitation of the Kelvin-Helmholtz instability. This tendency is similar to the electro-static g-mode theory [7].

[1] S. Sakakibara, *et al.*, 2015 Nuclear Fusion, **55** 083020.
[2] Y. Takemura, *et al.*, 2013, Plasma and Fusion Res. **8**, 1402123.
[3] M. Yoshinuma, *et al.*, Fusion Sci. Tech., **58** (2010), 103.
[4] K. Ichiguchi *et al.*, Proc. IAEA FEC 2016 Kyoto, TH/P1-4.
[5] Y. Suzuki, *et al.*, 2006 Nucl. Fusion, **46** L19.
[6] Y. Todo, *et al.*, 2010 Plasma and Fusion Res. **5** S2062.
[7] H. Sugama, *et al.*, Phys. Fluids, **B3**, 1110 (1991).

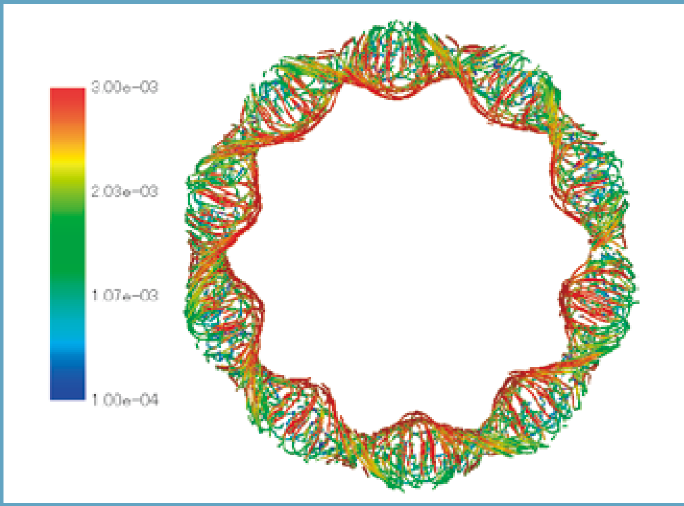

Fig. 1 3D profile of the stream lines of the global flow corresponding to the 1D experimental data.

Magnetic island generation mechanism in a resistive interchange mode

The magnetic island generation mechanism in a resistive interchange mode has been numerically investigated based on a two-fluid model [1]. It is found that one of the mechanisms is the nonlinear generation of a tearing parity mode due to a modulational parity instability. The formation of magnetic islands can be linked to the parity of the mode. The interchange mode has two types of parity modes, interchange and tearing parity modes. The electrostatic potential of the former and the latter modes are even and odd functions of the local radial coordinate around the mode resonance surface, respectively. The formation of the magnetic islands is represented by the appearance of the tearing parity mode. Figure 2(a) shows the time evolution of the kinetic energy of both parities of the n=1 mode where n is the mode number. Since the nonlinear mode coupling is weak at the beginning, the amplitude of the interchange parity mode with n=1 is significantly larger than that of the tearing parity mode in the initial nonlinear saturated state. However, the initial saturated state is unstable against the modulational parity instability. Then, the amplitude of the tearing parity mode with n =1 grows and becomes comparable to that of the interchange parity mode and a large magnetic island is formed as shown in Fig. 2(b).

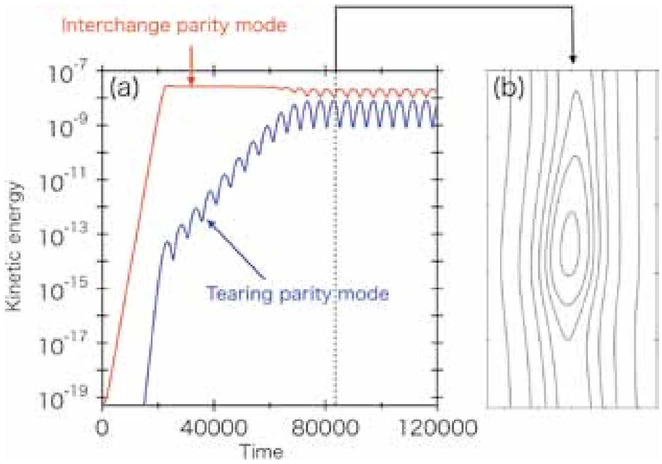

Fig. 2 (a) Time evolution of kinetic energies of both parities of the n=1 mode and (b) magnetic flux surfaces at the final saturated state.

[1] M. Sato and A. Ishizawa, 2017 Phys. Plasmas, **24** 082501.

MHD simulation on pellet injection in the LHD plasma with an m/n=1/1 island

In order to investigate the behaviors of the pellet plasmoids in the LHD plasmas with and without an m/n=1/1 island, we have performed MHD simulations with the extended CAP code [1]. As shown in Fig. 3, it is found that the peak position of the plasmoid density in the plasma with the island is located at more outboard side than that in the plasma without islands. The maximum density of the plasmoid within the island is greater than that without islands. On the other hand, the plasmoid density in the plasma with the island in the region between the magnetic axis and the island is less than that in the plasma without islands in the corresponding region. These results qualitatively agree with the rapid increments of the density in the experimental data [2]. The elongation of the plasmoid along the field line in the plasma with the island is also found to be inhibited as compared with that in the plasma without islands.

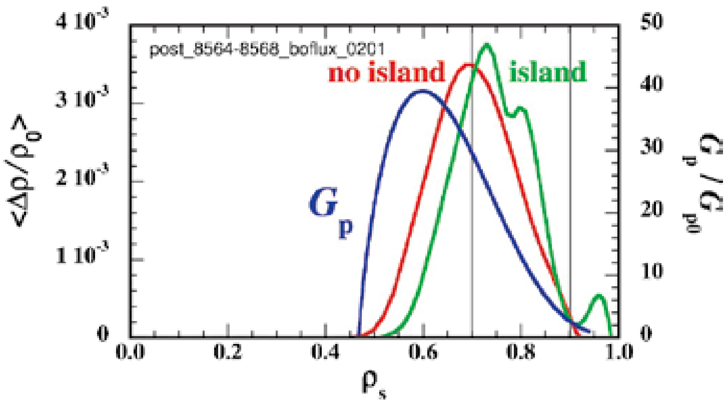

Fig. 3 Normalized plasmoid densities averaged on the flux surface <Δρ/ρ0> as a function of the minor radius ρs with the Boozer coordinate. The red and the green lines indicate those plasmoid densities in the plasmas without and with the islands, respectively. The blue line indicates the normalized ablation rate Gp/Gp0.

[1] R. Ishizaki, *et al.*, Plasma Phys. Control. Fusion **53**, 054009 (2011).
[2] T. E. Evans, *et al.*, EX/1-3, 25th IAEA Fusion Energy Conference (2014).

3D upgrade of global full-f kinetic simulations for 3D plasmas

Highlight

A global gyrokinetic toroidal 5D full-f Eulerian code, GT5D, is now upgraded to incorporate general 3D helical plasmas

The world's first global full-f kinetic simulations for helical plasmas

Predicting and improving the confinement performance determined by the particle/energy transport in magnetically confined plasmas has been a central issue for the fusion research activities. To this end, much effort has been devoted to understand the physical mechanisms on the transport processes and profile formations. A global full-f gyrokinetic simulation based on the first principle is regarded as one of the most promising tools for the whole plasma modeling, since it can predict a steady state of a plasma which is realized as a consequence of the self-consistent interaction among the turbulent/collisional transport, the time-developing plasma profile, and heat/particle sources. Despite the great advantages, however, the global full-f gyrokinetic simulations have been exclusively applied to axisymmetric tokamak plasmas, and no applications to three-dimensional helical/stellarator plasmas have been reported due to their complicated magnetic field structures.

Recently, a global full-f gyrokinetic simulation code, GT5D, which was originally developed for the transport studies of tokamak plasmas, has been upgraded to incorporate general three-dimensional magnetic field equilibria. To guarantee the numerical conservation of the particle and energy is essentially important. In addition, the pole singularity at the magnetic axis should be avoided. To overcome the issue, a novel coordinate system, in which the poloidal symmetry with respect to the axis holds, is proposed and the conservative non-dissipative finite difference scheme is applied on this coordinate system. For the numerical verification of the 3D extension of GT5D, a series of benchmarks on the neoclassical transport, the ambipolar radial electric field and the zonal flow damping in a typical LHD plasma are performed; good agreements with an existing simulation and a theory are confirmed, respectively.

GT5D for 3D helical plasmas have been developed based on a collaboration with Japan Atomic Energy Agency. Detailed descriptions of GT5D can be found in [1]. Further development of the code for the turbulence, impurity transport, and so on is being actively continued. Experimental analyses have been also initiated.

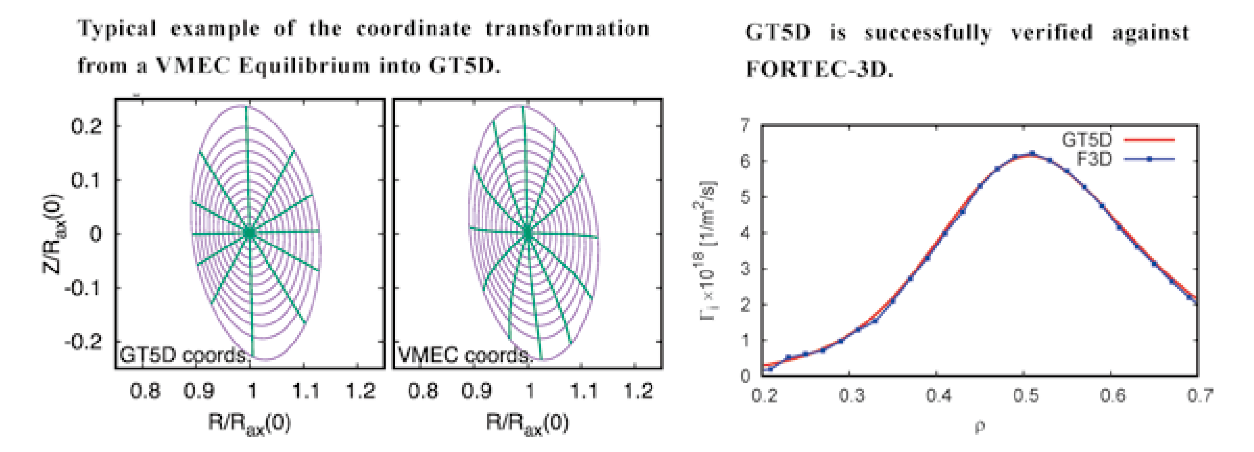

Fig. 1 Coordinate system and the numerical verification of the neoclassical transport in GT5D [1].

Multiple time-scale global transport simulations based on direct-coupling approach with gyrokinetic and transport solvers

Time-dependent global transport simulation is a powerful approach to predict the dynamic evolution of plasma profiles, the confinement performance, and the fusion power in future burning plasmas. To this end, a new global transport solver TRESS+GKV [2] has been developed by the collaborations with National Institutes for Quantum and Radiological Science and Technology. The dynamical transport problems with both the neoclassical and turbulent transport processes are solved by the direct coupling between the multiple fluxtube gyrokinetic simulations by GKV and macroscopic 1-D radial heat transport simulation by TRESS/GOTRESS (the left figure). The effects of realistic tokamak magnetic geometry, kinetic electrons, and multiple ion species are incorporated. Currently, the neoclassical and turbulent heat fluxes are calculated by using the matrix inversion method and the quasilinear approximation, respectively. Under the realistic heating conditions, the time evolutions of the ion and electron temperature profiles towards a power balanced steady state are simultaneously solved. Several acceleration methods, e.g., the adaptive source/sink and the Newton iteration, and the genetic algorithm [3] are implemented to perform global ITG-TEM driven turbulent transport simulations with less numerical costs.

Reduced transport model for ion heat diffusivity by gyro-kinetic analysis with kinetic electron response

A high ion temperature plasma in the Large Helical Device is examined in the case in which the ion temperature gradient mode is unstable. The nonlinear gyro-kinetic simulation is performed to evaluate the turbulent ion heat diffusivity with the kinetic electron response. To reduce the computational cost for applying to the dynamical transport simulation, an extended transport model for the ion heat diffusivity in terms of the mixing length estimate and the characteristic quantity for the linear response of zonal flows is proposed. The values for the ion heat diffusivity of the nonlinear gyro-kinetic results are compared with those for the reduced model by the linear simulation with the circles in the right figure [4]. The use of the linear simulation results enables us to reproduce the nonlinear simulation results by the reduced model. The decay of zonal flows with the kinetic electron becomes faster. The decay time of zonal flows is found to decrease radially outward and the ion energy transport increases outward due to the trapped electron.

[1] S. Matsuoka, Y. Idomura, and S. Satake, Phys. Plasmas **25** (2018) 022510.
[2] M. Nakata, M. Honda, and M. Nunami, Plasma Conference 2017, Himeji (2017).
[3] M. Honda, Comput. Phys. Commun., in press (2018).
[4] S. Toda, M. Nakata, M. Nunami, A. Ishizawa, T.-H. Watanabe, and H. Sugama, Plasma Fusion Res., **12** (2017) 1303035.

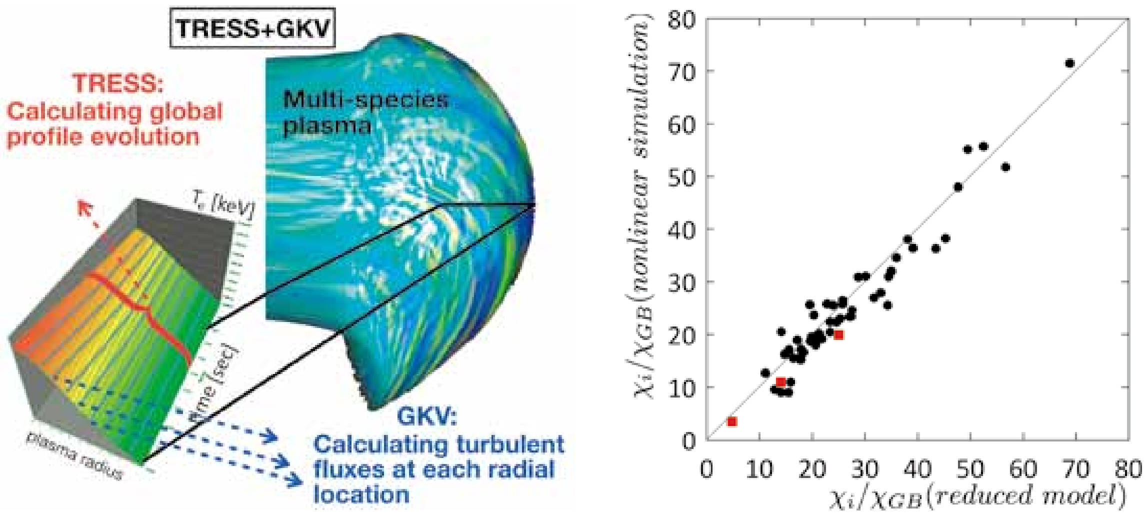

Fig. 2 Left: Joint framework in TRESS+GKV. Multiple local turbulent transport calculations by GKV directly couple to the 1-D global transport solver TRESS.
Right: The comparison of the nonlinear simulation results for the ion heat diffusivity with the reduced model.

Impurity transport in peripheral plasma

Highlight

Three-dimensional impurity transport modeling of neon-seeded and nitrogen-seeded LHD plasmas

Understanding the impurity transport in the peripheral plasma is an important issue to design the future fusion reactor, because the plasma is detached from the divertor by the radiation of the impurity. In this group, the transport in the peripheral plasma, which includes the impurity and neutral, is studied by three-dimensional kinetic and fluid codes on the supercomputer “Plasma Simulator”.

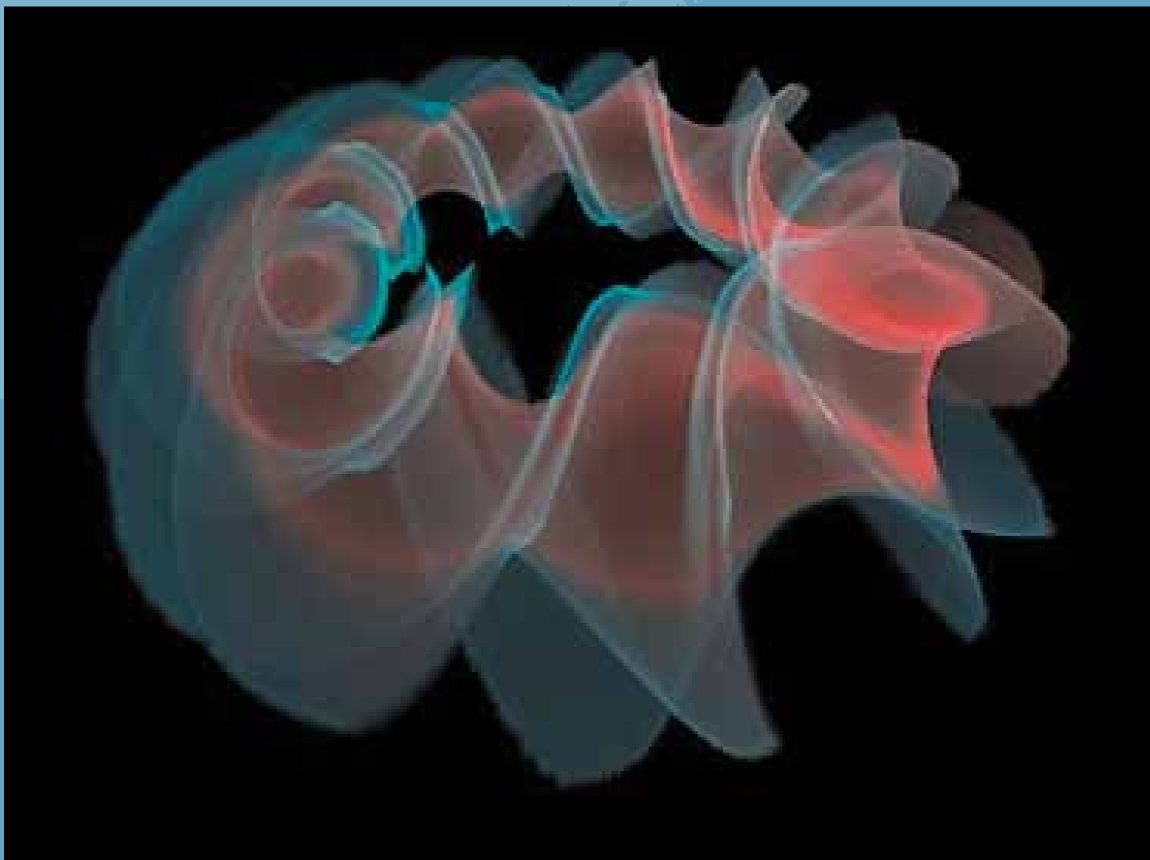

Fig. 1 Impurity radiation simulated by EMC3-EIRENE code.

Prediction of a plasma is essential for a reactor design to ensure safety margins to engineering limits and good controllability of discharges. Increase of core performance, enlargement of device size, and extension of discharge time lead to severe engineering issues such as high heat load on the plasma facing components statically or dynamically and accumulation of impurities and hydrogen isotopes on wall surfaces. These issues are closely linked to divertor plasma transport and, therefore, its modeling is strongly required to estimate the plasma parameters and the influence upon components surrounding the plasma. In particular, for the heat load issue, application of impurity radiation, optimization of divertor structure, and plasma detachment are the major topics.

Divertor plasma modeling of fusion devices is studied with calculation codes solving fluid equations of plasma along magnetic field lines with cross-field diffusive terms and kinetic equations of neutral particles. Codes for tokamak devices assume axisymmetry but plasmas with Resonant Magnetic Perturbations (RMP) in tokamak devices and plasmas in helical devices require a three dimensional calculation code. EMC3-EIRENE code is a three dimensional Monte Carlo code extensively applied to fusion devices with non-axisymmetric components. Fluid transport equations along magnetic field with perpendicular diffusive transport are solved by EMC3 code, and kinetic equations with atomic and molecular processes are solved by EIRENE code. Recently, impurity seeding experiments with gas puffing have been conducted with different gas species, such as neon, argon, krypton, xenon, and nitrogen. From an experimental analysis, toroidally symmetric/asymmetric distributions of particle flux on divertor plates and differences of transport characteristics of neon and nitrogen were revealed in LHD. A helical plasma intrinsically has a toroidal asymmetry, however usually it has a toroidal periodicity due to repeated toroidal structures of magnetic field coils. A toroidal symmetry in this work represents the periodicity, and a toroidal asymmetry represents violation of the periodicity. In this work, we present a modeling study of impurity-seeded plasma with EMC3-EIRENE code to reproduce the toroidal symmetric/asymmetric characteristics. Also, validation of the model with experimental measurements and open questions suggested from differences between model results and experimental measurements are addressed.

Figure 2 shows toroidal distributions of the particle flux on divertor plates. Bold lines indicate predicted results by EMC-EIRENE code and symbols of cross and circle indicate measured results in experiments. For the neo seeding case, the distribution is toroidally symmetric but for the nitrogen seeding case, the distribution is toroidally asymmetric. EMC3-EIRENE results well reproduce experimental observations. That means the prediction of EMC3-EIRENE code is well validated by the LHD experiment.

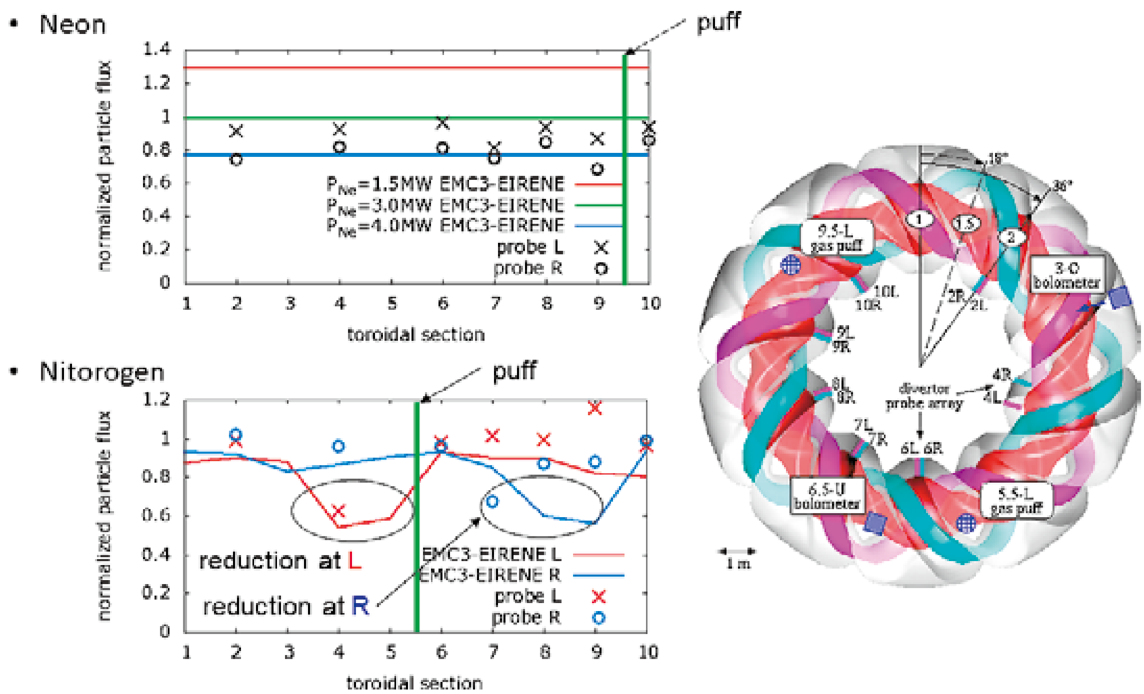

Fig. 2 Configurations of the puffing nozzles, the bolometer systems, and the divertor probe arrays in the LHD and the toroidal flux distribution of hydrogen ions for neon and nitrogen seeding cases.

Ion heating mechanism in magnetic reconnection

Highlight

Ion heating mechanism in magnetic reconnection is clarified by using our particle simulation model “PASMO”

For realization of fusion devices, high-temperature plasmas need to be produced. In a different type of device from the Large Helical Device (LHD), a spherical tokamak, two plasmas with low temperature are merged into a single plasma with high temperature. In this process, magnetic reconnection occurs, through which plasmas are heated. The comprehension of the heating mechanism can lead to the production of higher-temperature plasmas.

We investigate plasma heating processes during magnetic reconnection by using our particle simulation code “PASMO.” Figure 1 (a) shows the spatial profile of the ion temperature in the simulation region. The ion temperature is high in the downstream of the magnetic reconnection point, and this result is consistent with results of plasma merging experiments in spherical tokamaks. Our simulations further demonstrate ion velocity distributions by assembling velocities of individual ion particles. Figure 1 (b) is an ion velocity distribution in the low-temperature region, where a mountain shape, i.e., a Maxwellian distribution is seen. Figure 1 (c) is an ion velocity distribution in the high-temperature region, where we can see that a caldera-shape structure is formed. By investigating the formation process of the caldera-shape structure, we successfully clarify the detailed mechanism of the ion heating.

This work has been published in Physics of Plasmas [1].

[1] S. Usami, R. Horiuchi, and H. Ohtani, Phys. Plasmas **24**, 092101 (2017).

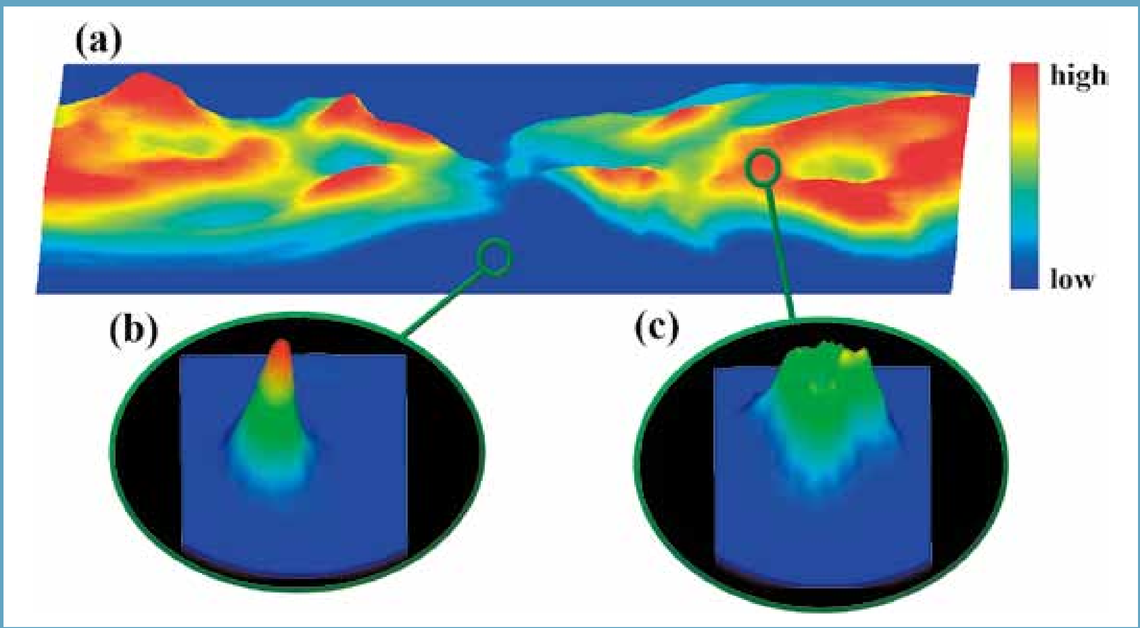

Fig. 1 PASMO simulation of magnetic reconnection. (a) Ion temperature in the magnetic reconnection surface. (b) Ion velocity distribution in the low-temperature region. (c) Ion velocity distribution in the high-temperature region.

Blob/hole dynamics study by the p3bd code

In the Multi-Hierarchy Physics Research Group, the three-dimensional (3D) electrostatic particle-in-cell (PIC) simulation code, called "p3bd" (**p**article-in-cell **3**-dimensional simulation code for **b**oun**d**ary layer plasma dynamics), for the study of blob and hole propagation dynamics has been developed, where the blob and the hole are the intermittent filamentary coherent structures observed in the boundary layer plasmas of various magnetic confinement devices. In order to verify the p3bd code, the relations between the radial propagation speed of coherent structures and the structure poloidal size, which are observed in the p3bd simulations, have been compared with the theoretical relations. As a result, it has been shown that the observed relations are in good agreement with the theoretical relations. Furthermore, the code has reproduced a larger distortion of a hole shape than that of a blob shape (Fig. 2), which arises from the larger propagation velocity shear, and has shown that the propagation of a blob or a hole becomes faster in the situation without end plates, which is similar to the detached state.

This work has been published in Plasma and Fusion Research [2].

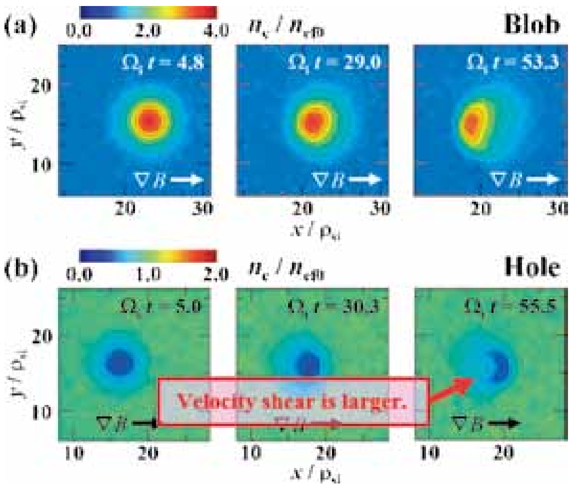

Fig. 2 Time evolutions of the electron density distribution on the poloidal cross-section in the blob (a) and hole (b) propagations. This figure appeared on the front cover of Journal of Plasma and Fusion Research Vol. 93, No. 12 and the top page of the Plasma and Fusion Research website.

[2] H. Hasegawa and S. Ishiguro, Plasma and Fusion Research **12**, 1401044 (2017).

Two-fluid tearing mode instability in cylindrical geometry

The two-fluid resistive tearing mode instability in a periodic plasma cylinder of finite aspect ratio was investigated analytically and numerically [3, 4]. The cylindrical dispersion relation was derived for general cases of the cylindrical aspect ratio and two-fluid effects. It shows that the non-zero real frequency of the mode arises due to the combination of two-fluid and cylindrical effects. Scaling laws for the growth rate and the real frequency of the mode with respect to the resistivity and ion skin depth, scale length of the two-fluid effect, were derived from the analytic dispersion relation in both limits of small and large ion skin depths. The real and imaginary parts of the mode growth rate become comparable for parameters such that the cylindrical aspect ratio and two-fluid effects are of order unity (Fig. 3). The numerically obtained eigenvalues agree very well with the analytic dispersion relation and the agreement improves the smaller the resistivity and the larger the ion skin depth are. Comparison between the numerical eigenfunctions and the inner solutions of the boundary layer theory shows that the eigenfunctions develop imaginary parts within the resonant layer, also due to the combination of two-fluid and cylindrical effects.

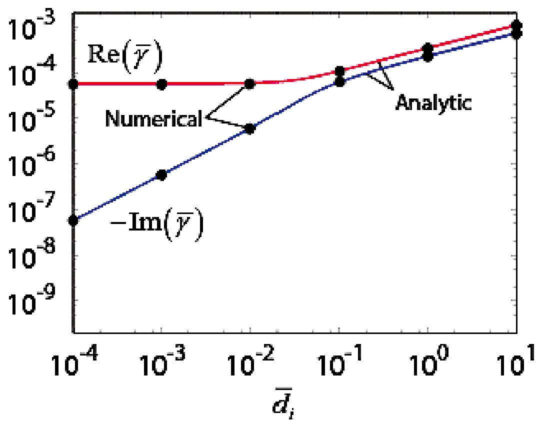

Fig. 3 Growth rates and real frequencies as functions of the ion skin depth obtained numerically from the eigenmode equations (points) compared with the analytic dispersion relation (lines).

[3] A. Ito and J. J. Ramos, Phys. Plasmas **24**, 072102 (2017).
[4] A. Ito and J. J. Ramos, Phys. Plasmas **25**, 012117 (2018).

3. Numerical Simulation Reactor Research Project

Construction of helical model reactor in virtual-reality space

Highlight

Virtual-reality technology is applied to the reactor design research: reactor design CAD data with robot arm system is visualized, the movement of the system can be confirmed, and the virtual hand grasps the component of the reactor.

It is important to design a reactor while considering previously how to assemble the components, because it will be possible to build up the reactor efficiently. Additionally, it is also significant to consider how to detach the components, such as blanket structure and divertor plate, in the reactor, how to move them through the reactor along toroidal direction, and how to pass them through the small port by moving and rotating them without collisions with the other components. The fusion reactor is designed to replace the components periodically in the fusion operation, and it is necessary to give consideration to the replacement process in advance. In the ITER project, the processes of assembling and exchanging the components are investigated by using CAD software, and the robotics system is studied for remote manipulation. However, it is expected that the handling will become difficult. Presently, NIFS is researching and designing the new concept reactor, that is, a cartridge-type reactor which does not require such complex movement of the components in the reactor in the replacement process. In this cartridge-type reactor, the robotics system for assembling and detaching the components from outside the reactor is investigated by using CAD software. However, it is not easy to determine how to move and rotate the components on the 2D monitor by using CAD software because the information regarding depth is lost. By motion parallax, a human being can also perceive the depth, for example, when the object is rotating. But it would be difficult to confirm the collision between the components and the movement of the component by the robot arm during their rotation.

Because the virtual-reality (VR) system gives a viewer deep immersiveness into the three-dimensional (3D) space by the stereo-viewer system, tracking system, and other methods, the viewer can watch the visual objectives before the viewer's very eyes in the real-scale VR world.

Our CAVE-type VR system "CompleXcope" visualizes the CAD data by VirDSE of Asahi Electronics. In this system, the viewer can come into the reactor and confirm the design [1]. It is also possible to measure the distance between the positions which the viewer indicates by Wand. The viewer can watch the movement of the components as animated graphics in the VR space. The viewer can also grasp the component by his virtual hand in the VR space, which moves corresponding to the real hand movement. In Fig. 1, the viewer watches the robot arm system, and grasps one component by his virtual hand. By using this system, the viewer can also perform collision detection when assembling. When the components collide with each other, the component struck is highlighted.

VR technology is also powerful for design of the reactor, and examination of the maintenance operation. We believe that the progress shown in this paper will enhance research in fusion plasmas and fusion engineering.

Fig. 1 Virtual-reality visualization of cartridge-type helical reactor CAD data. Left figure shows the reactor design data with robot-arm system, and right figure displays that one component is grasped by the virtual hand.

Analysis of periodic nanostructure formation mechanism by particle simulation

It was found in many experiments that repeated irradiations of short pulse lasers could form periodic nanostructures on metal surfaces, but its formation mechanism is not fully understood yet. We use 2D PIC simulations to investigate the formation mechanism. If the laser is relativistic intensity, the Weibel instability plays an important role to form the periodic nanostructure [2]. On the other hand, standing wave of surface plasma waves and oscillating two-stream instability can form the periodic nanostructure in the case of non-relativistic laser intensity [3]. Typical simulation results are shown in Fig. 2.

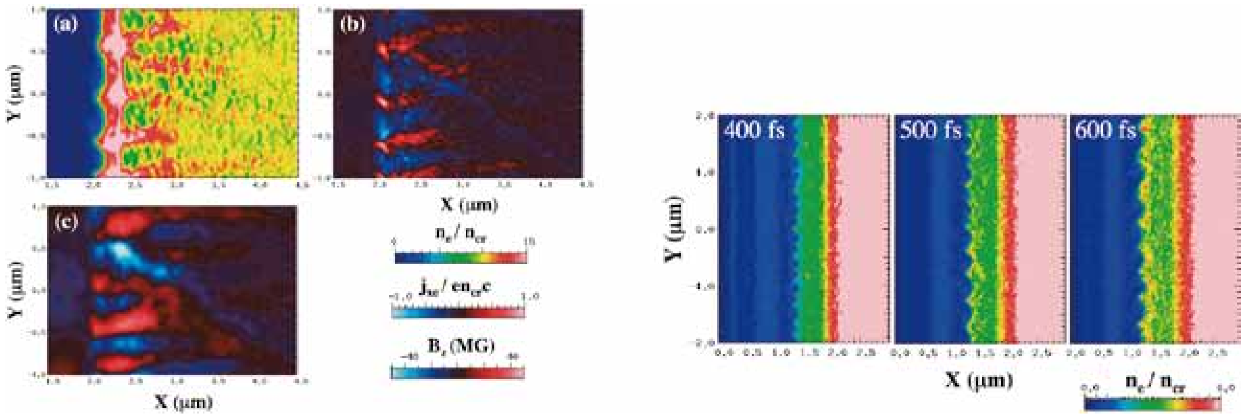

Fig. 2 Left: Weibel structure in the case of relativistic laser intensity at t = 250 fs. (a) electron density, (b) electron current density in X direction and (c) magnetic field in Z direction.
Right: Time evolution of electron density profile in the case of non-relativistic laser intensity.

Performance evaluation of three-dimensional fluid code written by XcalableMP

In order to adapt the parallel computer from a special kind of machines to general convenient tools for computational scientists, a high-level and easy-to-use portable parallel programming paradigm is mandatory. XcalableMP (XMP) [4], which is proposed by the XMP Specification Working Group, is directive-based language extensions to easily describe parallelization in programs for distributed memory parallel computers. IMPACT-3D is a three-dimensional Eulerian fluid code which performs compressible and inviscid fluid computation. We used XMP to parallelize the code, and measured its performance on the K computer. We found that programs converted by the XMP/F compiler prevent some optimizations by the native Fortran compiler and show lower performance than that by hand-coded MPI programs. Finally, almost the same performance is obtained by using specific compiler options for the native Fortran compiler [5].

In addition to the studies mentioned above, (1) application of dynamical load balancing library "OhHelp" to electromagnetic particle simulation code "PASMO" by H. Ohtani *et al.*, and (2) coding method for advancing of SIMD and pipeline in particle simulation code by S. Satake *et al.*

[1] H. Ohtani and S. Ishiguro, Proc. 36th JSST Annual International Conference on Simulation and Technology, 194 (2017).
[2] A. M. Gouda, H. Sakagami, T. Ogata, M. Hashida, and S. Sakabe, Appl. Phys. A, **122**, 454 (2016).
[3] A. M. Gouda, H. Sakagami, T. Ogata, M. Hashida, and S. Sakabe, Plasma Fusion Res., **11**, 2401071 (2016).
[4] XcalableMP, http://www.xcalablemp.org/.
[5] H. Sakagami and H. Murai, Proc. of the 30th International Supercomputing Conference, Frankfurt, Germany, July 12-16, (2015).

(S. Sugama)