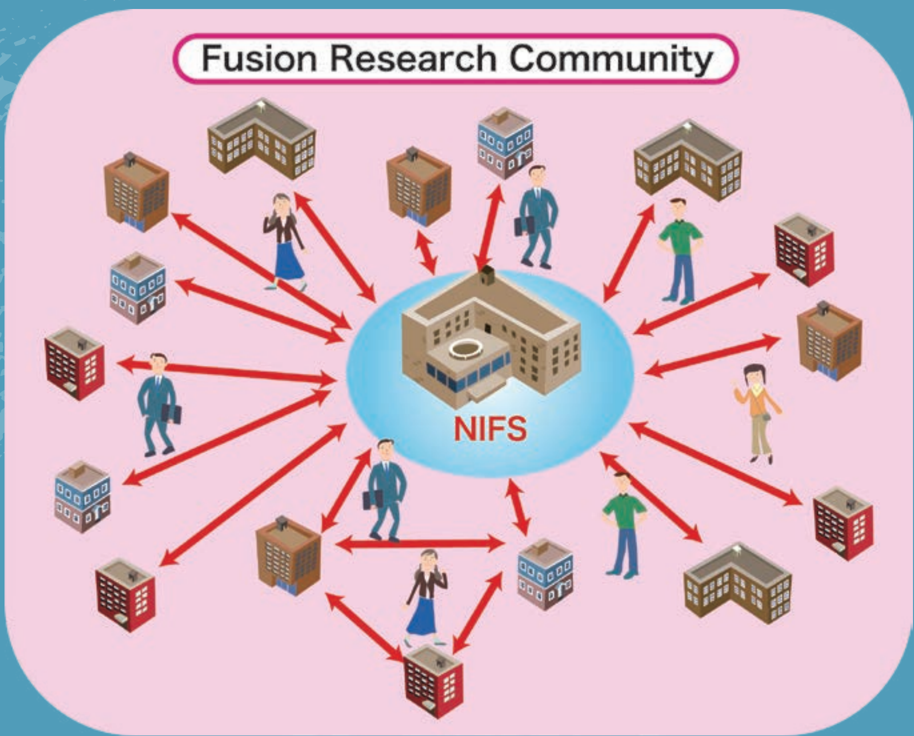
2. General Collaboration Research

General Collaboration Research is a system for collaborators to carry out their research by using the facilities or resources of NIFS, including experimental devices, diagnostics, the supercomputer, databases, and others. Because nuclear fusion encompasses a wide area of research in physics and technology, from fundamental research to application, General Collaboration Research has various categories: Network-type Research, Interdisciplinary Fusion Science Research, Fusion Plasma Science Research, Fusion Technology Research, Plasma Simulator Collaboration Research, and Workshops. In FY2024, 357 projects were conducted under General Collaboration Research.

The academic positioning and role of fusion science are undergoing a major transition due to advances in fusion energy development. NIFS transitioned to a new system in FY2023, forming units as collaborative research teams that involve experts from various fields outside the institute. In the call for General Collaboration Research proposals, each unit proposed research themes, and collaborative research projects were promoted through cooperation with the units.

(Y. Todo)


Fusion Research Community
NIFS

Network-Type Research

This research is eligible for collaboration with facilities owned by the National Institute for Fusion Science and multiple universities. In the fiscal year of 2024, the research shown below was steadfastly carried out. The titles and brief summaries of the research topics are described.

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

The aim of this study is to develop an active measurement method of MHD instabilities, predicting them before they occur, by using a small tokamak device, HYBTOK-II. As a result, in the second year of a three-year plan, the magnetic field response on the imposed resonant magnetic perturbation (RMP), i.e., a change in the amplitude, was observed before and after the $m/n=2/1$ tearing instability. Figure 1 shows the typical wave form of the discharge where the tearing instability is observed. As plasma current increases, the peripheral safety factor (q) value decreases, and magnetic fluctuation with the $m/n=2/1$ structure appears from 14.5 ms. The mode frequency is between 20 and 25 kHz. Figure 2 shows the magnetic fluctuation amplitude, which highly correlates with imposed external RMP. Figures 2(a), (b), and (c) correspond to data collected a sufficient time before, just prior to, and during the onset of the tearing instability, respectively. A sufficient time before the instability occurs, the magnetic fluctuation highly collated with external RMP, increases with the imposed RMP frequency (Fig. 2(a)). Also, the magnetic fluctuation reaches its maximum around the frequency of the tearing instability (Fig. 2(c)). In contrast, just before the tearing instability occurs, the magnetic fluctuation amplitude around the expected instability frequency increases (Fig. 2(b)). This observation may indicate an imminent onset of the tearing instability. We should analyze the change in the magnetic fluctuation phase just before the instability, in addition to the amplitude. This is a future subject of study.

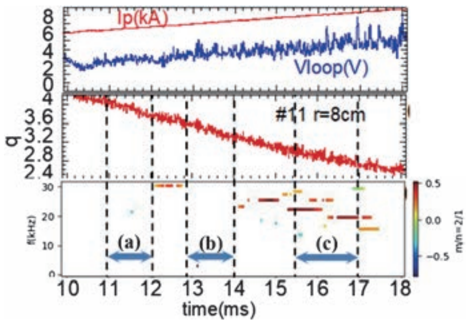


Fig. 1 Typical wave form of the discharge imposed by RMP. (a) Plasma current, I_p and one-turn voltage, V_{loop}. (b) Safety factor value at r/a~0.7. (c) Power spectrum of $m/n=2/1$ magnetic fluctuation.

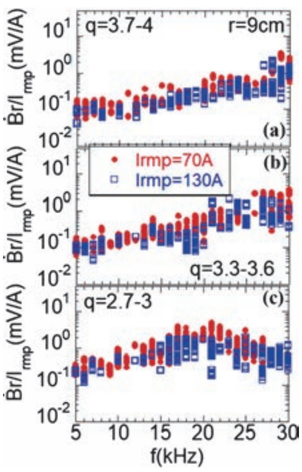


Fig. 2 Frequency dependence of power spectrum of magnetic fluctuation highly correlated with injected RMP by antenna during (a) 11–12 ms, (b) 13–14 ms, and (c) 15.5–17 ms.

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

Elucidation of ion turbulence in multi-ion species plasmas by inter-university device network

In a fusion plasma of multi-ion species, a transition from a non-mixing state, where the ratios of ion species are different, to a mixing state, where the ratios are equal, was observed. The transition was found to occur faster than the time scale determined by conventional transport theory based on particle diffusion. This fast transition suggests that the dominant transport is not diffusive due to collisions between ions. But it indicates anomalous non-diffusive transport created by "ion turbulence," which is fluctuations of the field interacting with the ion motion. In this study, the behavior of the ion turbulence is examined by developing an inter-university device network, which consists of several university-scale experimental devices. The plasmas in university-scale devices are not relevant to fusion plasma, but high spatial accuracy measurements become possible. From these measurements and inter-machine comparisons, the physics underlying the transition process of a multi-ion plasma to the mixing state, discussed in this project, is expected to be extended to the non-diffusive behavior observed in other general physical phenomena. In FY2024, to measure ion turbulence, a tomographic reconstruction based on an innovative idea, which consisted of L1 regularization and sparse modeling, was developed. Developed tomography was applied to the PANTA experiment in Kyushu University, and it could successfully reconstruct drift wave turbulence. This new tomographic reconstruction technique will apply to two-ion species plasma in FY2025.

(Y. Suzuki, Hiroshima University)

Network survey of tritium concentration in precipitation in Japan

Disseminating knowledge on the physicochemical properties and behavior of tritium, as well as its relevance to fusion research, is one of the important challenges in public communication. Therefore, by establishing an observation network with related institutions, samples of precipitation and tap water will be collected. Measuring tritium concentrations in these water samples will allow us to understand the distribution of tritium levels in environmental waters across Japan. Furthermore, the network will promote exchanges among students belonging to the participating institutions, thereby fostering the development of young researchers who will lead the next generation. In this study, a collaborative research network among researchers was utilized to establish an environmental water sampling network covering the entirety of Japan from north to south. As a result, tritium concentration has a clear seasonal trend, which is high in spring and low in summer. Furthermore, concentrations are higher in spring in northern Japan, with the highest values observed in Hokkaido.

As part of this network-type collaboration research, a "Workshop on Environmental Radioactivity" was held from December 5–6, 2024, with the aim of fostering young researchers in the field of environmental radioactivity. In cooperation with the NIFS, a tour of the Large Helical Device was also organized. The workshop featured 20 presentations by students from Hirosaki University, Kindai University, and Kobe Pharmaceutical University (including international students), as well as by young technical staff members of the National Institute for Fusion Science. Lively discussions were conducted among the participating students.

(N. Akata, Hirosaki University)

Interdisciplinary Fusion Science Research

As one of the NIFS collaboration categories, the interdisciplinary fusion science research has been established 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 FY2024 109 collaborative programs were performed 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)

Formation of semiconductor nanostructures by plasma irradiation and their device applications

Silicon (Si) is a promising negative electrode material for lithium-ion batteries (LIBs) due to its capacity, nearly ten times higher than graphite. Its use, however, is limited by ~400% volume expansion during cycling, which causes electrode damage. To address this, we developed porous Si thin films using helium (He) plasma. Si was sputter-deposited in a linear plasma device with high-density He plasma (~10^{18} m^{-3}) onto Cu substrates, forming porous Si–He co-deposited layers with ~0.5 porosity and ~1.5 μm thickness (See Fig. 1). A Transmission Electron Microscope (TEM) showed 100–200 nm Si clusters separated by nanopores, yielding an amorphous structure. Electrochemical testing gave ~3000 mAh g^{-1} initially. The 523 K film maintained ~1800 mAh g^{-1} after 100 cycles and ~1200 mAh g^{-1} after 250 cycles. These findings indicate that He–Si co-deposition is a promising method for fabricating porous amorphous Si thin films with high cycling stability for advanced LIB anodes [1].

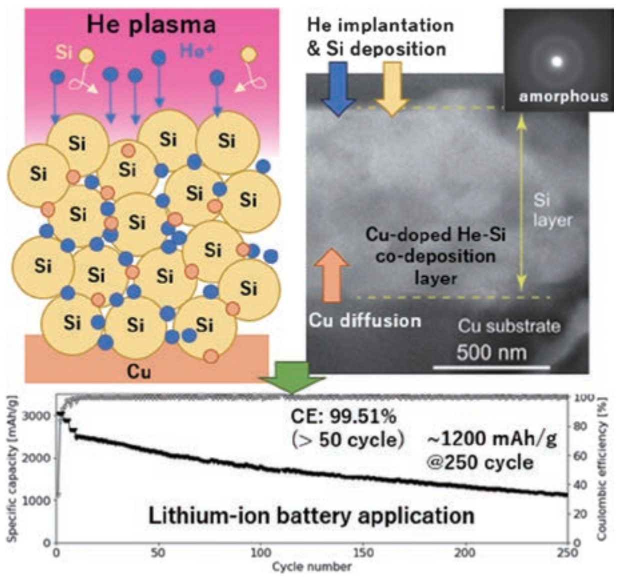


Fig. 1 A graphical overview of the porous Si amorphous layer with a TEM micrograph and the evolution of the discharge capacity and coulombic efficiency of the fabricated Si thin film [1].

(S. Kajita, Univ. Tokyo)

Application of singular spectrum analysis to a biological time-series data

Chronobiology is a discipline that investigates biological rhythms and often analyzes actograms, which are binary time-series data representing the timing of activity and rest. To detect periodicity in such time-series data, methods such as Fourier analysis, the chi-square periodogram, and the Lomb–Scargle periodogram have traditionally been employed. However, these methods assume stationarity of the data, and thus cannot be applied to non-stationary datasets in which the periodicity substantially changes. To address this limitation, the present study applied singular spectrum analysis, which is a nonparametric time-series analysis method primarily used in plasma hydrodynamics, to non-stationary actogram data [2]. As a result, periodicity could be successfully extracted from non-stationary data, which had previously been difficult to analyze with conventional approaches.

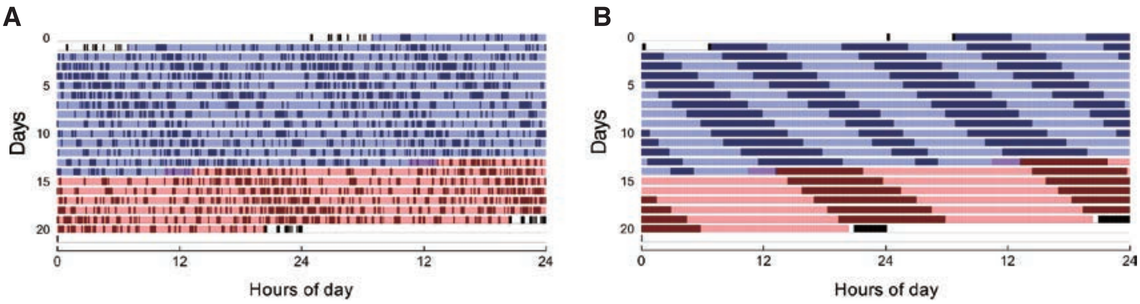


Fig. 2 A representative actogram of locomotor activity in the mangrove cricket *Apteronemobius asahinai*. (A) shows the actogram before denoising by singular spectrum analysis (SSA), and (B) shows the actogram after denoising by SSA. Unimodal and bimodal daily rhythms are significantly detected in the red and blue regions, respectively. The figure was created with the data presented in Ref. [2].

(K. Sakura, NIBB)

Direct observation of highly charged muonic ions

A highly charged ion (HCI) plays a crucial role in various scientific fields, including plasma physics and astronomy. In this study, we propose a new type of HCI: the highly charged muonic ion (HCμI). An HCμI is a unique few-body atomic system in which a negatively charged muon and a few electrons are simultaneously bound to a single nucleus. However, no experimental methods for its direct observation have been available until now.

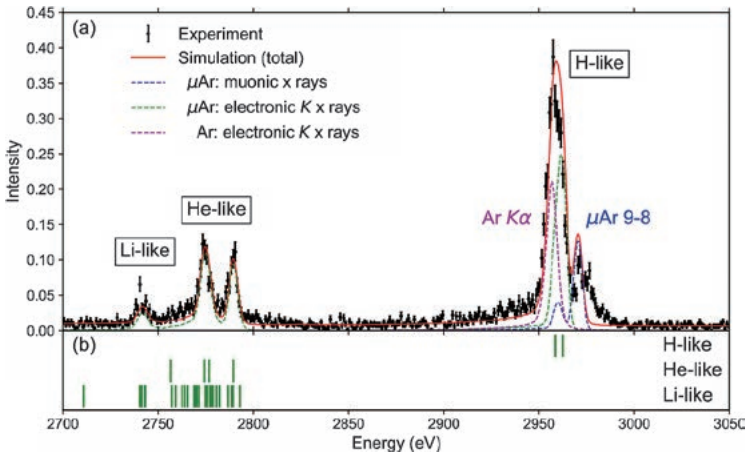


Fig. 3 (a) An electronic *K* x-ray spectrum measured with the TES detector. (b) Theoretical x-ray energies for the electronic transition of H-, He-, and Li-like Cl.

We report the first state-selective observation of highly charged muonic argon (μAr) using high-resolution electronic K x-ray spectroscopy with an array of transition-edge sensor (TES) microcalorimeters [3]. The TES microcalorimeter is a state-of-the-art x-ray detector that combines high energy resolution with high detection efficiency—ideal characteristics for HCμI spectroscopy. Fig. 3 shows the x-ray spectrum of μAr measured with the TES detector. The high-precision K x-ray spectrum clearly reveals the presence of HCμIs with one, two, and three electrons, corresponding to H-like, He-like, and Li-like μAr, respectively.

[1] S. Kajita *et al.*, Adv. Energy Sustainability Res. 2024, 2400300.
[2] K. Sakura *et al.*, Biol. Rhythm Res. 1–11 (2025).
[3] T. Okumura et al., Phys. Rev. Lett. **134**, 243001 (2025).

(T. Okumura, Tokyo Metropolitan Univ.)

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 includes a wide study area in physics and technology, from fundamental research to application, the system has a variety of categories. Regarding general collaboration research on fusion plasma in FY2024, NIFS received 63 applications from both home and abroad, and 59 collaboration research subjects were methodically undertaken. In this report, the following three collaboration research projects, highly evaluated in the screening process, are highlighted.

Study of neoclassical transport using FORTEC-3D in CFQS

The 3D-global δf Monte Carlo simulation code, FORTEC-3D, is utilized to investigate isotope effects on neoclassical transport in the CFQS-axisymmetric stellarator under self-consistent and biased radial electric fields (E_r) for the first time. Key numerical results reveal: (1) With self-consistent ambipolar E_r, hydrogen (H) plasmas exhibit higher neoclassical transport than deuterium (D) plasmas. This result is broadly consistent with experimental isotope results in tokamaks, as shown in the following figure: (2) Under biased E_r, a radial reversal emerges: H plasma transport is lower than D plasma transport in the core but higher in the periphery. This reversal is driven fundamentally by neoclassical poloidal viscosity (a momentum damping mechanism), which propagates radially from the periphery to the core, significantly faster in D plasmas than in H ones due to isotope mass effects. The non-local propagation of poloidal viscosity is caused by radial E_r gradients unobtainable in local theory, demonstrating a critical link between viscosity dynamics, E_r modulation, and isotope mass.

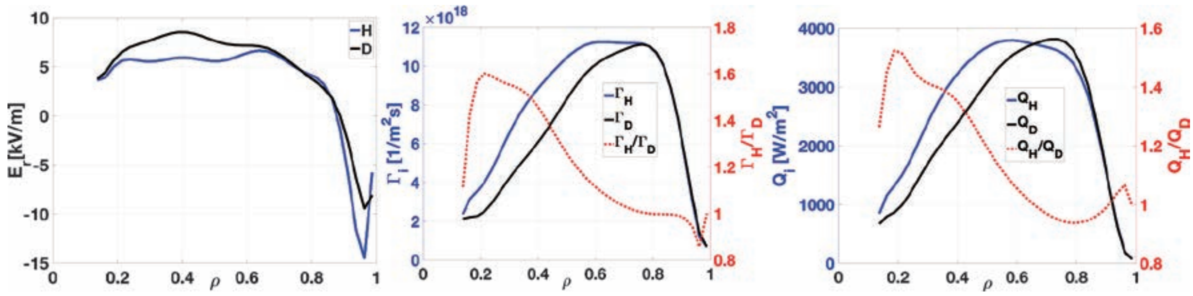


Fig. 1 (left) ambipolar radial electric field profiles, (middle) radial particle fluxes and (right) radial energy fluxes in hydrogen (blue) / deuterium (black) plasmas obtained with FORTEC-3D.

(H.F. Liu, Southwest Jiaotong University)

Investigation of nuclear elastic scattering effect on fusion plasma

Coulomb scattering dominates ion collisions in fusion plasmas, but at higher ion energies, nuclear elastic scattering from the nuclear force becomes significant. Unlike Coulomb scattering, which involves small angles and minimal energy transfer, nuclear scattering produces large angles and high energy transfer, enhancing ion heating and altering ion distributions—potentially improving fusion reactivity. Predictions from the Boltzmann collision integral and two-dimensional Fokker-Planck simulation indicate that the gamma-ray emission rate from the ^{6}Li(d, pγ)^{7}Li reaction strongly depends on the magnitude of the knock-on tail [1]. Investigation of the knock on tail formation via nuclear elastic scattering was performed in LHD [2] using $LaBr_3$:Ce gamma ray diagnostics. Following ^{6}LiF pellet injection into hydrogen-beam-heated deuterium plasma, we observed a gamma-ray peak of around 0.48 MeV. The peak seemed to correspond to the ^{6}Li(d, pγ)^{7}Li reaction. We are continuously improving the ^{6}LiF pellet size and discharge scenarios to obtain γ-ray spectra with higher statistical accuracy.

[1] H. Matsuura *et al.*, Plasma Fusion Res. **11**, 1403105 (2016).
[2] H. Matsuura *et al.*, J. Plasma Fusion Res. **99**, 120 (2023).

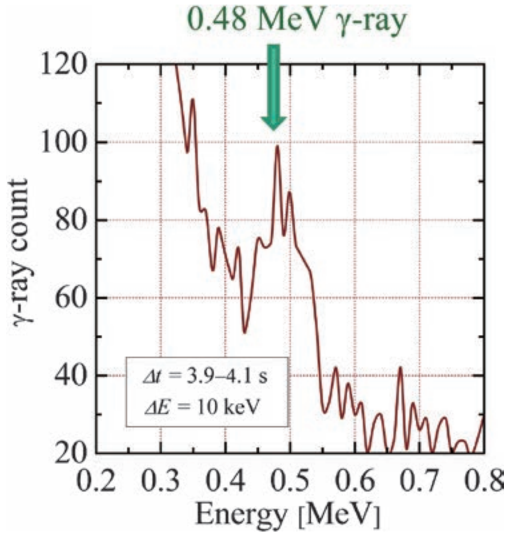


Fig. 1 Gamma-ray spectrogram obtained by summing signals from 20 ^{6}LiF pellet injection plasma discharges.

(H. Matsuura, Kyushu University)

Energetic ion charge exchange spectroscopy using higher energy beam

We conducted development of Fast Ion D-alpha (FIDA) spectroscopy, which detects Doppler-shifted Balmer-α emissions from fast ions that undergo charge exchange with neutral beam atoms, from a high-energy negative-ion source. Until now, FIDA measurements have been primarily demonstrated using positive-ion source neutral beams with relatively low energies. However, large-scale experimental devices, such as ITER/JT-60SA, will predominantly employ high-energy negative-ion source neutral beams. Our issues are whether FIDA diagnostics remain feasible under such conditions. In LHD, we implemented a new geometry with a reduced angle between the line of sight and the beam direction, and we successfully detected Doppler-shifted lights attributed to charge exchange of high-energy ions. The measured emission spectra showed qualitative agreement with results from FIDASIM, a numerical simulation code widely used for FIDA diagnostics. This consistency confirmed the first experimental verification that FIDA measurements are achievable with high-energy negative-ion neutral beams [1].

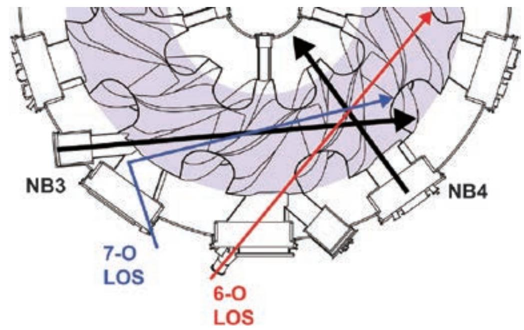


Fig. 1 Top view of FIDA measurement at LHD. The old 6-O LOS line of sight made it difficult to conduct FIDA measurements, but by adding a new 7-O LOS with a smaller angle to the neutral beam NB3.

[1] W.H.J. Hayashi *et al.*, “Charge-exchange measurements of high-energy fast ions in LHD using negative-ion neutral beam injection”, Journal of Instrumentation **19**, P12006 (2024).

(W. Hayashi, University of California, Irvine)

Fusion Technology Research

Highlight

Investigations on energization characteristics of liquid hydrogen-cooled high-temperature superconducting cable conductors for fusion reactors

Driven by helium depletion and an emerging hydrogen-based society, high-temperature superconducting (HTS) coils for fusion reactors, cooled by liquid hydrogen, are eagerly anticipated. Cable-in-conduit (CIC) conductors of REBCO wires with forced liquid hydrogen cooling, are particularly promising. A critical challenge is designing for stabilization to prevent thermal runaway, even in the event of quenching from cooling degradation, necessitating a clear understanding of conductor stability in liquid hydrogen. Using an external magnetic field coil fabricated in FY2023, a 6 kA-scale AC induction energization test setup was built in FY2024. Its principle was validated with a 1-turn short-circuited secondary coil made from a single REBCO wire. Another secondary coil was fabricated by short-circuiting three spirally wound REBCO single-layer conductors. Its AC inductive energization was examined under liquid hydrogen cooling. As shown in the figure, the maximum peak value of the secondary current $I_{2,peak}$ was 4,424 A in 1 Hz tests. This value showed a high degree of similarity with the simulated conductor I_C of 4,224 A (20 K, 0.1 T) from its I_C-B-T correlation. This successfully demonstrated HTS conductor energization exceeding 4 kA and validated the AC induction method for I_C evaluation. Future plans include inductive energization tests on multi-layer conductors.

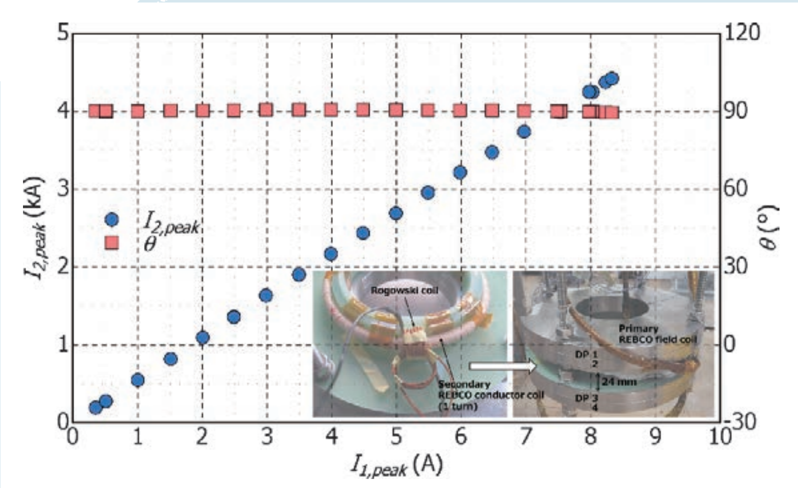


Fig. Results of AC induction energization test under liquid hydrogen cooling ($I_{1,peak}$ and $I_{2,peak}$ are the peak values of the primary and secondary current, respectively, and θ is the phase difference between the Rogowski coil voltage and the primary current)

(M. Ohya, Kwansei Gakuin University)

Formation of Laser Induced Periodic Surface Structures (LIPSS) for Fusion Rector Divertor and Optical Device Applications

Tungsten is a crucial material for plasma-facing components (PFCs), and the ITER project utilizes divertor structures where tungsten is joined with copper alloy cooling pipes. A key challenge in developing fusion reactors is improving the properties of dissimilar metal joints and coatings for tungsten. One approach aims to improve joint performance, including heat removal, by creating micrometer-scale textured surfaces on tungsten using laser irradiation before joining it with copper. This increases the anchoring effect and expands the contact area. In FY2024, the joining of laser surface-modified tungsten with copper was examined. NDB (Non-Defective Bonding) is a unique joining technology from Nippon Tungsten Co., Ltd. that directly bonds tungsten and copper. It has been adopted in the ITER divertor for joining tungsten to oxygen-free copper interlayers. In collaboration with the industry, NDB joining of laser surface-modified pure tungsten with oxygen-free copper was examined. Another joining method, Hot Isostatic Pressing (HIP) was also attempted. Microstructural analysis of the cross-section indicated no defects in the copper surrounding the laser-processed indentation to a depth of about 80 μm. However, in the tungsten, crack defects with opening widths from sub-micrometers to several micrometers formed radially from the interface. Notably, with the NDB method, copper infiltrated these crack openings, thus repairing them and making the interface structure more complex. This is expected to improve the anchoring effect and reduce thermal and electrical resistance. As a next step, evaluation of the bonding strength is planned through tensile and high-heat loading tests.

(R. Miyagawa, Nagoya Institute of Technology)

Corrosion of Vanadium Alloys in Liquid Lithium and Its Effect on Tritium Behavior

Fusion reactor blankets with vanadium (V) alloy structures and liquid lithium, which serve as both coolant and tritium breeder, are expected to provide excellent tritium breeding performance, high thermal efficiency, and low-activation characteristics. From the perspectives of safety evaluation and tritium balance design, research on tritium behavior affected by corrosion, is essential. However, such research has been limited due to the difficulties in handling liquid lithium and tritium. In FY2024, the primary objective was to understand the corrosion characteristics of vanadium alloys in liquid lithium without tritium.

In recent years, V alloys with reduced Ti concentration and increased Cr concentration have been developed to improve low-activation characteristics. In order to clarify the effects of the alloying elements, corrosion properties were investigated in liquid lithium by varying the composition within the range of V-(4-8 wt%)Cr-(1-4 wt%) Ti. As the Ti concentration decreased from 4 to 2 wt%, the mass gain rate due to lithium immersion decreased, and at 1 wt%, a mass loss was evident. Since the mass gain for 8Cr-2Ti and 6Cr-2Ti alloys was almost the same, it is thought that the Ti concentration had a greater influence than the Cr concentration. Observations of the 8Cr-1Ti alloy surface revealed the formation of numerous pits, corrosion products, and greater roughness, suggesting significant dissolution of metallic elements and enhanced corrosion thinning. Based on these experimental results, it is advantageous to maintain a Ti concentration of 2 wt% from the perspective of suppressing corrosion thinning.

(K. Katayama, Kyushu University)

Plasma Simulator Collaboration Research

Plasma Simulator Collaboration Research promotes fusion science research 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 parallelization techniques from the viewpoint of computational science. In FY2024, 83 research projects on the Plasma Simulator Collaboration Research were conducted by 258 researchers at NIFS and universities.

(Y. Todo)

Thermal equilibration in collisionless magnetospheric plasmas via entropy-mode turbulence

A planetary magnetosphere is a peculiar plasma environment where a high-temperature plasma is confined in a strongly inhomogeneous dipolar magnetic field generated by a planet. In such systems, turbulence driven by magnetic curvature and density gradient, called the *entropy mode*, is known to cause an inward particle pinch, whereby particles are transported against the density gradient to achieve high confinement. Although this phenomenon has been recognized for some time, a consistent and comprehensive understanding of how global plasma confinement in magnetospheres is maintained remains incomplete.

In our recent study [1], we discovered that the entropy-mode turbulence leads to thermal equilibration between species in magnetospheric plasmas, even without collisions. A classical stability analysis in terms of energetic considerations reveals that the roles of electrons and ions in destabilizing the system, through resonance with drift waves, interchange depending on their temperature ratio. The species with the lower temperature carries negative energy, extracting free energy from the background density gradient to drive turbulence. This turbulence, originating from a microscopic (kinetic) instability, naturally redistributes internal energy between species, predominantly via linear wave-particle interactions. As a result, the system tends to evolve toward a state of equal temperatures for electrons and ions.

To verify this thermal equilibration mechanism, we conducted numerical simulations using the gyrokinetic code GS2. The simulation results clearly show that the turbulent heating of ions (equivalently, the cooling of electrons) reverses sign as the temperature ratio of ions to electrons (τ) crosses unity (see Fig. 1). In other words, the hotter species consistently transfers energy to the colder species through turbulence, demonstrating that thermal equilibration occurs spontaneously.

This finding introduces a new ingredient into the energy transport processes in magnetospheric plasmas. It provides a more consistent and physically grounded explanation of the global self-organization phenomena observed in space plasma environments. Furthermore, this mechanism may also play a role in other magnetically confined plasmas, such as dipole fusion devices or astrophysical systems where collisionless conditions prevail.

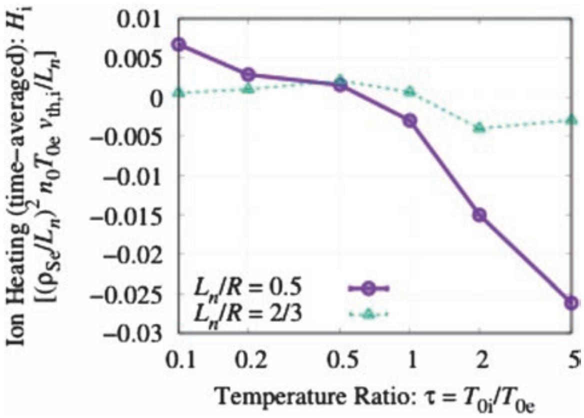


Fig. 1 The time-averaged ion heating H_i in the saturated states obtained from non-linear gyrokinetic simulations. Ions will be cooled (heated) for $\tau > 1$ ($\tau < 1$) to approach the equal temperature state [1].

[1] R. Numata, Mon. Not. R. Astron. Soc. Lett. **538**, L94–L99 (2025).

(R. Numata, University of Hyogo)

Spatio-temporal decomposition of abrupt particle transport via data-driven modal analysis

Understanding abrupt phenomena in magnetized plasmas is critical for predicting transport events that impact confinement. In this study we analyzed the onset of abrupt transport driven by turbulence using a three-dimensional numerical simulation, based on the Hasegawa–Wakatani model, by using data-driven modal analysis [2]. A limit cycle behavior of Kelvin–Helmholtz (KH) turbulence, in which an abrupt transport is driven, is realized by introducing an externally applied vorticity source.

To identify the underlying physical processes, we applied multi-field singular value decomposition (SVD) [3, 4] to simultaneously decompose the density and electrostatic potential fields in combination with hierarchical clustering [5, 6], as shown in Fig. 2. This technique enabled us to extract common spatio-temporal structures from the two fields and to classify the modes into four categories: background, zonal flow, coherent KH mode, and incoherent mode.

By computing the mode-wise product of density and radial E × B flow, we constructed a transport matrix to quantify the contribution of each mode coupling to the net radial transport. We found that abrupt transport events are driven by nonlinear interactions between the background density and the incoherent radial flow component.

Temporal analysis revealed that abrupt transport occurs when the phase alignment between density modes and the incoherent radial flow mode is satisfied. This study demonstrates that multi-field SVD is a powerful tool for disentangling complex mode interactions and elucidating the physical mechanisms underlying abrupt transport phenomena in magnetized plasmas.

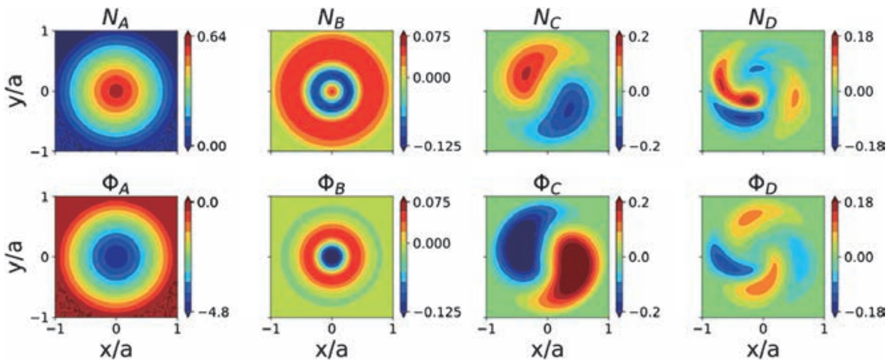


Fig. 2 Decomposed SVD modes [2]. Upper and Below panels correspond to the modes of density and electrostatic potential, respectively. Copyright 2025 IOP Publishing

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[4] G. Yatomi, M. Nakata, M. Sasaki, Plasma Phys. Control. Fusion **65**, 095014 (2023).
[5] A. Okuno, T. Kodahara, M. Sasaki, Plasma Fusion Res. **19**, 1201035 (2024).
[6] A. Okuno, M. Sasaki, Phys. Plasmas **32**, 032502 (2025).

(M. Sasaki, Nihon University)