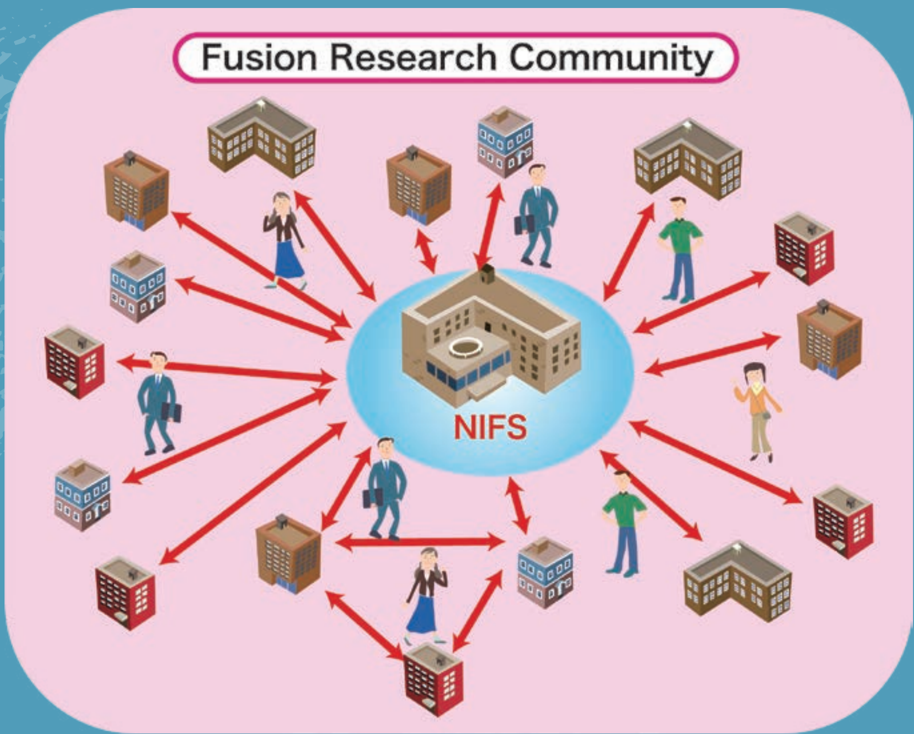
2. General Collaboration Research

General Collaboration Research is a system for collaborators to carry out their research by using the facilities or the resources of NIFS, including experimental devices, diagnostics, a supercomputer, databases, and other resources. Because nuclear fusion includes a wide research area in physics and technology, from fundamental research to application, General Collaboration Research is composed of a variety of -categories, Network-type Research, Interdisciplinary Fusion Science Research, Fusion Plasma Science Research, Fusion Technology Research, Plasma Simulator Collaboration Resarch, and Workshop. In FY2023, 366 research projects were conducted as General Collaboration Research.

In General Collaboration Research, the collaborators come to NIFS and carry out research. However, if it is necessary, NIFS staff can go to the university of a collaborator to perform joint research there. Since a graduate student can be a collaborator, it is useful for training young researchers. Furthermore, in the Network-type Research category, the collaborators may conduct experiments at other universities involved in a particular project.

(Y. Todo)


Fusion Research Community
NIFS

Network-Type Collaboration Research

Eligible research is that for study conducted by collaborating with facilities owned by NIFS and multiple universities. In this fiscal year, the research shown below was done. The titles and brief summaries of the research topics are listed below.

Study on the concentration and behavior of tritium, radon, and radium in environmental water in Japan

For an environmental impact assessment of nuclear fusion reactors, it is important to understand the characteristics of tritiated water in nature. The water has some geochemical features: the latitude effect, seasonal variation, air mass effect, etc. Thus, wide-area and long-term environmental monitoring are required to make this clear. In this research, we have established an observation network with universities in Japan and carried out long-term observation of tritium (half-life: 12.3 years) in precipitation from Okinawa to Sapporo, Japan, and radon (half-life: 3.8 days) in a hot spring at Oshamanbe, Hokkaido as an environmental tracer. For environmental tritium monitoring, monthly precipitation was collected at 11 sites in Japan. The sample water was analyzed by the liquid scintillation counting (LSC) method after pretreatment of it. The radon samples were collected quarterly (March, June, September, and December) and measured by the LSC method within several hours. Measurements of tritium concentrations in precipitation indicated latitudinal effects, seasonal variations, and the influence of air masses. Located in the Far East, Japan is subject to seasonal variations caused by continental and oceanic influences. Tritium produced in the upper atmosphere also exhibits seasonal variations and latitudinal effects, due to mixing between the troposphere and stratosphere as geochemistry. Wide-area and long-term observations have enabled identification of the characteristics of environmental tritium. On the other hand, the behavior of shallow water migrating from precipitation to the subsurface was inferred from seasonal variations in radon observations. Many students and young researchers joined this study, and through monitoring activities, they learned environmental radioactivity measurement and had opportunities to be introduced to a variety of environmental research and fusion development through research seminars. The promotion of collaborative research has also led to the development of young future talent.

(T. Sanada, Hokkaido University)

Comprehensive study of hydrogen isotope behavior in plasma-facing walls for fusion reactors through inter-university collaboration

Based on numerous fundamental studies conducted to understand the behavior of hydrogen isotopes in fusion reactor materials, in-vessel tritium behavior in DEMO can be predicted through systematic experiments using different scale devices, such as small-scale linear plasma devices, large-scale magnetically confined plasma devices, and analytical instruments owned by various universities. In this study, similarly characterized W and W-10% Re alloy samples were shared with universities, where various experiments were conducted, particularly focusing on understanding the irradiation effects on hydrogen isotope behavior in these materials. The physical constants related to hydrogen isotope behavior clarified in this study will contribute to research efforts on JT-60SA and ITER, as well as to the design of the DEMO reactor.

(Y. Oya, Shizuoka University)

New developments in CT-derived technologies for space and planetary magnetospheric plasma science

In research on compact-torus (CT) plasmas "spheromaks (Spk) and field-reversed configurations (FRC)", characteristics such as high density, high beta and transportability/mobility have been utilized for applications to plasma collision, merging, injection and irradiation. A NIFS network-type collaboration project aims to develop interdisciplinary researches based on knowledge of CT-derived technologies; the planetary magnetosphere, collisionless shock waves, space thrusters, and so on. The experimental and theoretical research network has been built by connecting the following six universities, the University of Tokyo, Nihon University, University of Hyogo, University of Toyama, Chubu University, and Gunma University, with NIFS, which has technologies and knowledge related to plasma and nuclear fusion. In this fiscal year, the project focused on improving and developing equipment for experimental research on aurora simulation in the planetary magnetosphere (Univ. Tokyo, Univ. Hyogo, and NIFS), space thruster development (Chubu Univ. and Univ. Hyogo) and collisionless shock waves (Nihon Univ and Univ. Toyama), Also researched was magnetic reconnection (Univ. Tokyo) and wave propagation in FRC (Gunma Univ.). On the FAT-CM device, the equipment was modified to enhance experimental parameters for collisional merging of FRCs, and then the operating conditions of density, ion temperature, and relative velocity during collisions were successfully expanded.

(N. Fukumoto, University of Hyogo)

Active measurement of MHD instabilities and its related MHD studies in magnetized torus plasmas

The aim of this study is to develop an active measurement method of magnetohydrodynamic (MHD) instabilities in magnetized torus plasmas, as in tokamaks, helicals, and reversed-field pinches (RFPs), and to confirm their capabilities. Here it should be noted that the active measurement method means to predict an occurrence of MHD instabilities before they occur. We are considering a system to know an indication of MHD instabilities by imposing external resonant magnetic perturbation (RMP) and detecting the response from plasmas. Now we shall apply this method to predict tearing MHD instability by using a small tokamak device, HYBTOK-II, which belongs to the Ohno laboratory in Nagoya University. In the HYBTOK-II, the shape of a plasma cross-section is almost circular, and it is limited by metal. The major and minor radius are 40 cm and 11 cm, respectively. The four loop antennas are installed in the vacuum chamber, and induce the RMP; the main component is $m/n = 1/1$, but those of $m/n = 2/1$ and 3/1 are fairly large. Now we are investigating the magnetic field response on the RMP by using magnetic probes inside and outside the vacuum chamber before and after the tearing instabilities with $m/n = 3/1$ and 2/1 occur. As the result, in the first year of the three-year plan, the magnetic field response on imposed RMP (change of amplitude) was observed before and after the $m/n = 2/1$ tearing instability. On the contrary, it was not observed for $m/n = 3/1$ mode. As a next step, we will investigate the magnetic field response before and after the tearing instabilities occur.

(M. Okamoto, National Institute of Technology, Ishikawa College)

Interdisciplinary Fusion Science Research

As one of the NIFS collaboration categories, interdisciplinary fusion science research has been done since FY2022. This category covers research that expands the knowledge, research methods, simulations, and equipment developed in fusion research to other fields, as well as research that will be the seeds for future fusion-related activities. In addition, research in the fields of sociology and informatics, such as the relationship between fusion and society and archives, is also eligible. Research in the field of astronomy, etc., using data obtained by the LHD, and research on social structural changes when nuclear fusion is realized fall into this category. In FY2023 100 collaborative programs were carried out in various fields, such as atomic physics, astrophysics, informatics, laser development, space propulsion, negative ion sources, environmental isotopes, plasma-material interaction, plasma-biology, agriculture, historical studies, science education, etc. Among them, three topics are introduced here.

(I. Murakami)

Laser-induced fluorescence Doppler spectroscopy using an asymmetric optical vortex

As a new method to measure plasma flow velocity, laser-induced fluorescence (LIF) Doppler spectroscopy using an optical vortex beam with asymmetric intensity distribution (see Fig. 1), referred to as aOVLIF, is proposed [1]. The aOVLIF method can measure the velocity vectors of ions and neutrals in plasmas, including the component perpendicular to the optical path. Figure 1 shows the numerically obtained LIF spectrum in the aOVLIF method, in which only the ion flow transversing the beam at 5 km/s is assumed. The aOVLIF method can also be applied to the determination of three-dimensional flow velocity vectors, and promises to enhance the usefulness of conventional LIF spectroscopy, using plane waves.

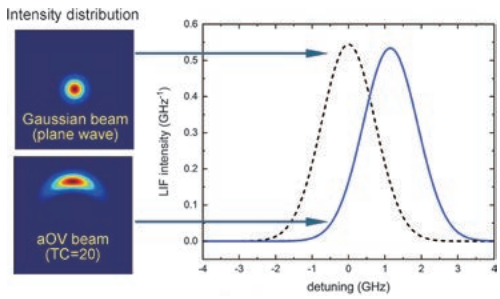


Fig. 1 Beam intensity distributions and numerically obtained LIF spectra in each beam. The figure was made with the data presented in Ref. [1].

A proof-of-principle experiment has been conducted in the HYPER-I device at the National Institute for Fusion Science. It is confirmed that the higher-order asymmetric optical vortex beams have been successfully produced with a spatial light modulator. The principle of the aOVLIF method will be demonstrated in the HYPER-I device.

(K. Terasaka, Sojo Univ.)

Data-driven modal analysis of nonlinear processes of plasma turbulence

Transport of particles and energy in magnetically confined plasmas is dominated by the interaction between turbulence and turbulence driven structures, such as zonal flows and streamers etc. Since such turbulent flows generally have large degrees of freedom, it is difficult to understand their nonlinear fundamental processes. Therefore, this study focuses on singular value decomposition (SVD) and proposes a method to reduce the number of degrees of freedom. In this method, common basis functions are derived for different physical quantities by simultaneous singular value decomposition of multiple physical quantities. Since the obtained basis functions have orthogonality, it is possible to define each mode energy, and it is also possible to evaluate energy transfer between SVD modes. In particular, by using the multi-field SVD proposed in this study, it is possible to quantify the interference process between different physical quantities. Multi-field SVD is applied to the resistive drift wave turbulence obtained from the Hasegawa-Wakatani model. It is demonstrated that multi-field SVD can extract the dominant spatial structures for turbulent transport and nonlinear energy transfer, preserving the multi-scale nature of the original turbulent fields.

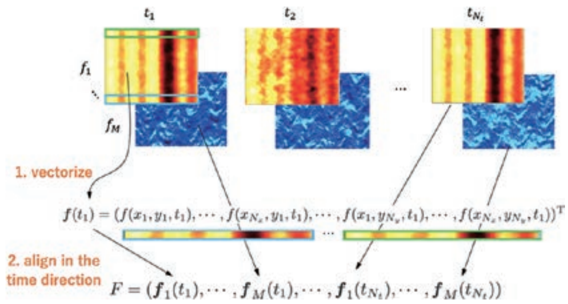


Fig. 2 Procedure of the multi-field SVD for the multi-field data F [2].

(M. Sasaki, Nihon Univ.)

Analysis of molecular transport of plasma-generated molecules to seeds

Plasma irradiation of seeds induces plant responses, making its mechanism and societal implementation important topics in plasma application research. Seeds can be seen as information repositories, with plasma irradiation capable of altering their "memory" after just a few minutes of exposure [3]. Understanding this requires examining both external factors like exposure time and internal factors such as the amount of plasma-induced reactive species introduced into the seeds. In this study, we focused on NO_3^-, a compound linked to seed germination, developing a method to measure trace amounts of NO_3^- introduced by plasma irradiation, which drives growth responses [4]. While this research shows promise for technological advancements, a key obstacle remains — the lack of studies on the health effects of crops from plasma-irradiated seeds. To address this, we conducted a subacute toxicity study on rice grown from plasma-irradiated seeds (*Oryza sativa* L.), feeding the harvested rice to mice as shown in Fig. 3. The rice showed improved growth, with a 4% yield increase, and repeated oral administration of the rice to mice over four weeks showed no adverse effects on organ weights or metabolic profiles when compared to controls (Fig. 4). This study found no significant subacute health impacts from consuming rice grown from plasma-irradiated seeds [5]. We are continuing collaborative research to better understand the mechanisms behind plasma-induced plant responses.

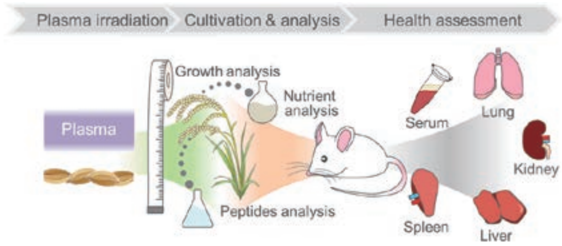


Fig. 3 Graphical overview of experimental flow in terms of harvest of plasma-irradiated rice seeds through subacute effect assessment for mice.

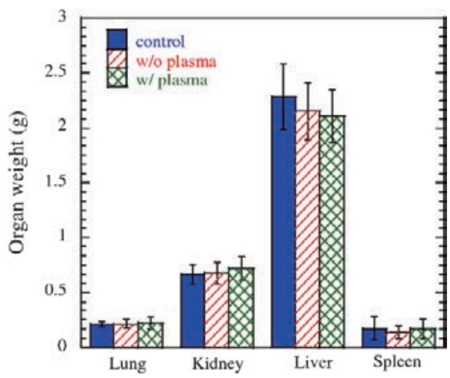


Fig. 4 Organ weight on the 28th day since the administration.

(T. Okumura, Kyushu Univ.)

[1] K. Terasaka *et al.*, Sci. Rep. **15**, 2005 (2024).
[2] G. Yatomi, M. Nakata, M. Sasaki, Plasma Phys. Control. Fusion **65**, 095014 (2023).
[3] C. Suriyasak *et al.*, ACS Agric. Sci. Technol. 1 (2021).
[4] T. Okumura *et al.*, Scientific Reports **12**, 12525 (2022).
[5] T. Okumura *et al.*, Scientific Reports **13**, 17450 (2023).

Fusion Plasma Research

General Collaboration Research is a system for collaborators to carry out their research by using the facilities or resources of the National Institute for Fusion Science (NIFS), including experimental devices, diagnostics, the supercomputer, databases, and others. Because nuclear fusion covers a wide area of physics and technology, from fundamental research to end-application, the system has a variety of categories. Regarding General Collaboration Research on fusion plasma in FY2023, NIFS has received 67 applications from both at home and abroad, and collaborative subjects were steadily completed. In this report, the following three collaborative research projects, highly evaluated in the screening process, are highlighted.

Real-Time Predictive Control of LHD Plasma Applying Data Assimilation System ASTI

Controlling fusion plasmas is challenging yet crucial. We have introduced a new approach, the data assimilation (DA) method, which has excelled in predicting complex systems like weather forecasting. This method is being applied for the first time to control fusion plasma. The DA-based predictive control system, which has been developed, ASTI [1,2], conducts numerous real-time simulations (more than 200 processes) and predicts the probability distribution of future plasma states. The ASTI system has been successfully implemented in the Large Helical Device (LHD). This system can adapt to LHD plasma through real-time observations and estimates control input under model uncertainties by applying data assimilation techniques. It was applied to control the central electron temperature, T_e, using electron cyclotron resonance heating (ECH) and the real-time Thomson scattering measurement system[3]. Figure 1 shows the control results of an LHD experiment (#186500). The electron temperature increases to that of the target (4 keV) and is maintained beyond 3.9 s. This control experiment has demonstrated an improved predictive capability by optimizing turbulent thermal-diffusivity models with real-time T_e and density observations. These results demonstrate the effectiveness of real-time adaptation and control estimation using the DA-based control system.

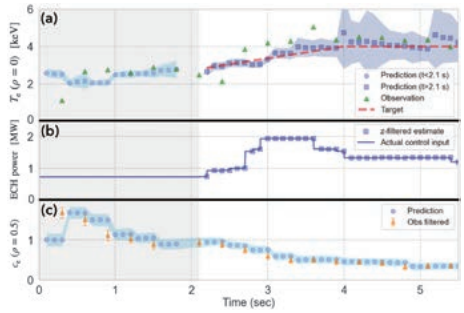


Fig. 1 Results of a control experiment (#186500); (a) control result of T_e at the plasma center, (b) ECH power adjusted using ASTI, (c) distribution (expected value and one standard deviation) of Ce at ρ = 0.5 used in the prediction step and filtered.

[1] Y. Morishita *et al.*, Comput. Phys. Commun. **274**, 108287 (2022).
[2] Y. Morishita *et al.*, J. Comput. Sci. **72**, 102079 (2023).
[3] Y. Morishita *et al.*, Sci. Rep. **14**, 137 (2024).

(S. Murakami, Kyoto University)

Development of deep learning assisted MD-kMC hybrid method for plasma material interaction

Understanding the hydrogen recycling process under detached plasma conditions is crucial for the design of fusion reactors. Our calculations [1,2] using the molecular dynamics (MD) method reveal that a significant amount of hydrogen molecules in relatively high rovibrational states are released from a tungsten wall under these conditions. Our group is working to investigate the effectiveness of emitted hydrogen molecules in edge plasma, particularly through processes like molecular-assisted recombination (MAR). However, these MD calculations were performed using a fixed atomic configuration where the hydrogen and helium densities in the wall were assumed. In real scenarios, these densities are determined by the balance between emission and inflow, governed by a dynamically evolving material configuration. To better analyze the hydrogen recycling process when the atomic structure of the wall changes dynamically due to hydrogen and helium irradiation, we are developing a hybrid simulation method that combines MD and kinetic Monte Carlo (kMC) simulations, with deep learning assistance to accelerate the computation. In this simulation, deep learning will be employed to instantly predict trapping sites and migration barriers. As a first step towards realizing this hybrid simulation, we are developing a deep learning model capable of predicting the three-dimensional binding energy of a hydrogen-tungsten system. The model predicts the spatial distribution of binding energy in 128×128×128 voxel data from two input channels that represent the positions of hydrogen and tungsten atoms. Figure 1 illustrates (a) the true spatial distribution of binding energy, (b) the predicted distribution, and (c) the absolute error between the true and predicted values. The binding energy becomes large when the test hydrogen atom is located near tungsten or hydrogen atoms in the material, due to the strong repulsive forces between the nuclei. In Fig. 1 (a), red spheres are observed at the positions of the tungsten and hydrogen atoms, representing high-binding energy regions. The prediction successfully reproduces these red spheres. However, as shown in Fig. 1 (c), the absolute error increases at the edges of the spheres, where the gradient of the binding energy is steep, compared to other areas.

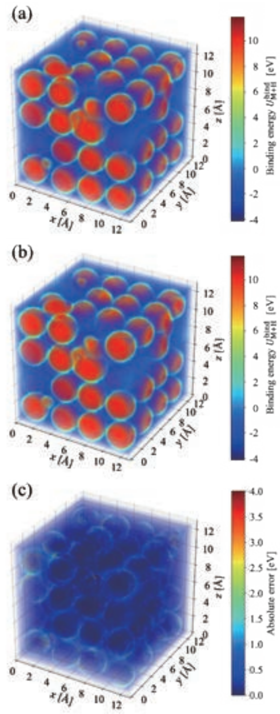


Fig. 1 An example of (a) the spatial distribution of the true values, (b) that of predicted values, and (c) the absolute error between the true and predicted values. [3] (Copyright (2024) The Japan Society of Applied Physics)

[1] S. Saito *et al.*, Synopsis of IAEA-FEC 2023, 1733 (2023).
[2] S. Saito *et al.*, Contrib. Plasma Phys. e201900152 (2020).
[3] S. Saito *et al.*, Jpn. J. Appl. Phys. **63**, 09SP03 (2024).

(S. Saito, Yamagata University)

Development of data science technique for quantitative analyses of plasma transport in first-principle plasma simulations

Simplified models that predict turbulent transport levels with fewer computational resources have been actively developed. However, most models are based on existing simulation or experimental results, making it difficult to predict beyond interpolation. Here, we focus on bounded space effectively formed by solution trajectories in space parameterized by turbulent fluctuations and zonal-flow amplitude in turbulent transport phenomena obtained from first-principle gyrokinetic simulations; and discuss a model that can be extrapolated to the structure of this space. We construct an effective model with a certain functional form that can represent bounded space using an objective function for the model's accuracy in parameter space, which defines the model function. By optimizing the integral of the objective function over parameter space, we restrict the form of the model functions.

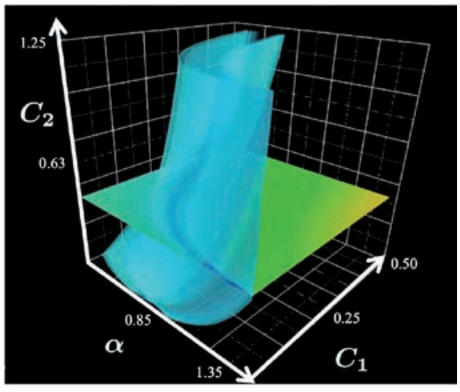


Fig. 1 Objective function for the model accuracy in parameter space of the model function.

(S. Nunami)

Fusion Technology Topics

Highlight

Research and development of cooling technologies for high-temperature superconducting coils with a combination of magnetic refrigeration and circulation cooling

Magnetic refrigeration is promising for cooling of high-temperature superconducting coils in fusion reactors [1]. As a fundamental study on magnetic refrigeration, magnetic shielding effects were investigated using YBCO bulk materials 5 mm-square and 10 mm-thick (plate specimen), in addition to the ones with a diameter of 28 mm and various thicknesses of 2, 5 and 10 mm (column specimens). Figure 1 depicts the experimental results of magnetic shielding at 77 K. A shape effect is indicated, where the 10 mm-thick plate specimen shielded the magnetic flux more than the same 10 mm-thick column specimen. On the other hand, size effects were complicated, because the thinner 2 mm-thick specimen exhibited greater magnetic shielding, compared with the 5 mm-thick specimen, though the shielding is expected to be enhanced by increasing the specimen size. The former shape effect suggests that the magnetic line structure was improved for shielding in the case of the plate specimen. Since the magnetic shielding was also affected by the specimen direction, the latter size effects were probably induced by inhomogeneous chemical composition and microstructure in the original YBCO bulk materials. Further analyses on the homogeneity of magnetic properties are expected to help understand the intrinsic size effects.

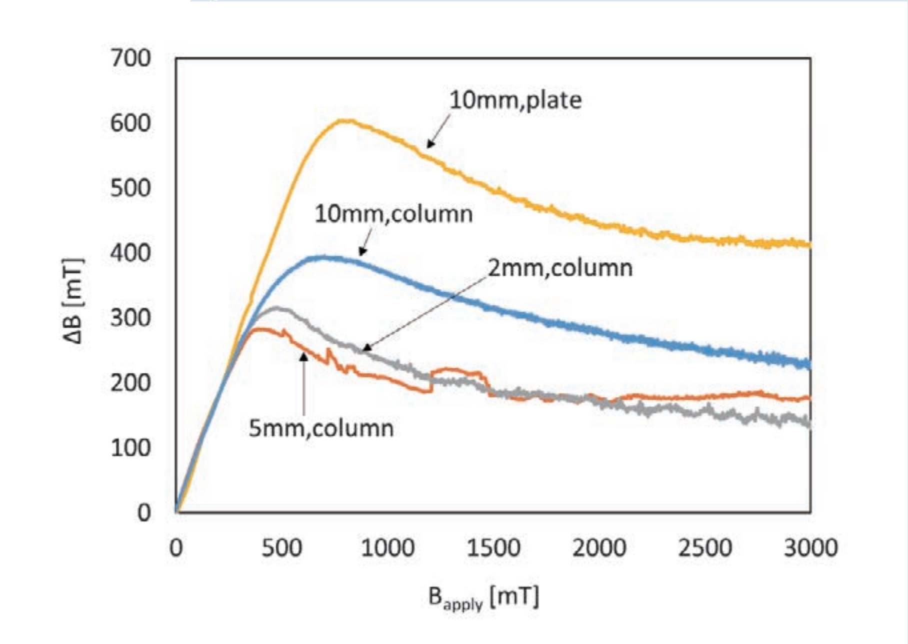


Fig. 1 Magnetic flux density (ΔB) shielded by the plate and column YBCO bulk specimens under the magnetic fields (B_{apply}) at 77 K.

(T. Okamura, Tokyo Institute of Technology)

Three dimensional fabrication of SiC fiber reinforced SiC matrix composites by direct ink writing, and evaluation of their mechanical bending properties

Continuous fiber-reinforced SiC matrix (CF/SiC) composites are promising for applications in nuclear energy and aerospace, due to their good strength-to-weight ratio and heat resistance. 3D fabrication, especially direct ink writing (DIW) technology, is essential for the complicated shaping of the CF/SiC composites. The DIW method consists of three shrinkage processes such as desiccation, dewaxing and sintering. Since the matrix shrinks however, and fiber does not, internal-tension stress occurs in the matrix due to a mismatch of the shrinkage between the matrix and fibers, leading to crack initiation in the matrix. In order to prevent the cracking, the present study proposes to use polyvinyl alcohol (PVA) as a stress- relaxation layer between the matrix and fibers. Carbon fibers coated with PVA were sintered with the SiC powder matrix after 3D fabrication by the DIW method. The PVA coating was 176 μm in average thickness, and successfully reduced cracking, especially during the desiccation process. The resulting composite specimens were approximately 40 mm in length, 11 mm in width and 5 mm in thickness. Based on bending tests on the composites after the sintering, the fracture strength achieved was 150 to 200 MPa. However, the fracture mode was still brittle and remains to be improved, because pseudo-ductile behavior is preferable for composite materials. The fracture surface was almost flat without significant pullouts of the carbon fibers. This indicates that the crack propagating in the SiC matrix penetrated the carbon fibers. Control of fiber-matrix interface strength to more fiber pullouts should be examined to enhance the pseudo-ductile behavior of the composites.

(H. Kurita, Tohoku University)

Short pulsed heat-loading tests on advanced divertor materials using plasma gun

The remaining issues for a fusion reactor diverter are heat resistance to loading more than 100 MW/m^2, its maintenance, radioactive waste management, and so on. Liquid metal divertor concepts are proposed to deal with the issues, instead of the conventional solid divertor structure of tungsten etc. However, with a liquid metal divertor arises another problem, such as flow control against MHD effects with considerable Lorentz force, due to the current in the liquid-metal flow under a high magnetic field. Therefore, small solid pebble divertor concepts are also proposed to eliminate the current path and avoid the MHD effects. Heat loading tests are essential to accelerate the research and development for these advanced divertor concepts. In the present collaboration, a new test stand for short pulsed heat loading was designed using magnetized coaxial plasma gun (MCPG) technology. The present study focuses on the construction of a prototype plasma irradiation apparatus, evaluation of its performance, and a preliminary heat-loading test on the divertor materials. The constructed plasma irradiation apparatus consists of a prototype plasma gun, combined with a high output acceleration power supply, leading to shorter pulsed plasma irradiation and high-heat loading. Based on previous results by a similar configuration apparatus, plasma-particle velocity and plasma density for materials irradiation is expected as high as 100 km/s and 10^{21} m^3, respectively, which will provide sufficient high-heat loading for divertor materials evaluation. The plasma irradiation apparatus will start operation in JFY2024.

(N. Fukumoto, University of Hyogo)

[1] N. Hirano *et al.*, 16th European Conf. Applied Superconductivity, Sep. 3–7, 2023, Bologna, Italy.

Plasma Simulator Collaboration Research

Plasma Simulator Collaboration Research promotes fusion science study using the supercomputer, Plasma Simulator. It also covers subjects that could contribute to the development of simulation science as a new academic field, as well as collaboration research on the development of new algorithms and new parallelization techniques from the viewpoint of computational science. In FY2023, 82 projects in Plasma Simulator Collaboration Research were conducted by 271 researchers of NIFS and universities.

(Y. Todo)

Enhancement of the isotope effect of anomalous transport in multi-scale turbulence

Recent multi-scale simulations of drift-wave turbulence in magnetically confined fusion plasma have demonstrated interactions of turbulences excited on different spatiotemporal scales. In our recent work [1], we found growth-rate reduction of trapped-electron mode (TEM) instability due to electron temperature gradient (ETG) turbulence by means of a gyrokinetic code, GKV. The gyrokinetic simulation of TEM/ETG instabilities in a toroidal flux tube manifests cross-scale interactions of the two turbulences, as shown in Figure 1 (left), where a snapshot of the toroidal component of the electric field is plotted on the midplane of a torus. The TEM instability exponentially grows in time, while the TEM growth rate γ is decreased from that of the linear TEM growth rate $\gamma_{\rm lin}$ by the effective diffusion $\delta_{\rm eff}$ caused by the ETG turbulence, such as $\gamma = \gamma_{\rm lin} - k_y^2\delta_{\rm eff}$, where k_y denotes the poloidal wavenumber [see Figure 1 (right)].

Our recent simulations have newly revealed the isotopic dependence of TEM/ETG interactions. It is known that the linear TEM growth rate $\gamma_{\rm lin}$, as well as the nonlinear saturation level, has ion-mass dependence through collisionality. In contrast, the effective diffusion coefficient $\delta_{\rm eff}$ has little dependence on the ion mass, as it is mainly driven by electron dynamics. Thus, the resultant TEM growth rate γ in the case with ETG turbulence shows stronger isotopic dependence. In the nonlinear saturation phase of the TEM instability growth, we have also found steepening of the turbulence-energy spectrum in wavenumber space, as the ion mass increases from H, D, to T, causing strong nonlinear oscillations but with a mean reduction of the transport flux. The obtained results clearly confirm enhancement of the isotope effect in the TEM turbulence due to multi-scale interactions.

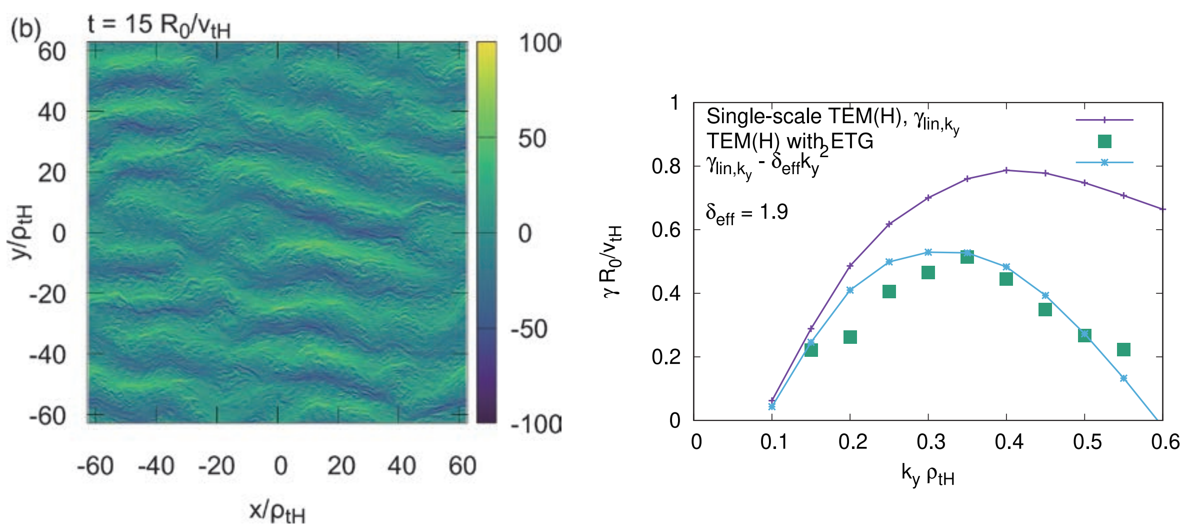


Fig. 1 (left) A snapshot of the toroidal component of an electric field in a growth phase of the trapped electron mode (TEM) in electron temperature gradient turbulence, and (right) growth rates of the TEM instability [1].

Effective diffusion driven by the ETG turbulence can also make non-negligible contributions to the ion temperature gradient instability and zonal flows. Comprehension of the multi-scale turbulence should deepen our understanding of turbulent transport phenomena in magnetic fusion plasma.

[1] T.-H. Watanabe, S. Maeyama, and M. Nakata, Nuclear Fusion **63**, 054001 (2023).

(T.-H. Watanabe)

Plasma-beta dependence of turbulent transport suggesting an advantage of weak magnetic shear

Understanding the β dependence of plasma confinement is important for predicting a fusion reaction rate which is directly related to pressure, and the generation of bootstrap current which is needed for the steady operation of tokamaks. Experimental studies show no clear trends of β dependencies of confinement, and their tendencies of β-scaling are contradictory, and thus further understanding by numerical simulations is needed. In finite-β plasmas, turbulent fluctuations are electromagnetic, and magnetic fluctuations are known to have a stabilizing effect on the ion-temperature gradient (ITG) mode, suggesting a reduction of turbulence level with increasing β. On the other hand, magnetic fluctuations also suppress zonal-flow shear by the stochastic field, resulting in an enhancement of the turbulence level with increasing β. The existing work presents that, at small β the former effect dominates and reduces turbulent transport with increasing β, while the latter dominates and causes the non-saturation of ITG turbulence above a critical β value lower than the kinetic ballooning mode (KBM) stability limit.

We investigate key physical processes that regulate the β dependence of turbulence by means of both local and global gyrokinetic simulations. We find that the turbulent transport does not decrease as β increases [2], because the electromagnetic stabilizing effect is cancelled out by the Shafranov shift. This influence of the Shafranov shift is suppressed when the magnetic shear is weak, and thus electromagnetic stabilization is prominent in weak shear plasmas, suggesting a better β dependence of turbulent transport in an ITER-hybrid scenario [3]. Suppose that a high-β regime is achieved by the hybrid scenario, then the next issue is to identify the turbulence that limits the achievable β, but we encounter trouble in local gyrokinetic simulations in this regime, leading to a non-saturation of turbulence known as the non-zonal-transition problem. We have resolved this non-saturation issue by global gyrokinetic simulations (Fig. 2). The electromagnetic ITG turbulence gets saturated by the turbulence spreading in the radial direction with the generation of strong zonal flows by preventing damping, due to magnetic fluctuations [4]. This is ascribed to global effects, which enable us to explore a higher β regime.

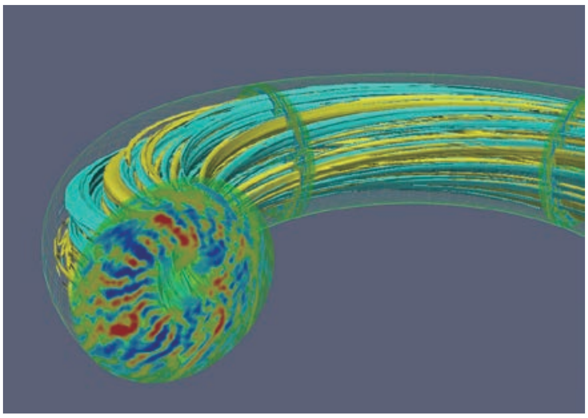


Fig. 2 Electromagnetic ITG turbulence at finite β.

[2] A. Ishizawa, D. Urano, Y. Nakamura, S. Maeyama, and T.-H. Watanabe, Phys. Rev. Lett. **123**, 025003 (2019).
[3] A. Ishizawa, Y. Kishimoto, K. Imadera, Y. Nakamura, S. Maeyama, Nuclear Fusion **64**, 066008 (2024).
[4] H. Masui, A. Ishizawa, K. Imadera, Y. Kishimoto, Y. Nakamura, Nuclear Fusion **62**, 074001 (2022).

(A. Ishizawa)