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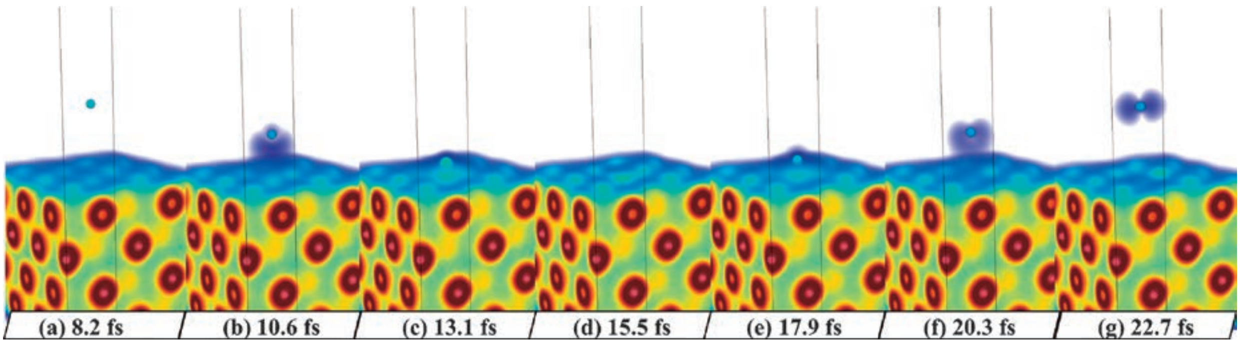
ANNUAL REPORT OF NATIONAL INSTITUTE FOR FUSION SCIENCE

April 2023 – March 2024



NATIONAL INSTITUTE FOR FUSION SCIENCE
TOKI CITY, JAPAN

Front Cover Caption:

Time-dependent density functional theory (TDDFT) simulation for the electron transition process from a tungsten surface to an incident He^{2+} ion.

Reprinted from Nuclear Materials and Energy, Volume 42, Atsushi M. Ito, Yuto Toda, Arimichi Takayama, Quantum electron dynamics in helium ion injection onto tungsten surfaces based on time-dependent density functional theory, 101836, Copyright (2024), with permission from Elsevier

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ANNUAL REPORT OF NATIONAL INSTITUTE FOR FUSION SCIENCE

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NATIONAL INSTITUTE FOR FUSION SCIENCE

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National Institute for Fusion Science
April 2023 – March 2024

Towards a new era of fusion science

Fusion science is a comprehensive area encompassing various disciplines with extremely high potential. Not only the immense merit of fusion energy, but also the possibilities of new discoveries give us the motivation to climb a high mountain – the history of overcoming every challenge has brought academic depth and breadth to fusion science. While the physics of fusion reactions is already well known, we have yet to understand how a "system", called high-temperature plasma, can maintain a stable condition. It is a macroscopic system producing an internal energy by which autonomous dynamics sustains. The aim of fusion science is to elucidate the mechanism of such a spontaneous process; the fundamental principle must be common to the dynamics of the universe, society, or life. Recognizing the problem in a wide context, we pave the way in a zone of fundamental studies. On the way to fusion, the ultimate energy source, we will encounter many crossroads leading to future science and technology.

As we know, there are three different states of matter, i.e., solid, liquid, and gas. Even if the same molecules constitute matter, its "slate" varies as the temperature is changed. At a high temperature, all matter becomes gas, in which molecules are disconnected and distribute sparsely, moving freely. When the temperature is raised further, molecules are broken into ions (positively charged heavy particles) and electrons (negatively charged light particles) by disconnecting the electrical bonding of ions and electrons; we call such a high temperature state "plasma". While plasma is not common on Earth, it is the most typical state of matter in the universe. Our sun is a huge mass of plasma, consisting mainly of hydrogen. Inside it fusion reactions produce enormous energy. A star is a naturally made sustainable system of high temperature plasma, energized by fusion reactions.

Although the fusion energy is often likened to a "sun on Earth", we need to think of a system that is completely different from stars. The challenge of fusion science is, indeed, to build a sustainable fusion system, based on a thoroughly new mechanism that we cannot find an example of in nature. A star confines plasma by gravity, but it is a very weak force, only effective against huge masses such as celestial bodies. We have to invoke a much stronger force to create a compact confinement system; magnetic force is the recourse. However, magnetic force acts like a "vortex" and its role in creating macroscopic structures is an interesting subject of contemporary physics and mathematics. We also need a much higher temperature than that at the center of the sun. In a typical star like our sun (the main sequence star), the reaction of synthesizing a helium atom from a hydrogen atom proceeds slowly. This reaction (a so-called p-p chain reaction) is too slow for producing sufficient fusion power in a compact system. We need to apply a faster reaction than that of the sun; the easiest is the deuterium-tritium fusion reaction, which produces helium and neutrons, but occurs at temperatures of around 100 million degrees Celsius. On the other hand, several meters away from the plasma, we have to place super-conducting magnets to generate the magnetic field, which are operated at ultra-low temperature. Therefore, fusion on Earth requires an extreme technology, dealing with ultra-high and ultra-low temperatures, separated only by several meters.

The road to fusion power is purgatorial and much harder than the prediction made at the beginning (the mid-20th century). However, it is not necessarily unfortunate that we encounter unexpected challenges. As many great researchers say that discovery is born from failure, unknown truths exist outside the range that one can predict. Fusion energy is a steep peak for development researchers to climb, but it is also a treasure trove for academic researchers. The task of the academic researcher is to generate new knowledge from the input of difficult problems.

All members of the National Institute for Fusion Science (NIFS) are working on the construction of a lighthouse that illuminates the direction of fusion science in choppy academic waters ahead. NIFS is a broad avenue for many researchers, through which the scope of "fusion science" will extend in the world of science. We hope that many people will pay attention to our endeavor and participate in these activities.

YOSHIDA Zensho
Director General of National Institute for Fusion Science

1. Unit

As an inter-university research institute, the National Institute for Fusion Science (NIFS) is required to continue to conduct cutting-edge academic research that supports the development of fusion science as interdisciplinary collaborative research, with the active participation of researchers and students from a wide range of fields. To strengthen and expand collaboration between NIFS and universities through interdisciplinary research, a new "Unit System" was established over two years of discussion and founded in FY2023.

Fusion science is an exhaustive research field that aggregates many complex issues. NIFS has the role of realizing collaborative research in coordination with other fields by dividing the challenge of fusion energy into several themes and generalizing each problem. Units are interdisciplinary collaborative research teams that come together under a common research theme, and the Department of Research consists of the following ten Units.

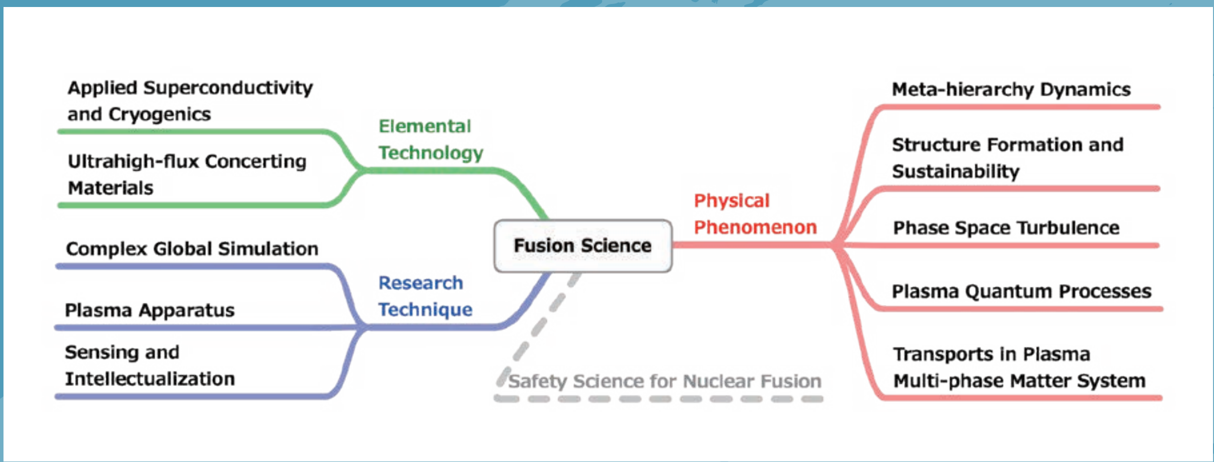

Fig. 1 The Unit System in NIFS. Five Units are focused on physical phenomena, two focus on elemental technology, and three on research techniques. Discussions are continuing on establishing an 11th Unit, "Safety Science for Nuclear Fusion."

Units are organizations constituting NIFS and are managed in conjunction with the community through the Unit Research Strategy Council, which includes members from outside NIFS. Thus, the community's opinions are directly reflected in the management of NIFS. In addition, many collaborators from universities and research institutions in Japan and overseas participate in the Units' research activities, as shown in the figure.

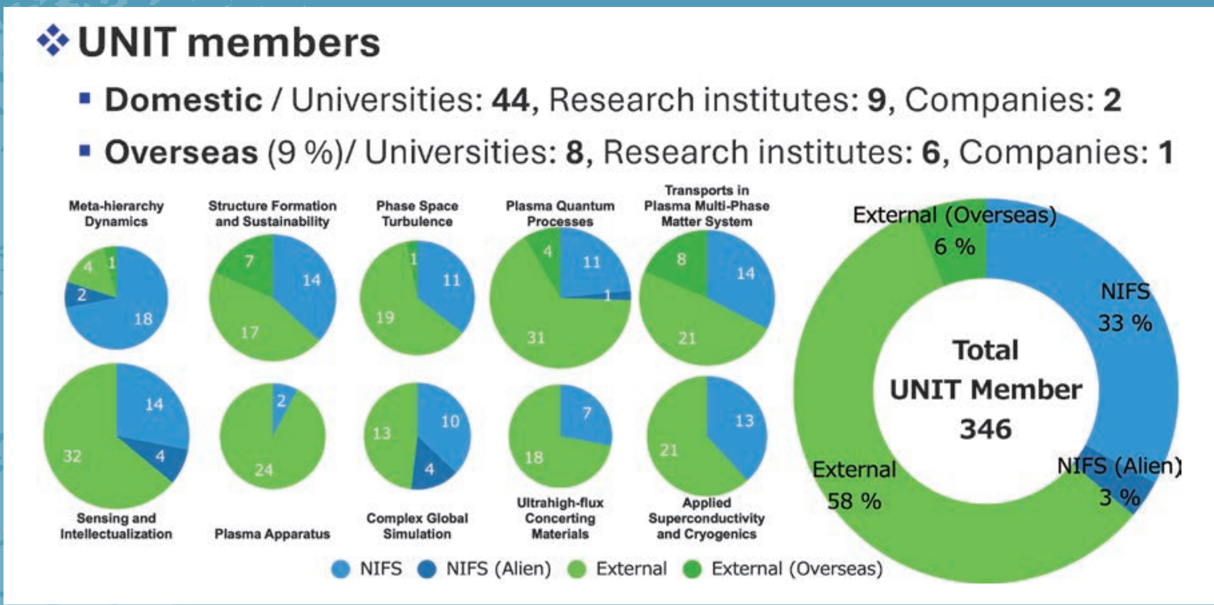

Fig. 2 Composition ratio of Unit members who contribute to arranging an academic plan for the Units from domestic and international universities and research institutions.

The Unit System has established a methodology for conducting cutting-edge academic research that supports the development of fusion science as interdisciplinary collaborative research, with the active participation of researchers and students from various fields.

(R. Sakamoto)

Meta Hierarchy Dynamics Unit

Highlight

Nested invariant tori foliating a vector field and its curl: toward MHD equilibria and steady Euler flows in toroidal domains without continuous Euclidean isometries

We have tackled the challenge of finding a three-dimensional solenoidal vector field where both the field itself and its curl are tangential to a set of given toroidal surfaces. Our approach translates this problem into finding a periodic solution with periodic derivatives for a two-dimensional linear elliptic second-order partial differential equation on each toroidal surface. In the case of magnetohydrodynamics (MHD), the equilibria in a smooth toroidal domain Ω are described by magnetohydrostatic (MHS) equations as

$$(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \mu_0 \nabla P, \quad \nabla \cdot \boldsymbol{B} = 0 \text{ in } \Omega, \ \nabla P \times \boldsymbol{n} = \boldsymbol{0} \text{ on } \partial\Omega, \qquad (1)$$

where $\boldsymbol{B}$ and P are the magnetic field and the pressure, respectively, μ_0 is the permeability in a vacuum, $\partial\Omega$ is the bounding surface of Ω, and $\boldsymbol{n}$ is the unit vector normal to $\partial\Omega$. Given a set of nested flux surfaces $\Psi(x)$, it has been shown that there exists an integration factor $\lambda(x)$ and a solenoidal vector field $\boldsymbol{B}$ such that $(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \lambda \nabla \Psi$ [1]. An example of the result is shown in Fig. 1.

Additionally, we have constructed explicit examples of smooth solutions that are foliated by toroidal surfaces but are not invariant under continuous Euclidean isometries. These solutions are identified as equilibria in anisotropic magnetohydrodynamics.

This investigation addresses a simpler version of a fundamental mathematical problem in MHD and fluid mechanics. Specifically, it concerns the existence of regular equilibrium magnetic fields and steady Euler flows in bounded domains that lack continuous Euclidean isometries. Resolving this problem is crucial for designing confining magnetic fields in nuclear fusion reactors, such as stellarators.

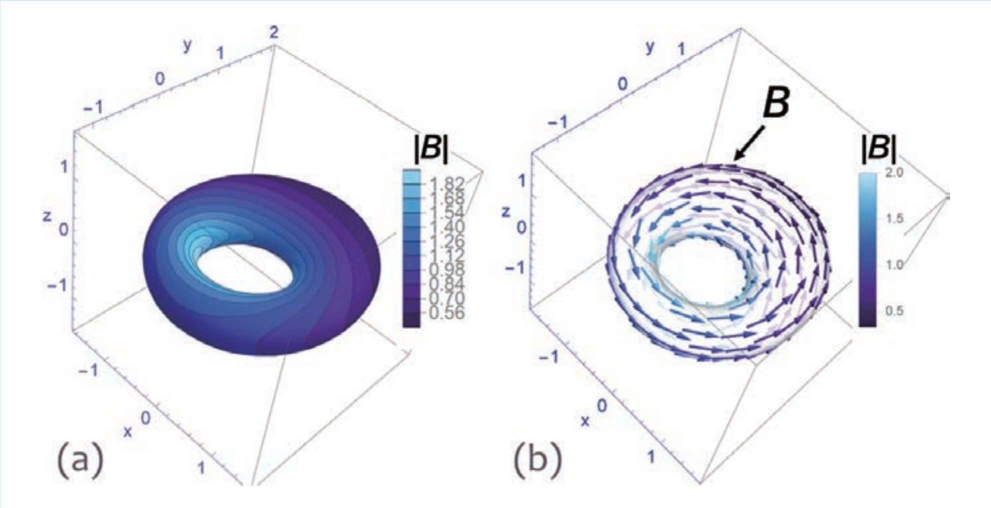

Fig. 1 Example of the result: (a) Contour plot of $|\boldsymbol{B}|$ and (b) Vector plot of $\boldsymbol{B}$. Cited from Ref. [1]

[1] N. Sato and M. Yamada, J. Math. Phys. **64**, 081505 (2023).

(N. Sato)

Experimental study of the effect of geodesic curvature on turbulent transport in magnetically confined plasma

An experimental study utilizing the Large Helical Device has elucidated the influence of the geodesic curvature of magnetic field lines on turbulent ion-heat transport in magnetically confined plasmas. Statistical analyses, employing the corrected Akaike Information Criterion and multiple regression techniques, have identified geodesic curvature as a significant factor affecting ion-heat transport.

Further evaluation of the geodesic curvature's impact on the zonal-flow effect was conducted using a reduced model based on gyrokinetic simulations. Figure 2 shows the summary of an experimentally obtained data set of the ion-heat transport and turbulence intensity with almost the same non-dimensional parameters. It is seen that the ion-heat transport tends to increase with geodesic curvature. Furthermore, the zonal-flow effect is evaluated and plotted as a function of the geodesic curvature in Fig. 3. This analysis suggests a notable enhancement of the zonal-flow effect when the geodesic curvature is small. Collectively, these independent analyses indicate the potential for external control of zonal flows through manipulation of the magnetic field's geodesic curvature.

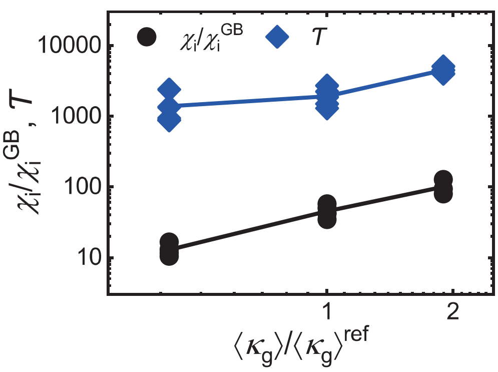

Fig. 2 Normalized ion-heat transport coefficient χ_i/χ_i^{GB}, and turbulence intensity T as a function of normalized-geodesic curvature ($\langle\kappa_g\rangle/\langle\kappa_g\rangle^{ref}$). Cited from Ref. [2].

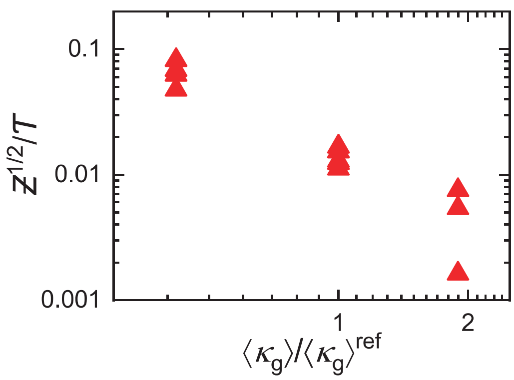

Fig. 3 Zonal-flow effect $Z^{1/2}/T$ as a function of normalized-geodesic curvature ($\langle\kappa_g\rangle/\langle\kappa_g\rangle^{ref}$). Cited from Ref. [2].

[2] S. Nishimoto *et al.*, Plasma Phys. Control. Fusion **66**, 04501 (2024).

(K. Nagaoka)

An Inductively Coupled Plasma System for Investigating Spectropolarimetric Responses of Solar Plasmas to Anisotropic Fields

Accurate measurements and modeling of atomic polarization in three-dimensional radiation transfer are essential for understanding the structure of magnetized solar plasmas. To develop and validate spectropolarimetric measurements and analyses, we have constructed an inductively coupled plasma (ICP) generator specifically designed for plasmas with ~1 eV electron temperatures, interacting with radiation and weak magnetic fields. This device was positioned in front of the focal plane of the Horizontal Spectrograph at the Domeless Solar Telescope, Hida Observatory, Kyoto University.

In helium discharges, the electron temperature, electron density, and helium column density of the ICP closely match those found in solar prominences. Comparative spectral analysis reveals nearly identical opacity at He I 1083 nm. By introducing magnetic and radiation fields into the ICP, the system successfully reproduces spectropolarimetric signals as shown in Fig. 4. The results are consistent with those observed in solar prominences [2].

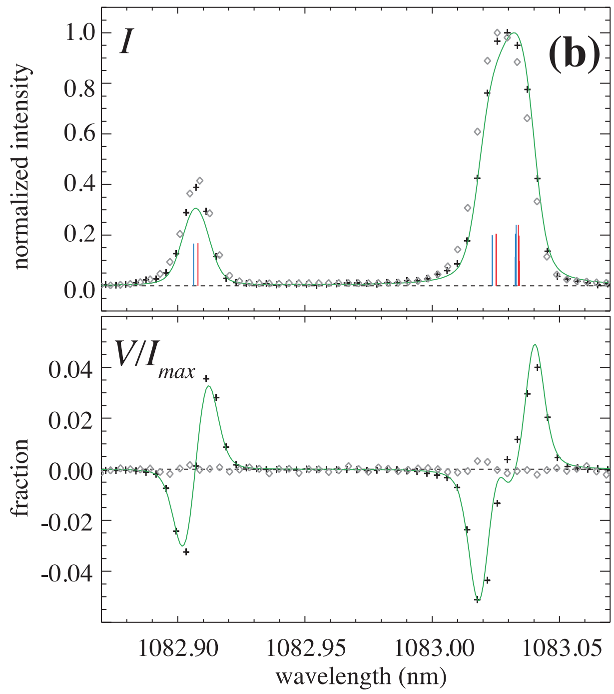

Fig. 4 Normalized intensity I/I_{max} and circular polarization V/I_{max} from ICP with (black pluses) and without (gray diamonds) magnets under RF power of 100 W and neutral pressure of 5.0 Pa. Blue and red bars show intensities of −σ and +σ components, respectively. Green curves show best fit function. Cited from Ref. [3].

[3] T. Kawate *et al.*, Plasma and Fusion Research **18**, 1401037 (2023).

(T. Kawate)

Structure Formation and Sustainability Unit

Improving plasma performance and establishing steady-state confinement are central challenges in research to develop fusion reactors that are efficient and compact. The key is to understand the mechanism by which plasmas spontaneously form and maintain their internal structure. When energy is injected into a macroscopic system formed of many components, such as particles, the energy tends to spread among the components. Suppose the system is isolated, meaning there is no energy, momentum, or particle exchange between the system and its environment. In that case, after a sufficiently long time, the system becomes so homogeneous that there is no more “spreading” of energy— it is a maximum-entropy state. However, many systems in the real world are virtually not isolated. In these systems, inhomogeneous structures often emerge and persist. Elucidating the principles that describe structure formation and sustainability in such non-equilibrium systems is one of the biggest challenges of modern science. Fusion science shares this challenge with other research fields, as magnetically confined fusion plasma is a treasure trove of structure formation and self-organization phenomena. Structure formation in plasmas is also common in celestial bodies such as magnetospheres and accretion disks, and is a fundamental concept for understanding the universe. The Structure Formation and Sustainability (SFS) Unit aims to elucidate the principles of structure formation through plasma experiments, theories, and simulations. We comprehensively cover the energy flow through fusion plasma as a system, from the generation of energetic particles to the transport processes that carry energy outside of the plasma. Our research target includes the development of precise measurement of energetic particles and theoretical models/simulations of micro- and macroscopic structure formation, revisiting fundamental physics concepts such as symmetry and entropy production. We are also developing tools to design an innovative fusion reactor. Based on these, we explore the high-performance confinement of fusion plasma.

Highlight

Design of new experimental device by advanced optimization technique

Fusion plasma is full of fluctuations of electric and magnetic fields associated with the collective motion of charged particles. These fluctuations are not only considered to be the primary cause of deterioration of plasma confinement but also known to regulate themselves to form ordered structures sustaining confinement. Clarifying the origin and consequence of these fluctuations is critical to developing a compact and efficient fusion reactor. The SFS Unit has started designing a new experimental device to study how collective motion emerges and is regulated in plasma by manipulating the motion of charged particles with a magnetic field. The design process of this device utilizes a new optimization method for the magnetic coils of toroidal fusion devices that the National Institute for Fusion Science has been developing since 2018 [1]. Conventional techniques optimize magnetic configuration and coil shape separately. Our new method optimizes coil shape and the resulting magnetic configuration simultaneously. This new approach enables us to find a coil geometry that can flexibly change the magnetic field while maintaining good plasma confinement. In FY2023, we completed the first conceptual design, confirming that there are coil geometries that realize two types of three-dimensional magnetic configurations with different symmetries, only by changing coil current patterns. Symmetry is an essential parameter of magnetic configuration, as a lack of symmetry can lead to less efficient plasma confinement by complicating the particle motion. Our coil design can realize excellent quasi-symmetry similar to a tokamak and another symmetry similar to a mirror device. We find that the particle motion in these magnetic configurations is drastically different (Fig. 1). We expect that experiments using this new device will open a path to a universal understanding of how the energy of particle motion is converted into collective fluctuations and drives structure formation. Such understanding will contribute to an innovative design of fusion reactors that realizes improved plasma performances.

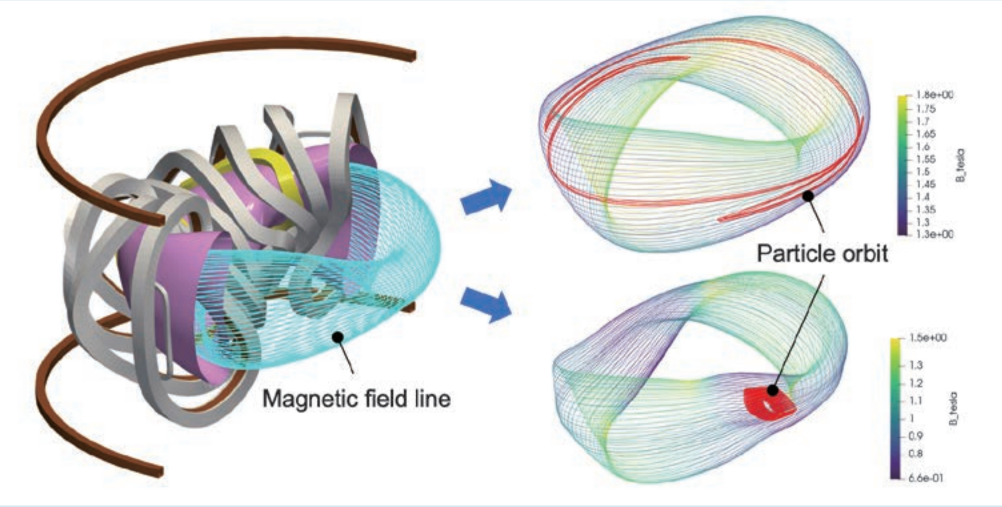

Fig. 1 (Left) the magnetic coils and vacuum vessel of the first conceptual design of a new experimental device (only for a 180° section) and magnetic field line. (Right) typical particle orbit (red curves) in two different magnetic configurations.

(H. Yamaguchi)

Development of gamma-ray diagnostics for high temporal and energy resolution measurements

Clarifying how often and where fusion reactions occur inside plasma is crucial for deepening the understanding of burning-plasma physics. A useful method to accomplish this is by detecting the radiations emitted by byproducts of fusion reactions. Gamma-ray diagnostics are essential for measuring energy production in burning-fusion plasmas, complementing neutron flux measurements. In fusion research, these diagnostics have been used to measure the temperature of fuel ions and to study the confinement of energetic particles. In the Large Helical Device (LHD), a gamma-ray diagnostic based on an $LaBr_3$:Ce scintillation detector (Fig. 2), characterized by high detection efficiency and high temporal resolution, was newly installed through a collaboration between the National Institute for Fusion Science, Kyushu University, and Mahasarakham University of Thailand. Mitigating the effects of stray neutrons and gamma rays is key for this new diagnostic system to detect the gamma rays originating from a fusion reaction inside plasma. To this end, we designed shielding based on simulations using the Monte Carlo method. The new diagnostic system worked effectively, and gamma ray spectra were measured in deuterium plasma discharges where hydrogen-beam injection and ^{6}LiF pellet injection were conducted. A significant peak in the gamma-ray spectrum at approximately 0.48 MeV was observed, most likely due to the fusion reactions between deuterium ions and ^{6}Li ions (^{6}Li(d,γ)^{7}Li reaction) inside the plasma. The improvements in the detector performance have extended its operating range and allowed the observation of gamma rays [2]. This is an important step toward experimentally elucidating the behavior of energetic alpha particles produced by fusion reactions.

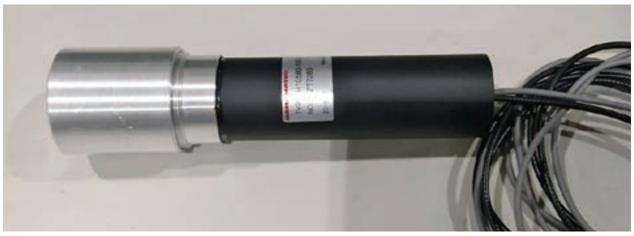

Fig. 2 $LaBr_3$:Ce scintillation detector

(K. Ogawa)

Degradation of energetic-ion confinement independent of MHD instabilities is observed.

Neutral beam injection (NBI) is one of the most reliable methods of plasma heating in magnetic confinement fusion devices. Although the total power injected into plasma by a beam injector is measurable, the actual power absorbed in the plasma (in other words, heating efficiency) is not directly measurable. For this reason, estimating energetic-ion loss and clarifying its mechanisms are necessary. In the LHD, deuterium experiments were conducted from 2018 to 2022. Neutron emission due to a fusion reaction between a neutral beam deuterium-ion and a thermal deuterium-ion contains valuable information on how long energetic ions are confined in plasmas. We conducted the deuterium experiments in LHD and simulated the neutron emission rate using the integrated simulation code TASK3D-a to investigate the energetic ion loss mechanisms. By utilizing the integrated simulation, together with the measured data of neutron emission and impurity-ion density in the deuterium plasma discharges of the LHD, we discovered a confinement degradation phenomenon of energetic ions that had not been recognized before. This degradation, depending on NB power, was observed without the increase in the intensity of magnetic fluctuations associated with magnetohydrodynamic (MHD) activities. Due to this degradation, the neutron emission rate per NBI power decreased by up to 20% after the NBI power was doubled (Fig. 3). We have also found that this degradation is localized around the magnetic axis, which is the center of the plasma. Energetic-ion losses due to MHD activities have been intensively studied as they are concerned with limiting the heating efficiency in fusion reactors in the future. On the other hand, the confinement of energetic ions produced by NBI had been considered to be able to be estimated accurately when MHD activities inside the plasma are negligibly weak. Our discovery of this confinement degradation phenomenon in LHD, enabled by the deuterium experiment, improves the accuracy of predicting energetic ion confinement without MHD activities. This is a basis for obtaining a deeper understanding of MHD-induced energetic-ion losses. Our next step is to identify the mechanisms of this confinement degradation. This research result was published in Nuclear Fusion, a journal specializing in fusion science, on April 18th, 2024.

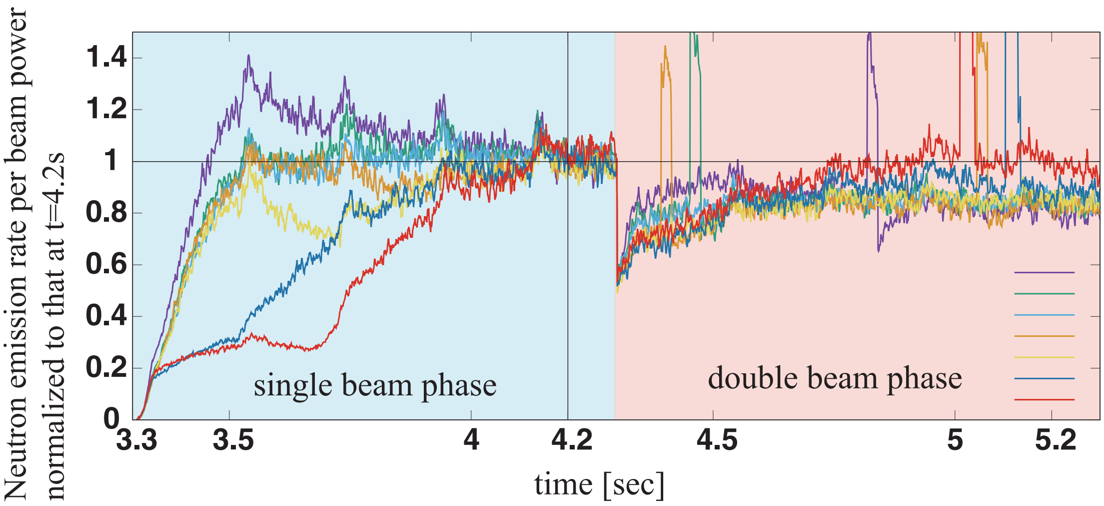

Fig. 3 The vertical axis indicates the neutron-emission rate per beam power normalized to that at t=4.2s, and the horizontal axis indicates the time from the start of the discharge. The beam power increases by two times after t=4.3s. Curves in different colors indicate the discharges with different plasma densities. In most discharges, the neutron-emission rate per beam power is reduced by up to 20% after the beam power increases. This reduction reflects the degradation of the confinement of energetic ions.

(H. Nuga)

[1] H. Yamaguchi *et al.*, “Development of coil-shaping-based optimization code for magnetic fusion devices” 29th IAEA Fusion Energey Conference, TH/P2-14 (2023).
[2] K. Ogawa, S. Sangaroon, L.Y. Liao, H. Matsuura *et al.*, Journal of Instrumentation **18**, P09024 (2023).
[3] H. Nuga, R. Seki, K. Ogawa, H. Yamaguchi, S. Kamio, Y. Fujiwara, Y. Kawamoto, M. Yoshinuma, T. Kobayashi, Y. Takemura, M. Isobe, M. Osakabe and M. Yokoyama, “Degradation of fast-ion confinement depending on the neutral beam power in MHD quiescent LHD plasmas”, Nuclear Fusion **64**, 066001 (2024).

Phase Space Turbulence Unit

Phase-space tomography

Magnetically confined fusion plasmas are generally very low in density, so particle collision rarely occurs. Particles have electric charges therefore can be trapped or expelled in a phase of electrostatic waves. Those trapped particles travel with the waves while being bounced by wave potential, like surfing (Fig. 1). During this motion, the waves and particles can exchange their energy and momentum, leading to more complicated behaviors. As a result, different nonlinear phenomena that significantly impact on plasma confinement can occur: for example, enhanced-plasma transport that makes the plasma confinement worse and collisionless plasma heating. So far, direct observation of those wave-particle interactions has been extremely challenging and therefore experimental knowledge obtained is limited. A key quantity is the velocity distribution function, which describes statistical properties of particle dynamics. In a non-fluctuation situation the velocity-distribution function follows Gaussian (normal) distribution.

One of the issues that makes phase-space structure measurement challenging is the trade-off relationship between time, real-space, and velocity-space resolutions and signal intensity. As the total signal intensity that is determined by the diagnostic system and plasma condition is constant, improving resolution results in a decrease of signal intensity at a single detector pixel [1]. Recently, a new signal processing algorithm has been proposed to overcome the trade-off relationship between resolutions and signal intensity, that is, phase-space tomography [2]. In this algorithm, a set of three integrated signals with the same viewing sight is used to recover three-dimensional resolution in phase-space. Integrations are performed in each dimension, i.e., time, real-space, and velocity-space. As a tomography technique, the maximum likelihood expectation maximization (MLEM) method is used. For test data generated according to an LHD observation, it was proven that the proposed method reasonably recovered the resolution from a set of integration data through this algorithm.

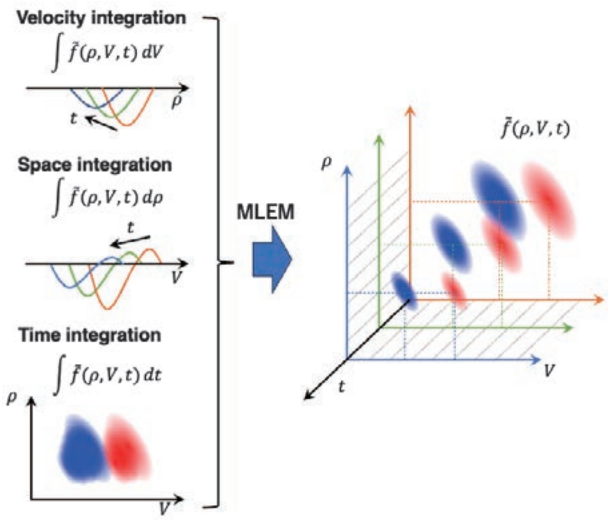

Fig. 1 Schematic of phase-space tomography

[1] T. Kobayashi, “Prospect for experimental investigation of phase-space turbulence in magnetically confined fusion plasmas”, Plasma and Fusion Research **18**, 2402059 (2023).
[2] T. Kobayashi, M. Yoshinuma, W. Hu, K. Ida, “Phase-space tomography in magnetically confined plasmas”, Physics of Plasmas **30**, 052303 (2023).

(T. Kobayashi)

First demonstration of predictive control of fusion plasma by digital twin: application of data assimilation to adaptive predictive control

Fusion energy, particularly through magnetic confinement, is a promising solution to global energy problems. This method involves confining high-temperature plasma within a reactor using a magnetic field to convert fusion energy into electricity. Predicting and controlling the complex behavior of fusion plasma is essential for success. One approach, digital twin control, uses a simulated plasma to guide the actual plasma control. This is challenging due to the need to consider factors like plasma flow, heating, fuel supply, impurities, and neutral particles, along with limited measurement capabilities in future reactors.

A new control system to optimize predictive models using real-time observations has been developed in collaboration with the Phase Space Turbulence Unit, the Structure Formation and Sustainability Unit, the Sensing and Intellectualizing Technology Unit, the Plasma Quantum Processes Unit, and the Complex Global Simulation Unit. This system, called ASTI (Assimilation System for Toroidal Plasma Integrated Simulation), employs data assimilation to improve the accuracy of numerical simulations by incorporating observed data. ASTI adapts the simulation model to the actual behavior of the fusion plasma in real time, allowing for accurate predictions and control. It performs numerous parallel simulations to probabilistically predict the plasma's future state, adjusting to real plasma observations and target states for optimal control estimation. This system was tested on the Large Helical Device (LHD), a leading superconducting plasma experimental facility. An experiment to control the electron temperature of the plasma using electron cyclotron resonance heating (ECH) demonstrated the successful predictive control of fusion plasma by a digital twin, based on data assimilation. The electron temperature was brought close to the target while improving the prediction accuracy, marking a world-first achievement. This control approach is expected to be fundamental for fusion reactor control, addressing issues like plasma density and temperature-profile control and controlling quantities not directly measured.

The development of the control system represents a significant step toward advanced controls necessary for fusion power generation. Future plans include expanding the control system and conducting more advanced demonstrations at the LHD and other experimental devices worldwide. This data assimilation-based method provides a foundation for adaptive-predictive control in scenarios where high accuracy prediction by simulation alone is difficult. It also has potential applications in solving complex societal issues with many uncertain factors, such as road traffic control and river water level management.

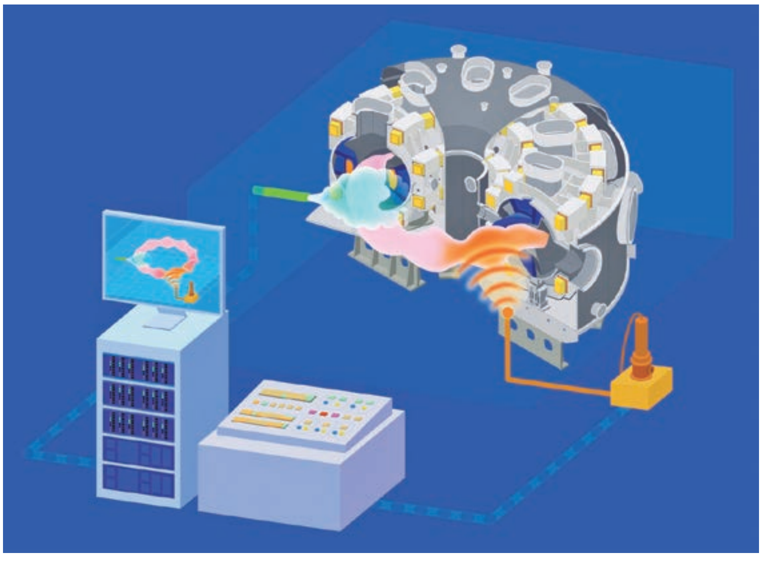

Fig. 1 Image of digital twin control, in which real plasma is controlled by virtual plasma reproduced on a computer.

[1] Y. Morishita *et al.*, Scientific Reports **14**, 137 (2024).

(N. Kenmochi)

International joint research for development of output power of 1 MW with a 35 GHz gyrotron

In FY2022, we agreed a research partnership with Kyoto Fusioneering, a fusion start-up company, to collaborate on “research on the long pulse of high-power gyrotrons, etc.” As part of this joint research, we focused on developing a beam oscillation and transmission system for a gyrotron operating at low frequencies (28 GHz/35 GHz). This system will be utilized for plasma heating and current-drive experiments in the MAST-U fusion spherical tokamak device at UKAEA. Since high-power oscillation and transmission in this low-frequency range is unprecedented, we needed to develop the gyrotron and its associated components. We tested a dual-frequency gyrotron tube designed for a nominal-beam output of 1 MW-3 s and its peripheral components for testing at our institute. We conducted magnetic field measurements with a superconducting magnet (Fig. 1), installed and adjusted the gyrotron (Fig. 2 left), performed mode-purity measurements of the output beam at the exit of the gyrotron and after passing through mode matching unit (MOU) (Fig. 2 right), and carried out high-power and second-order oscillation tests. The dual-frequency gyrotron successfully achieved the output of 1 MW-3 s. Once developed, the gyrotron will be shipped to the UK for plasma experiments to gather valuable information for the design of future power plants and to address physics challenges.

Fig. 1 Magnetic field measurements carried out prior to installation of the gyrotron.

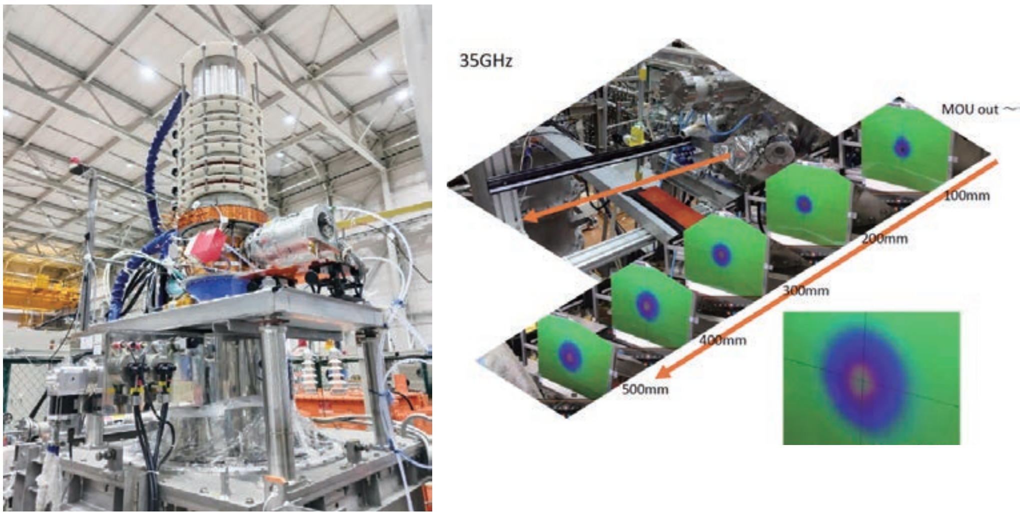

Fig. 2 A dual frequency gyrotron installed for oscillation and transmission testing (left figure). Output beam after passing the MOU. The expected Gaussian beam shape was obtained (right figure).

[1] Press release, Kyoto Fusioneering, National Institute for Fusion Science, Tsukuba University, UK Atomic Energy Authority, CANON ELECTRON TUBES & DEVICES, January 12, 2024, https://www.nifs.ac.jp/news/collabo/240112.html
Expert contact. M. Nishiura

[2] Newspaper interview, “Road to Compact of Fusion Reactor”, Gifu Shinbun, morning newspaper, page 3, February 10 2024.

(M. Nishiura)

Plasma Quantum Processes Unit

The goals of the Plasma Quantum Processes Unit are to advance interdisciplinary plasma research based on quantum processes, and to promote international collaborations. Toward these goals, each member of the Unit is pursuing research with the following academic strategies.

Advancement

- Advancement of plasma measurement based on highly-charged ion spectroscopy/quantum processes
- Inclusion of quantum physics in plasma kinetics and enhancement of accuracy of kinetic transport calculations including highly-charged ions
- Fusion reactor edge plasma modeling, including atomic and molecular processes and plasma-wall interactions

Interdisciplinary

- Collaboration with other fields using atomic and molecular data/promoting applications by developing databases
- Research on ultra-relativistic plasma dynamics, including quantum electrodynamics processes, and development of laboratory astrophysics using intense lasers
- Promoting collaboration with other units and interdisciplinary research with physics fields other than fusion, from the viewpoint of data-driven science and materials informatics for advanced measurements
- Interdisciplinary collaboration with particle-physics fields through research on quark-gluon plasma, and obtaining hints for new measurements in fusion-plasma experiments from detectors in high-energy accelerator experiments
- Applying cryogenic engineering technology developed in fusion research to high-energy density sciences

To ensure that the Unit's research activities are carried out with the participation of the broader academic community, a Unit Research Strategy Council was organized, inviting 15 external members from various research fields.

The unit regularly holds seminars with external collaborators to disseminate its research activities. From April 2023 to March 2024 ten seminars were held on relevant topics, i.e. highly-charged ion spectroscopy, data-driven sciences, quark-gluon plasmas, X-ray imaging and Spectroscopy Mission (XRISM), neutron star mergers and kilonovae, and intense laser-matter interaction and its applications.

Workshops and seminars for "2DMAT," a data-driven software framework developed in collaboration with ISSP, University of Tokyo, were organized to facilitate its applications to advanced plasma measurements.

The unit is developing numerical databases of atomic and ion-surface collisions for fusion and plasma applications by international collaborations. The databases are available on the internet (https://dbshino.nifs.ac.jp/index-j.html).

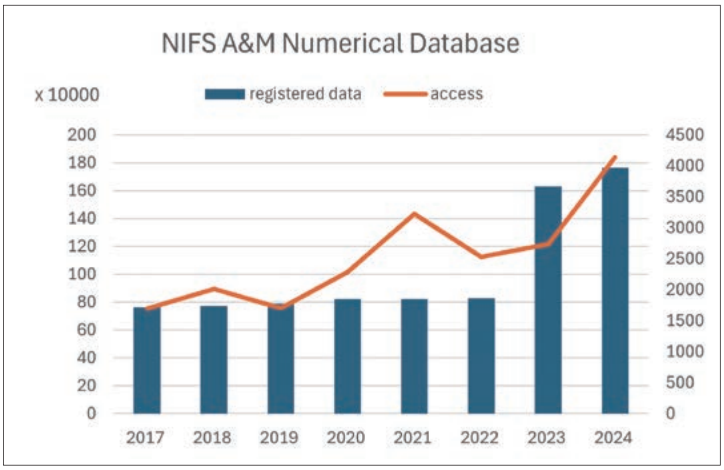

Fig. Annual changes in the number of registered data (left) and access (right) to the NIFS database. The numbers are shown until April of each year.

(D. Kato)

Highlight

Spectroscopy study of Kr^{25+} ion for krypton seeding experiment in the Large Helical Device [1]

A krypton gas impurity seeding experiment was conducted in the Large Helical Device. Emission lines from Na-like Kr ions in the extreme ultraviolet wavelength region, such as 22.00 nm, 17.89 nm, 16.51 nm, 15.99 nm, and 14.08 nm were observed. A suitable Collisional-Radiative (CR) model was developed to produce the synthetic spectrum of the Kr^{25+} ion. For this, the relativistic multiconfiguration Dirac–Hartree–Fock method was employed, along with its extension to the Relativistic Configuration Interaction (RCI) method for atomic structure calculations using the General Relativistic Atomic Structure Package-2018. In addition, another set of calculations was carried out utilizing the relativistic many-body perturbation theory and RCI methods integrated within the flexible atomic code. In addition, we undertook calculations of the cross-sections for the fine structure transitions of the Kr^{25+} ion using the relativistic distorted wave method [1]. We incorporated important electron impact excitation processes, along with their reverse processes in the CR model. Rate-balance equations were solved simultaneously for an electron temperature of 600 eV and an electron density of 6×10^{19} m^{-3}. To validate our findings, the emission lines measured in the experiment, were compared with the CR model spectrum and shown in Figure 1. Our comparative analysis revealed an overall good agreement with the CR model calculations.

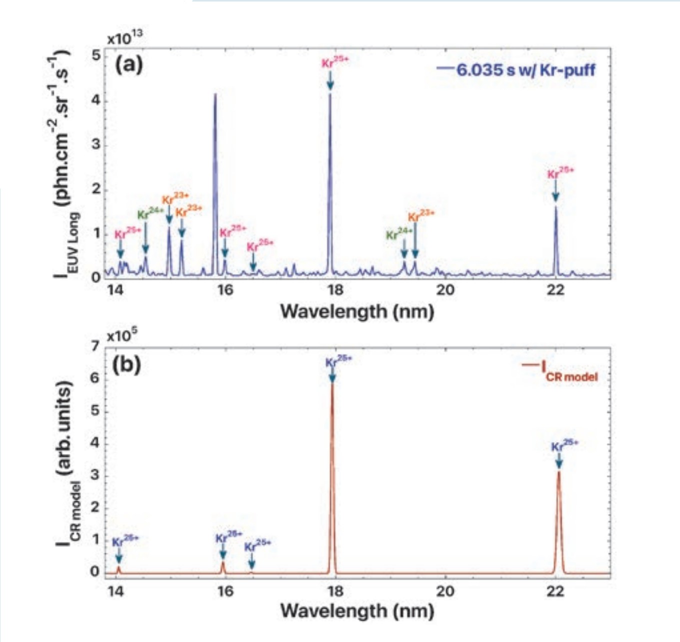

Fig. 1 (a) Experimental extreme ultraviolet spectrum of highly-charged Kr ions (14–23 nm) in the LHD, (b) comparative synthetic Kr^{25+} spectrum from the CR model

[1] S. Gupta, T. Oishi, I. Murakami, "Study of Electron Impact Excitation of Na-like Kr Ion for Impurity Seeding Experiment in Large Helical Device" Atoms, **11**, 142 (2023).

(S. Gupta, National Cheng Kung University, Taiwan)

Highlight

Abnormal ionization equilibrium mediated by long-lived metastable excited states [1]

The charge-state distribution of atomic ions in plasmas is fundamental to various plasma applications. For instance, industrial applications using highly-charged ions, e.g., an extreme-ultraviolet light source based on a laser-driven plasma, should maintain efficient production of the objective charge-state ions. The population distribution of charge states also provides crucial information for plasma diagnostics because it generally depends on the plasma condition. In particular, the electron-temperature dependence of the abundance ratio between neighboring charge states (higher to lower) generally shows a monotonical increment with increasing electron temperature. This general behavior is advantageous for plasma diagnostics of astrophysical and fusion plasmas. It is also useful for emission-line assignments, since the charge state of the ions can be easily identified by observing the electron temperature (energy) dependence of line intensities in a laboratory plasma.

In our recent activity on highly-charged ion spectroscopy using a compact electron beam-ion trap (CoBIT), we experimentally found that the above general behavior does not hold in some cases. The electron energy dependence of the line intensity ratio of Ba^{10+}/Ba^{9+} decreases with increasing electron energy in a particular energy region, implying there is a characteristic electron energy dependence of each ion abundance. We successfully reproduced the experimentally observed characteristic behavior using a state-of-the-art theoretical simulation based on fine-structure-resolved collisional-radiative modeling with ionization balance. The calculation results suggested that this anomalous behavior was caused by indirect plasma ionization processes from metastable states in Ba^{9+} and Ba^{8+}. The present study provides a new insight into plasma physics relevant to highly charged ions.

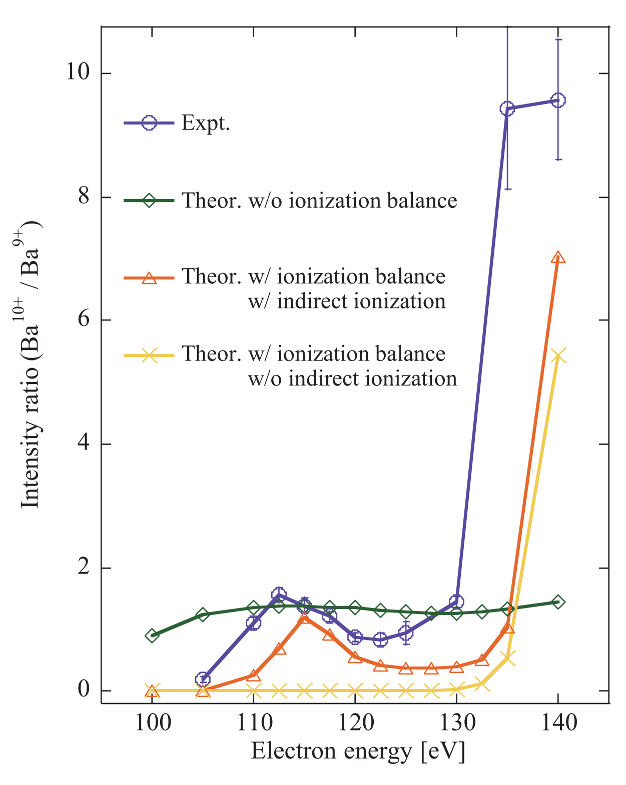

Fig. Electron-energy dependence of the intensity ratio between the extreme ultraviolet emission lines of Ba^{10+} and Ba^{9+}.

[1] N. Kimura, Priti *et al.*, "Anomalous plasma ionization balance induced by 5*s* and 4*f* metastable states", Physical Review A **108**, 032818 (2023).

(N. Kimura, Tokyo University of Science)

Highlight

Improvement of electron temperature and density accuracy in Thomson scattering diagnostics by an accumulation of 100 laser pulses within 5 milliseconds [1]

In electron temperature (T_e) and density (n_e) measurement by Thomson scattering diagnostics for high T_e and low ne plasmas, scattered light intensity is usually small because the total intensity of the scattered light and the Doppler broadening of the spectrum are related with n_e and T_e, respectively. In order to improve this, the signals from multiple laser pulses are accumulated. A Nd:YAG laser with a high repetition rate of up to 20 kHz is used in the Thomson scattering system in the LHD. In a 20 kHz operation, 100 laser pulses, each of which has almost 1 J of pulse energy, were irradiated in 5 ms with intervals of 50 μs. This method was tried for a plasma with ne lower than $2x10^{18}$ m^{-3} and almost in a steady state during this time range. The S/N ratio in raw signals by one laser pulse seems to be almost in the order of one. When more than ten signals are summed, the signal components become clear. Although the background level is important for the integration of the signals in time, it is still affected by noise in the case of the summation of the ten signals. The effect of the noise seems to disappear in the case of the summation of 100 signals. Figure 1 shows the spatial profiles of T_e (red) and n_e (blue) from (a) 1 signal, (b) 10 signals and (c) 100 signals. In Fig. 1 (a), the magnitude of T_e error is large and the T_e data are scattered. In Fig. 3 (c), the magnitude of error near the center is smaller than in (b). In this plasma, T_e around the center region is evaluated to be more than 15 keV, by averaging of the Thomson scattered signals from 100 laser pulses which are injected into the plasma within 5 ms.

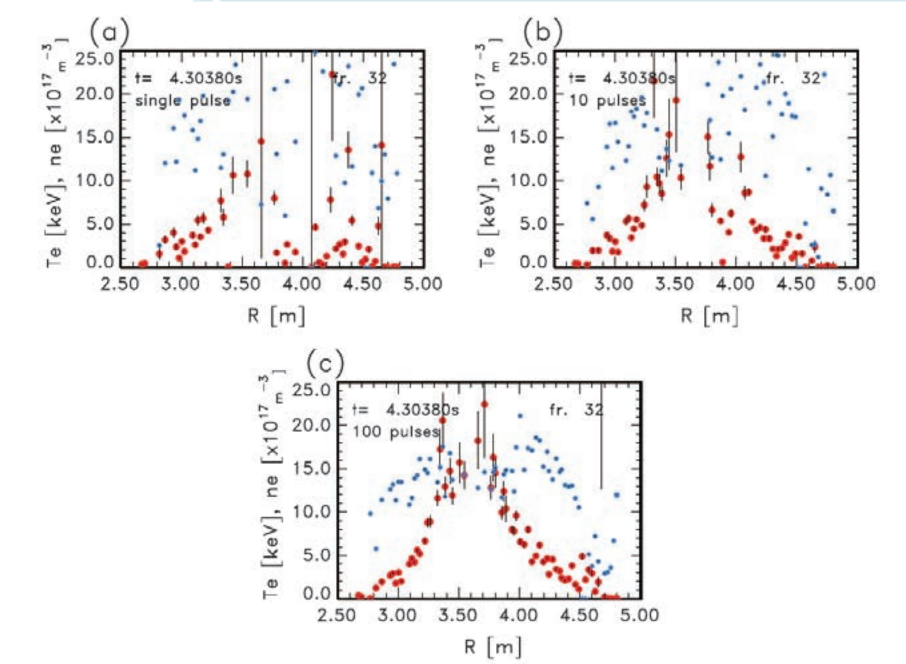

Fig. 1 The red closed circles show the T_e profile and the blue closed circles show the n_e profile. (a) Data by a single laser pulse is used. (b) Signals of ten laser pulses are averaged. (c) Signals of 100 laser pulses are averaged. [1]

[1] H. Funaba *et al.*, Journal of Instrumentations **18**, C11015 (2023).

(H. Funaba)

Highlight

Experimental investigations on space and astrophysical plasmas with lasers: magnetic reconnection in complex magnetic fields

The underlying physics of space and astrophysical phenomena has been investigated using scaled laboratory experiments, which is referred to as "laboratory astrophysics" in the field of laser-produced plasmas. In this fiscal year, we published an international collaborative paper with Japan, Taiwan, Czechia, and Indonesia on the structure formation during electron-scale magnetic reconnections in self-generated and external magnetic fields, using laser-produced plasmas [1]. We performed an experiment with complex magnetic-field lines due to two origins of the magnetic field: self-generated (Biermann battery) and external magnetic fields. Both magnetic fields formed anti-parallel magnetic-field configurations to drive magnetic reconnections. The emission images of plasma expansion in the presence and absence of the external magnetic field are compared in Fig. 1. In the absence of the external magnetic field in Fig. 1 (a), the plasma vertically expands at x~6 mm, which is a typical structure generated by magnetic reconnection in Biermann magnetic fields. The image with the external magnetic field in Fig. 1 (b) shows the horizontal separation of the plasma at x~4-5 mm, which is a signature of the magnetic reconnection in the external magnetic field. There is a vertical expansion with the external magnetic field; however, the signal intensity is weaker than that without the external magnetic field. This indicates that the magnetic reconnection in the self-generated magnetic fields can be suppressed in the presence of the external magnetic field. As a step beyond this, we are planning to investigate the connection between electron to magnetohydrodynamic (MHD) scales, using a co-creation platform of magnetic fields and lasers.

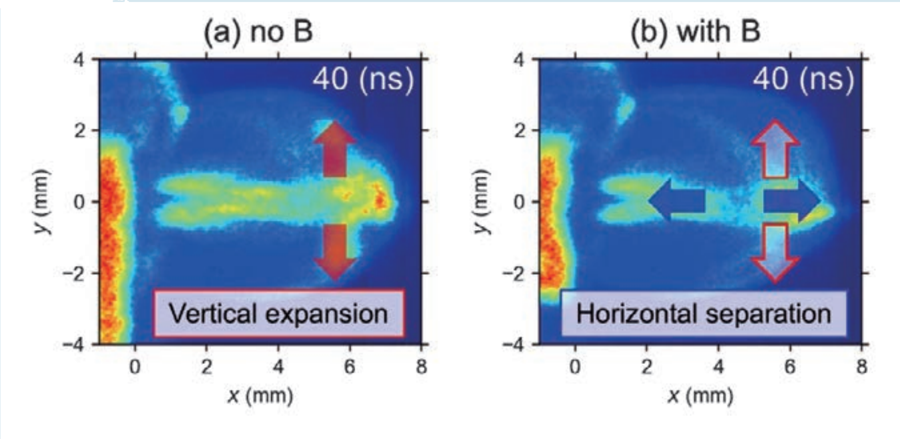

Fig. 1 Self-emission images of the plasma expansion obtained at 40 ns after the irradiation of the drive laser pulse (a) without and (b) with the external magnetic field.

[1] K. Sakai *et al.*, "Competition of magnetic reconnections in self-generated and external magnetic fields" High Energy Density Phys. **52**, 101132 (2024).

(K. Sakai)

Highlight

Transition Probabilities of Near-infrared Ce III Lines from Stellar Spectra: Applications to Kilonvoae [1]

Coalescence of binary neutron stars (NSs) is the promising site for the rapid neutron capture nucleosynthesis and thus for the origin of heavy elements in the universe. In 2017, associated with the detection of gravitational waves from an NS merger (GW170817), thermal emission powered by the radioactive decay of freshly synthesized nuclei in NS-merger ejecta (“kilonova”) was observed in ultraviolet, optical, and near-infrared (NIR) wavelengths. The observational properties of the kilonova provided us with evidence that the NS merger is a site where heavy elements are produced.

Nevertheless, a detailed abundance pattern, i.e., the species and amounts of synthesized elements is not clear and an important subject to study. One of the direct ways to find the synthesized elements is the identification of absorption lines in the observed spectra of a kilonova. Domoto et al. [2] have reported that one of the absorption features in the observed NIR spectra of the kilonova can be explained by the lines of Ce III. However, due to a lack of experimental data, they used theoretical transition probabilities (gf-values) of the Ce III lines whose accuracy is uncertain [3].

To verify this identification, in the present study [1], we derived the gf-values of three Ce III lines by utilizing stellar spectra showing Ce III absorption as a plasma laboratory. We modeled high-resolution NIR spectra of four stars by assuming the stellar parameters derived from optical spectra in the literature. We found that the derived values were broadly consistent with the theoretical values available from literature, within the uncertainties. We confirmed that the absorption features by Ce III appeared in the spectra, even considering the uncertainties in the derived gf-values. This supports the identification of Ce in the observed spectra of the kilonova.

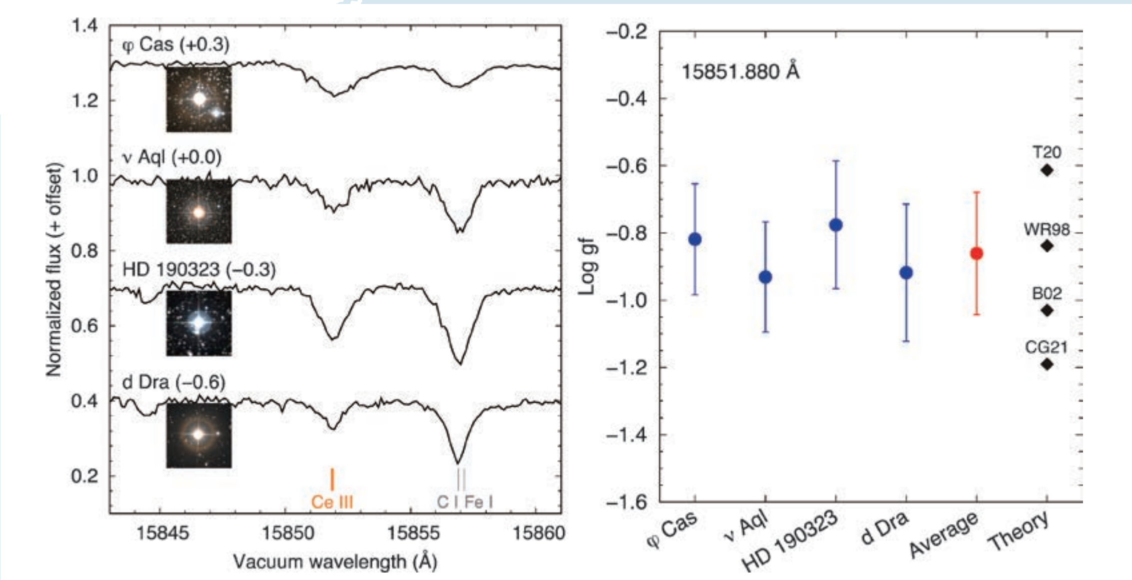

Fig. 1 Left: the stellar spectra used for this work, focusing on one of the Ce III lines (at 15851.880 Å). The position of the Ce III line is indicated by the orange line. The names and images of the stars are also shown. Right: the gf-values of one of the Ce III lines (at 15851.880 Å) derived from the four stars (blue), and their average as the final result (red). Black diamonds show the theoretical values available from literature.

[1] N. Domoto *et al.*, “Transition Probabilities of Near-infrared Ce III Lines from Stellar Spectra: Applications to Kilonovae” Astrophs. J. **956**, 113 (2023).
[2] N. Domoto *et al.*, “Lanthanide Features in Near-infrared Spectra of Kilonovae” Astrophs. J. **939**, 8 (2022).
[3] M. Tanaka *et al.*, “Systematic opacity calculations for kilonovae” Mon. Not. R. Astron. Soc. **496**, 1396 (2020).

(N. Domoto, Tohoku University)

Transports in Plasma Multi-phase Matter System Unit

The research aims of this Unit are: to understand, predict, and control heat, particle, and momentum-transport phenomena in systems where plasma contacts solids, liquids, and gases from the open magnetic field region of a magnetic confinement fusion reactor to the wall, coolant, exhaust system, and the fuel circulation system; to apply the knowledge and techniques gained from the studies mentioned above to various fields outside fusion, contributing to their advancement.

Here, the results obtained from research in this Unit and published as papers in FY2023 are introduced.

Simulation analysis of the ablation positions of boron dust particles dropped from the impurity powder dropper in LHD [1]

Control of the ablation positions of boron dust particles dropped from an Impurity Powder Dropper (IPD) is critical for effective real-time boronization. The movement of the ablation positions of dust particles toward the outboard side of the torus has been observed with an increase in plasma density. Figure 1 (a) presents fast-framing camera observations of the ablation of the dropped boron dust particles for two different line-averaged plasma densities $\bar{n}_e$ of 1 and 5×10^{19} m^{-3}, showing that the ablation position moved toward the outboard side with the plasma density. A dust particle transport simulation using the DUSTT code successfully reproduced the observations. Figure 1 (b) illustrates a simulation of the dropped dust particle trajectories in background plasmas with three different plasma densities at the Last Closed Flux Surface neLCFS of 1, 2, and 4×10^{19} m^{-3}, in which three-dimensional plasma parameter profiles were calculated by the EMC3-EIRENE code. The simulation revealed that the dropped dust particle trajectories were deflected toward the divertor plates at an upper divertor leg by the effect of the plasma flow. It also shows that the plasma-flow effect increased with the plasma density, resulting in the movement of the ablation positions toward the outboard side.

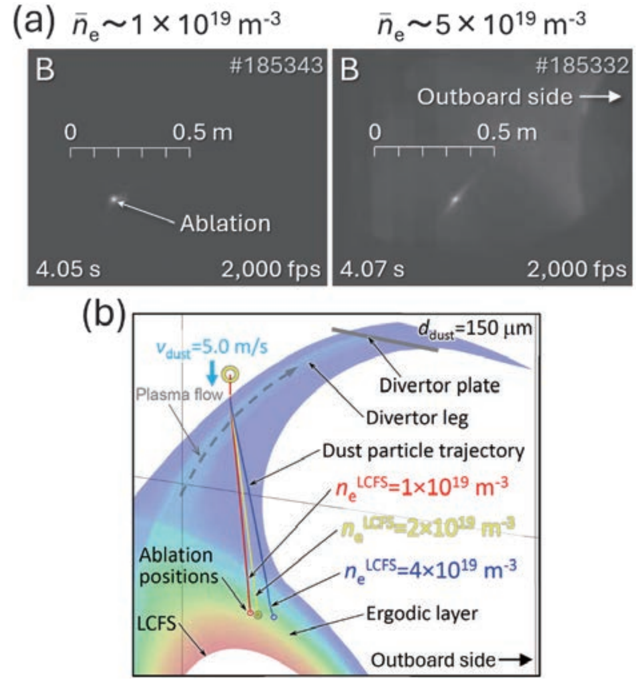

Fig. 1 (a) Images of the ablation of the dropped boron dust particles observed with a fast-framing camera for two different line averaged plasma densities $\bar{n}_e$ of 1 and 5×10^{19} m^{-3}. (b) the simulations of the dropped dust particle trajectories in background plasmas with three different plasma densities at the Last Closed Flux Surface n_e^{LCFS} of 1, 2, and 4×10^{19} m^{-3}.

(M. Shoji)

Ultra-high neutral pressure achieved in the divertor [2]

For the first time, a very high neutral pressure in a divertor region has been observed in a high-density experiment in the Large Helical Device (LHD). The divertor plays a role in removing impurities and improving particle control by increasing the number of neutral particles inside and efficiently exhausting them. Previous research has shown that hydrogen-neutral particles can be highly compressed inside the divertor (Fig. 2 (a)) if the position of the center of the plasma (magnetic axis) is inwards, However, this time the magnetic field configuration was shifted to 3.55 m, only 5 cm inwards from the magnetic axis condition (3.60 m), which is commonly used. As shown in Fig. 2 (b), a neutral pressure more than seven times higher was achieved. One of the possible reasons for this was that the plasma inside the divertor was relatively cold, a condition known as volume recombination, and the research team named the ultra-high neutral pressure phenomenon inside the divertor "low-temperature mode". The present results mean that the neutral pressure inside the divertor can be increased by optimization of the magnetic field configuration, which provides important insights for the design of fusion DEMO reactors.

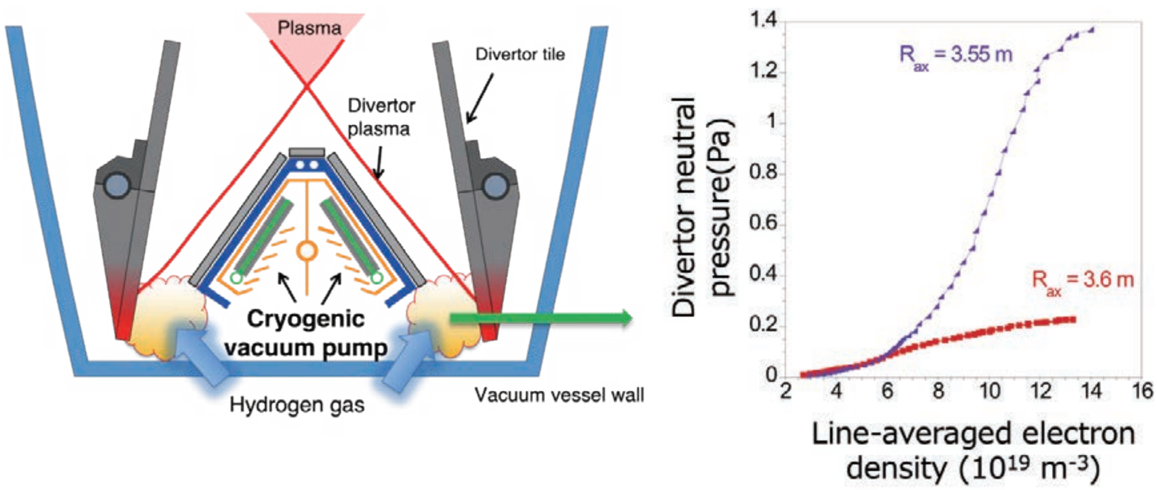

Fig. 2 At the edge of the plasma confined by the magnetic field in the Large Helical Device (LHD), the plasma is drawn into a region called the divertor system, where the plasma becomes neutral gas. In this achievement, a very high neutral pressure of 1.4 Pa is achieved in a specific magnetic field configuration.

(U. Wenzel and G. Motojima)

Plasma-wall interaction (PWI) on a new type of divertor-heat removal component in LHD [3]

A novel method, called Advanced Multi-Step Brazing (AMSB), has been developed to fabricate a new type of divertor heat removal component with W armor and an oxide-dispersion-strengthened copper (GlidCop®) heat sink. A new type of divertor-heat removal component, which has a rectangular-shaped cooling channel with a V-shaped staggered-rib structure in the GlidCop® heat sink, has been developed. The new component was installed in the divertor-strike position of the Large Helical Device (LHD), as shown in Fig. 1 and exposed to neutral beam injection–heated plasma discharges with 1180 shots (~8000 s) in total. Fig. 3 shows a photograph of

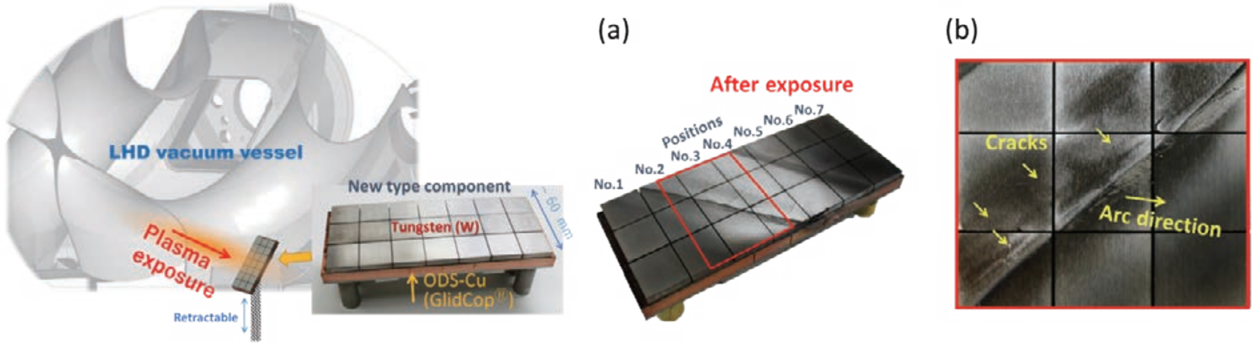

Fig. 3 (left) Schematic view of experimental set-up for irradiation of the new type of divertor heat removal component in LHD. (a) Photograph of the new type of divertor heat removal component after exposure to LHD divertor plasma. (b) Enlarged image of W surface corresponding to red rectangular area of photograph (a).

the exposed component. Though submillimeter-scale damage, such as unipolar arc trails and microscale cracks, was identified on the W surface, the extremely high heat removal capability did not show any sign of degradation over the experimental period. On the other hand, remarkable sputtering erosion and redeposition phenomena, due to the strong influx of the divertor plasma, were confirmed on the W armor.

(M. Tokitani)

OL impurity transport analysis with SONIC code with a kinetic effect on a thermal force transport model in JT-60U [4]

The latest version of the SONIC code, edge plasma transport simulation code, with an extended thermal force model, which is capable of treating collisionality dependence of the force, has been applied to JT-60U plasmas to investigate the kinetic effect on the scrape-off layer (SOL) impurity transport [4]. It is found that maximum

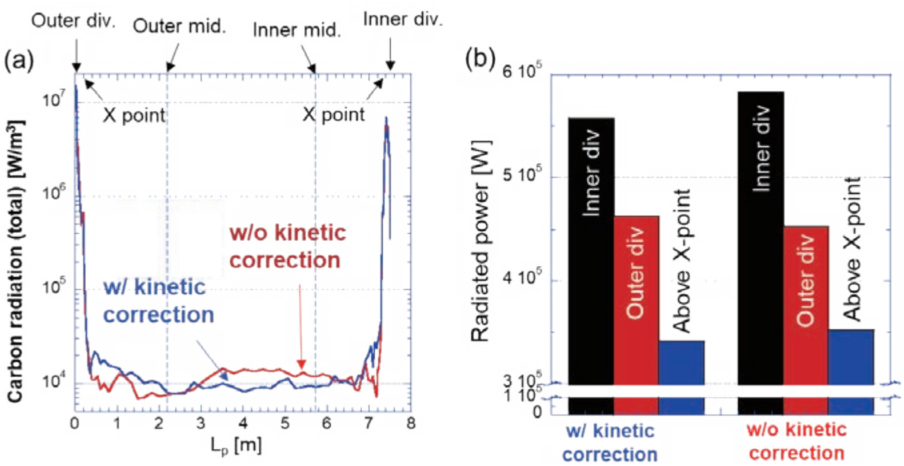

Fig. 4 (a) Impurity radiation profiles along magnetic flux tubes 1 mm outside the separatrix with (blue) and without (red) kinetic correction. (b) Impurity radiation power integrated over the inner, outer, and the main SOL (above the X-point) with and without the kinetic correction.

values of the impurity density in the SOL are reduced by a factor of two. This is due to reduced thermal force by kinetic correction in a low-collisional region between the X-point and the inner and outer midplanes (Fig. 4 (a)). The impurity profiles near the divertor plates, where collisionality is high, are not affected by the kinetic correction (Fig. 4 (b)). Overall effects of the kinetic correction on total impurity radiation and the divertor heat load are about a few percent in the discharge condition analyzed. The kinetic correction is found to be more pronounced for higher-charge impurity states, due to charge dependence of the parallel impurity force balance. This indicates the importance of the effect for high-Z impurities such as tungsten in future devices.

(M. Kobayashi)

Molecular Dynamics Simulation on Hydrogen Trapping on Tungsten Vacancy [5]

This study employs molecular dynamics to elucidate the influence of hydrogen on the structural transformation of vacancies in tungsten. The objective is to gain insight into the interaction between vacancies and hydrogen in tungsten. The simulations were performed at varying temperatures and with differing numbers of hydrogen atoms present within the vacancies. Figure 5 shows a snapshot of the atomic structure. The evaluation of four key parameters, namely the isopotential surface for the increase of total potential energy, the root mean square deviation of tungsten atoms, the root mean square fluctuation of tungsten atoms, and the density distribution in the radial direction, revealed that the presence of a substantial number of hydrogen atoms within a vacancy at each temperature resulted in notable alterations to the structural configuration. This finding supports the experimental observation that hydrogen retention activates the coalescence of two tungsten vacancies.

(H. Nakamura)

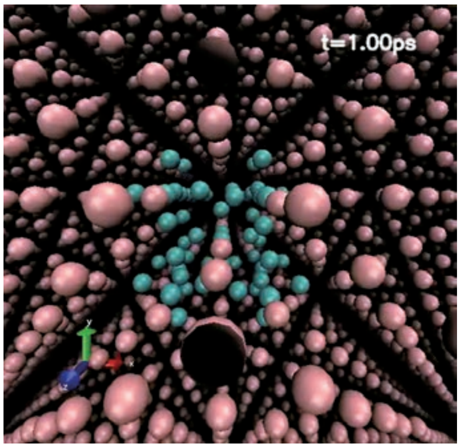

Fig. 5 Snapshot of the atomic structure at 1 ps simulation was performed by randomly injecting 54 hydrogen atoms into a vacancy created by the removal of 9 atoms from a tungsten bcc crystal. The blue and peach balls represent hydrogen and tungsten atoms, respectively.

Enhanced Classical Radiation Damping of Electronic Cyclotron Motion in the Vicinity of the Van Hove Singularity in a Waveguide [6]

We study the damping process of electron cyclotron motion and the resulting emission in an electromagnetic rectangular waveguide, using the classical Friedrichs model without relying on perturbation analysis such as Fermi’s golden rule. In this study, we consider the classical system where an electron inside the waveguide exhibits cyclotron motion with variable frequency under the influence of a (static, uniform) external magnetic field that is applied in parallel with the length of the waveguide (Fig. 6). A Van Hove singularity appears at the cutoff frequency of the dispersion associated with each of the electromagnetic field modes in the waveguide. In the vicinity of the Van Hove singularity, we find that not only is the decay process associated with the resonance pole enhanced (amplification factor ~10^4) but the branch-point effect is also comparably enhanced. As a result, the timescale on which most of the decay occurs is dramatically shortened. Further, this suggests that the non-Markovian branch-point effect should be experimentally observable in the vicinity of the Van Hove singularity. Our treatment yields a physically acceptable solution without the problematic runaway solution that is well known to appear in the traditional treatment of classical radiation damping, based on the Abraham–Lorentz equation.

(Y. Goto)

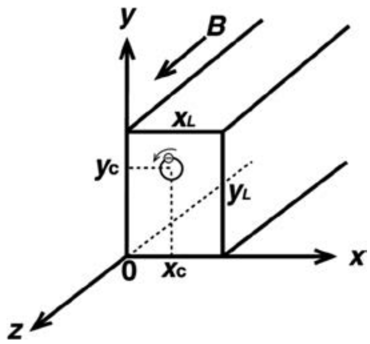

Fig. 6 Physical model and coordinate system.

Theoretical and simulation studies of crescent-shaped ion velocity distributions in magnetic reconnection [7]

Crescent-shaped velocity distributions have been actively studied as one of the important issues related to magnetic reconnection. Crescent-shaped distributions have been observed by satellites in the Earth's magnetosphere since the 1990s and analytical theories have recently been proposed. Consequently, it is believed by many researchers that magnetic-field reversal is necessary to the production of crescent distributions.

We, however, challenge the above accepted notion. We formulate a new theory which indicates that crescents are constructed under a uniform magnetic field alone. This implies that magnetic- field reversal is not required for crescents. Furthermore, according to our theory, three-dimensional crescents are formed by a combination of uniform and reversed components of the magnetic field. We carry out particle simulations of magnetic reconnection with a strong guide field. Figure 7 (a) shows the magnetic field lines and the guide magnetic field Bz, and Fig. 7 (b) displays velocity plots of ions in the boxed area of Fig. 7 (a). A three-dimensional crescent is clearly seen.

We expect that 3D crescent-shaped ion velocity distributions will be detected in the outflow region of magnetic reconnection with a guide magnetic field at the Earth's magnetopause.

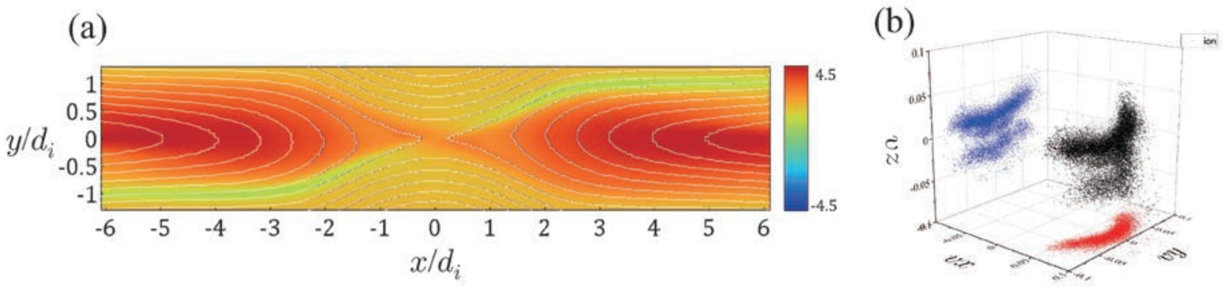

Fig. 7 (a) Magnetic field lines and B_z (color). Magnetic reconnection is driven in the center. (b) Velocity plots of ion particles as black points. We can see that the 3D structure of a crescent structure is formed in velocity space. Red and blue points are projections into the (v_x,v_y) and (v_y,v_z) planes, respectively.

(S. Usami)

[1] Mamoru Shoji *et al.*, “Simulation Analysis of Transport of Boron Dust Particles Injected by Impurity Powder Dropper in the Large Helical Device”, J. Adv. Simlat. Sci. Eng. **11**, pp. 12–20 (2024).
[2] U. Wenzel, G. Motojima *et al.*, “Ultrahigh neutral pressures in the sub-divertor of the Large Helical Device”, Nucl. Fusion **64**, 034002 (2024).
[3] M. Tokitani *et al.*, “Plasma Wall Interaction of New Type of Divertor Heat Removal Component in LHD Fabricated by Advanced Multi-Step Brazing (AMSB)”, Fusion Sci. Technol. **79**, pp. 651–661(2023).
[4] M. Kobayashi *et al.*, “SOL impurity transport analysis with SONIC code with a kinetic effect on a thermal force transport model in JT-60U”, Contrib. Plasma Phys., e202300141 (2024). https://doi.org/10.1002/ctpp.202300141
[5] Hiroaki Nakamura *et al.*, “Molecular Dynamics Simulation on Hydrogen Trapping on Tungsten Vacancy”, J. Adv. Simlat. Sci. Eng. **10**, pp. 132–143 (2023). DOI: 10.15748/jasse.10.132.
[6] Y. Goto *et al.*, “Enhanced Classical Radiation Damping of Electronic Cyclotron Motion in the Vicinity of the Van Hove Singularity in a Waveguide”, Prog. Theor. Exp. Phys., 033A02 (2024).
[7] S. Usami and S. Zenitani, Phys. Plasmas **31**, 022102 (2024).

Sensing and Intellectualizing Technology Unit (S&I)

Observing, predicting, and controlling the behavior of ultra-high temperature plasma are essential subjects for improving the performance of fusion reactors. In S&I unit, we will develop dramatically high-precision plasma measurement methods and construct a system that enables holistic and precise plasma observation. Furthermore, we will analyze the data using data science and convert it into visual, auditory, tactile, and other information to make it “intellectualizable”. This effort, in which researchers specializing in measurement, data analysis, and expression methods work together to systematize the intellectual inquiry process, will revolutionize the understanding of phenomena in fusion science and many other scientific fields.

This chapter reports selected notable results from the S&I Unit in FY2023 related to plasma diagnostics, visualization, open science, isotope science, and other interdisciplinary research.

Turbulence Transition in Magnetically Confined Hydrogen and Deuterium Plasmas

In toroidal devices, ion scale turbulence, of which wavelength is order of ion Larmor radius, plays a essential role for confinement. The ion scale turbulence changes its characteristics depending on plasma parameters and affects energy, particle and momentum transport. In LHD, we discovered turbulence transition from ion temperature gradient (ITG) to resistive interchange (RI) turbulence[1]. Figure 1 shows electron density dependence of turbulence level and phase velocity in laboratory frame. Turbulence level, which is normalized turbulence amplitude by local electron density and turbulence phase velocity were measured by the two-dimensional phase contrast imaging. In Fig. 1, the data was taken from the shot-by-shot basis density scan experiments under constant heating power with 1.4MW electron cyclotron resonant heating. Experiments were performed for hydrogen (H) and deuterium (D) plasma. As shown in Fig. 1 (a), turbulence level decreases to a transition density (n_{tr}) and increase above it. Simultaneously, the propagation direction of turbulence phase velocity changes from ion diamagnetic direction to electron-diamagnetic direction. The turbulence level is almost comparable in H and D plasma under n_{tr} however, it is clearly lower in D plasma above it. Power balance analyses showed thermal conductivity driven by turbulence process scales with turbulence level and becomes minimum at n_{tr}. These results suggest that turbulence characteristics

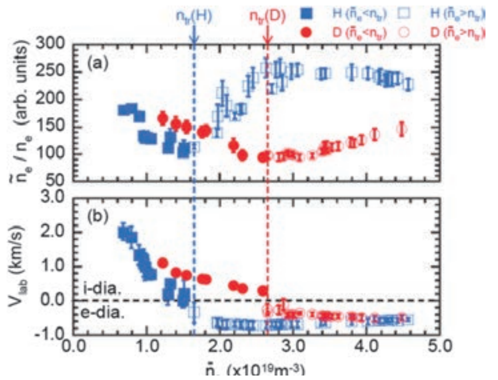

Fig. 1 The line averaged electron-density dependence of (a) the turbulence level and (b) phase velocity of turbulence in the laboratory frame. n_{tr}(H) and n_{tr}(D) represent the transition densities in the H and D plasmas, respectively. The blue and red symbols represent the H and D plasmas, respectively. The closed and open symbols represent $\bar{n}_e < n_{tr}$ and $\bar{n}_e > n_{tr}$, respectively. The values are averaged at $\rho = 0.5–0.7$

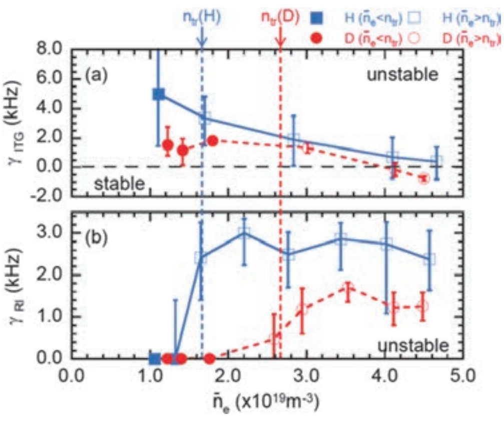

Fig. 2 Electron-density dependence of the linear growth rate of (a) ITG turbulence (γ_{ITG}) and (b) RI turbulence (γ_{RI}). The errors in γ_{ITG} and γ_{RI} were evaluated by changing the normalized ion temperature gradient and pressure gradient by 20 %, respectively.

changes at n_{tr}.

Then, theoretical investigation was performed. Firstly, gyro-kinetic linear analyses was done. Dominant instability was ITG turbulence in whole experimental regime. As shown in Fig. 2 (a), its growth rate (γ_{ITG}) decrease with increase of density. This results qualitatively agree with observed density dependence at lower than n_{tr}, however, does not account at higher than n_{tr}. Then, we employed two-fluid MHD simulation. Figure 2 (b) shows density dependence of growth rate of RI turbulence (γ_{RI}). γ_{RI} can not be evaluated by gyro-kinetic simulation, because of non-ballooning structure of Eigen function. RI can be unstable due the nature of magnetic hill in LHD. As shown in Fig. 2 (b), γ_{RI} becomes positive indicating RI is unstable above n_{tr}. Also, γ_{RI} is lower in D plasma at $\bar{n}_e > n_{tr}$ and qualitatively account for the reduced turbulence level. At $\bar{n}_e > n_{tr}$, turbulence driven anomalous thermal conductivity is lower and global energy confinement time is higher in D plasma than H plasma. The reduced transport in D plasma at $\bar{n}_e > n_{tr}$ is due to weaker RI turbulence. Weaker RI turbulence is due to the lower resistivity, heavier ion mass and lower pressure gradient due to the hollower density profile in D plasma.

[1] T. Kinoshita *et al.*, Physical Review Letters **132**, 235101 (2024).

(K. Tanaka and T. Kinoshita (Kyushu Univ.))

New Parity Transition of Radial Structure of MHD Modes

The parity of the radial displacement profile of low-order MHD modes observed in magnetically confined plasmas is closely related to the topology of the magnetic field structure. The odd-parity structure typically reflects a large magnetic island structure, whereas the even-parity structure does a structure without an island. Thus, understanding parity transitions is key to elucidating the physical mechanisms of magnetic island formation and stabilization in magnetized plasmas such as fusion and astrophysical plasmas.

In tokamaks and the LHD, parity transitions from even to odd functions have been observed, providing circumstantial evidence of the contribution of even-parity MHD modes to magnetic island formation. Detailed mode structures have been obtained in the LHD using high-spatial-resolution interferometry, leading to the discovery of parity transitions from odd to even in addition to those from even to odd. This suggests that even-parity MHD modes also contribute to stabilizing magnetic islands, offering crucial new insights for developing predictive modeling for magnetic island formation and stabilization.

(Y. Takemura)

Anomaly detection of radiative collapse using 2-D radiation measurement and imaging analysis

In the case of a divertor detachment using impurity injection to reduce the divertor heat load, increasing the amount of impurity injection can reduce the thermal load further, but if the injection amount is too much, radiative collapse occurs. Therefore, to control the amount of impurity injection and maintain the divertor detachment, it is necessary to detect the precursor of radiative collapse.

In multi-pulse neon (Ne) injected plasma in the LHD, by learning 1,086 images of 520 pixels measured by an infrared imaging video bolometer using an autoencoder, the precursor was detected as an increase in abnormality before the Ne pulse that induced the radiative collapse.

(K. Mukai)

Suppression of resistive interchange instability by external RMP

In the LHD, which is a heliotron type fusion device for the experiments, the resistive interchange MHD instabilities could disturb the stable and high discharges of the high beta plasma discharges. Then, the method to avoid and/or suppress the instabilities are being investigated. As our previous works [2], it is found that the imposing the RMP (resonant magnetic perturbation) by the external coils is effective to suppress the fluctuation due to the interchange instability. Here it should be noted that imposing the RMP field is also effective to suppress the MHD instabilities in the tokamaks. On the contrary, it is well known that the RMP field induces the strong degradation of the plasma confinement due to the magnetic island formation beyond a threshold of the RMP amplitude. Recently, we obtain the following empirical scaling law on the RMP amplitude to completely suppress the fluctuation due to the interchange instability through the LHD experiments with various plasma parameter regimes,

$$I_{RMP}/B_0 = 6.6 \times 10^2 \cdot \beta^{1.8} \cdot \nu^{*0.24} \cdot \rho^{*0.85}$$

Here I_{RMP}, B_0 are the coil current for the RMP and the operational magnetic field strength, respectively. And are the beta value, the normalized collisionality and gyro-radius at the rational surface. Moreover, the empirical scaling law on the RMP amplitude to degrade the confinement is obtained as follow,

$$I_{RMP}/B_0 = 4.9 \times 10^3 \cdot \beta^{1.3} \cdot \nu^{*-0.25} \cdot \rho^{*1.2}$$

From the above results, it is found that, in a heliotron type fusion device, (β, ν*, ρ*) = (0.60%, 4.2×10^{-2}, 4.2×10^{-4}) [3], we could completely suppress the interchange MHD instability due to the imposing RMP externally without the strong degradation of the plasma confinement.

[2] S. Ito *et al.*, Nucl. Fusion **63**, 066016 (2023).
[3] T. Goto *et al.*, Nucl. Fusion **57**, 066011 (2017).

(K. Watanabe, Y. Takemura, S. Sakakibara,
S. Ito (Nagoya Univ.), H. Beniya (Nagoya Univ.) and S. Masamune (Chubu Univ.))

Integrated virtual-reality visualization of simulation results and 3D model

Plasma, where various and complex phenomena take place, is one of the optimal subjects for applying visualization using virtual reality (VR) technologies. This paper reports the enhancement of the VR visualization software for the CAVE system, “VFIVE”. VFIVE is a general-purpose VR visualization software for the CAVE system, utilizing several visualization methods such as streamlines, arrows, isosurfaces, contour plots, and more. We have added three functions to VFIVE: 1) Streamlines from predefined starting points. 2) New streamline representations. 3) A fusion display of visualization results by VFIVE and the 3D model rendered by Unity. With

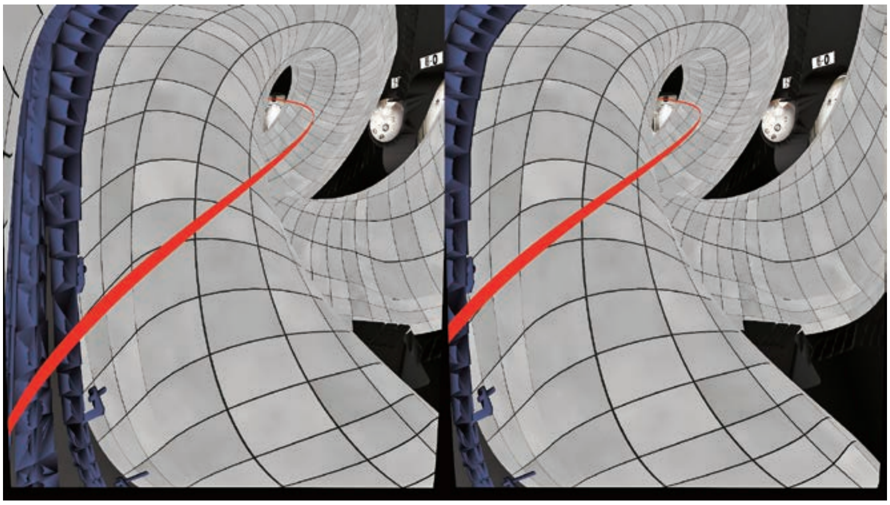

Fig. 3 Fusion visualization by VFIVE with libraries GLMetaseq and CLCL incorporated. Right and left figures are for right and left eyes, respectively.

Function 1, we can estimate the backward streamlines from the starting points. Function 2 can show tube and ribbon representations in addition to the colored line, which is already implemented in VFIVE. Function 3 is realized by two methods: the commercial software "FusionSDK" by FiatLux and Cybernet on the CAVE system, and the GLMetaseq library on the head-mounted display system. The GLMetaseq library is a free library for C and C++, which reads MQO formatted 3D model data and displays it using OpenGL. MQO formatted data is generated by the free 3D modeling software, Metasequoia 4. In this process, after rendering by Unity is finished, Unity exports FBX formatted data. Metasequoia 4 imports the data and exports the old-style MQO formatted data. The figure shows a snapshot of the inside of the LHD vessel with tube streamlines by VFIVE, with the GLMetaseq and CLCL libraries incorporated. Visualizing simulation data within a device represented by a 3D model is expected to aid the observer's intuitive understanding.

(H. Ohtani)

25 years of massive fusion energy experiment data completely open on the "cloud", to be available to everyone

The National Institute for Fusion Science (NIFS) has been strongly promoting the "Open Data" in fusion research, and all the accumulated data through the past 25 years of operation of the Large Helical Device (LHD) fusion plasma experiments have been made fully open to the public on Amazon Web Services (AWS), with the support of the "AWS Open Data Sponsorship Program".

To promote the use of large-scale experiment data, an important possibility exists in "cloud service" computer environment in which anyone can begin data analyses very quickly and easily. Therefore, about 17 million clusters of raw data (about 1.5 petabytes in archived size) acquired from LHD have been made freely available to the public on the same cloud storage, Amazon S3, since April 2024. An additional 24 million analytical results will be also open. (Figure 4) [4,5].

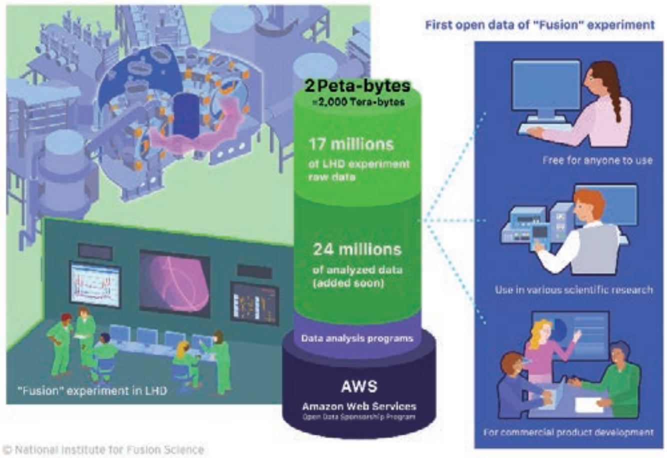

Fig. 4 All diagnostic and analyzed data of LHD, having more than 40 million items and 2 petabytes in total, are open to the public on AWS's cloud storage.

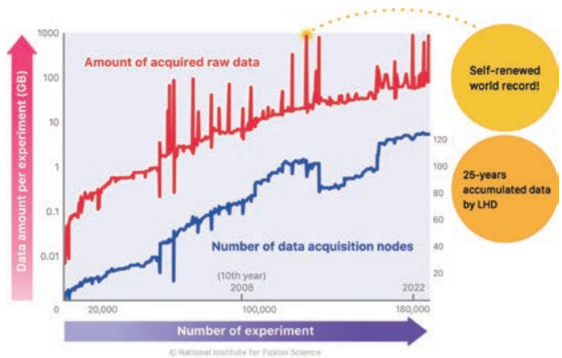

Fig. 5 Amount of acquired raw data per LHD experiment (red line) and the number of diagnostic devices (blue line).

This is the first time in the world of fusion research that all experiment data have been made publicly open, making the newest research data available to anyone via the Internet. It is a major step toward making fusion energy research an "Open Science". NIFS considers the fulfilment of the FAIR Principles, which is regarded as an important indicator toward Open Science, in diagnostic raw and analyzed data to be an important proposition of the "Academic Research Platform" LHD and continues its efforts. We also have started assigning DOIs (Digital Object Identifiers) to approximately 40 million LHD data to facilitate their findability and accessibility in accordance with the FAIR Principles.

The LHD diagnostic and analyzed data repository, which is the world's largest accumulation of fusion energy research data, is a very valuable digital research asset. It is expected that the datasets will be used not only for research purposes within and outside fusion research but will also attract new entrants from citizens, industries and other countries that are interested in starting fusion energy research and development. Barriers for new entrants are expected to be significantly lowered. It will also serve as a major digital platform for research knowledge exchange, human exchange, and human development not only in Japan but also around the world. To this end, NIFS is intensively promoting this large-scale data repository under the name of the "**Plasma and Fusion Cloud**" by utilizing the NII RDC, the research data cloud infrastructure of the National Institute of Informatics (NII).

This research is supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) under the contract with NII, which is implementing the "Research Data Ecosystem Development Project to Promote the Use of AIs" and has been selected as use case creation project No. 2023-6.

[4] AWS blog, https://aws.amazon.com/jp/blogs/news/25years-huge-fusion-experiment-data-fully-open-on-s3-via-odp-2024/ (2024).
[5] NIFS press release, https://www.nifs.ac.jp/news/collabo/240614.html (2024).

(H. Nakanishi and M. Emoto)

Analysis of molecular hydrogen (H_2) in the atmosphere for understanding the behavior of atmospheric tritiated hydrogen (HT)

Tritium would be the fuel of the first-generation nuclear fusion reactor. Since it is radioactive material, the environmental monitoring of tritium would be required in the vicinity of the fusion facility site from the viewpoints of radiation safety and public acceptance. As one of the environmental tritium monitoring items, atmospheric tritium measurement is important. Tritium in the atmosphere has three chemical forms: tritiated water vapor (HTO), tritiated molecular hydrogen (HT), and tritiated methane (CH_3T). The atmospheric tritium monitoring system with different chemical forms has been developed and operated at the NIFS Toki site since 2004 [6]. The tritium monitoring results indicated that the specific activity of HT and CH_3T is much higher than that of HTO [7]. To investigate the cause of high specific activity, we focus on the behavior of molecular hydrogen (H_2) in the atmosphere and develop a continuous measurement system based on a gas chromatograph and trace reduction detector. Monitoring results showed that the range of the H_2 mixing ratio at the NIFS Toki site was 0.4~0.6 ppm over the observation period. Atmospheric H_2 concentrations were higher during the daytime and long daylight seasons such as summer, suggesting the generation of hydrogen by photochemical reactions. Preliminary results suggest that there does not appear to be a clear correlation between the concentration of atmospheric HT and the concentration of H_2 in the atmosphere. This suggests that the source of HT is different from the source of H_2 in the atmosphere. For future studies, long-term observational data of both HT and H_2 and the seasonal variation of HT in the wide latitude range with a joint research project are needed to obtain clear conclusions [8].

[6] T. Uda *et al.*, Fusion Engineering and Design **81**, 1385–1390 (2006).
[7] M. Tanaka and T. Uda, Radiation Protection Dosimetry **167**, 187–191 (2015).
[8] M. Tanaka *et al.*, Plasma and Fusion Research **18**, 2405038 (2023).

(M. Tanaka)

Femtosecond Optical Vortex Laser Processing for Fusion Materials

We have research about laser processing for fusion materials employing optical vortex laser to improve the material properties and processing efficiency. In the FY2023 research, we investigated femtosecond vector vortex laser processing for tungsten including laser-induced periodic surface structure (LIPSS) formation. Optical vortex laser processing showed an ablation threshold three times higher than that of conventional Gaussian beams (Fig. 6 (a)). Furthermore, the vector vortex laser with controllable the structured two-dimensional spatial distribution of polarization realized fabrication of the complex LIPSS pattern like a helical surface relief (Fig. 6 (b)). Femtosecond vector vortex laser processing would provide us with robust and flexible surface processing method, and open the door to innovative applications of tungsten materials.

This research is the collaboration project between NIFS, the RIKEN (Dr. Sugioka) and the Nagoya Institute of Technology (Dr. Miyagawa), and these results were published in the academic journal of “Optical Material Express” (IF: 2.8) published by Optica Publishing Group (USA).

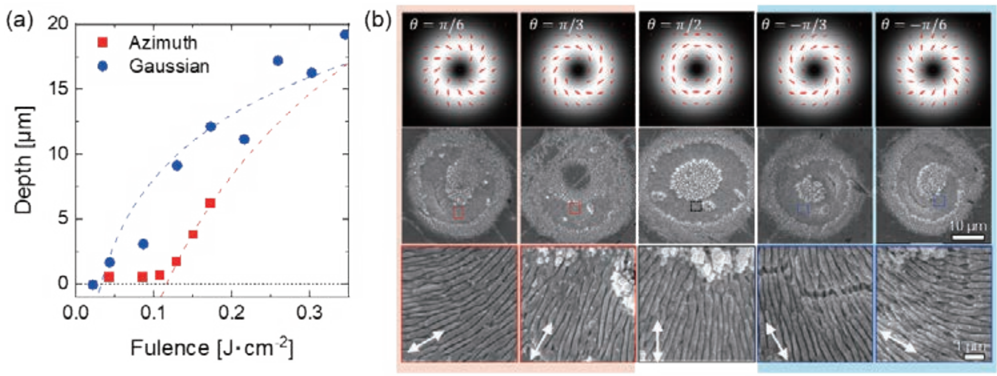

Fig. 6 (a) Dependence of ablation depth D on laser fluence in the laser irradiation to tungsten surface, (b) Fabricated chiral surface structures employing vector vortex laser. by H. Kawaguchi. (Figure adapted from “Opt. Mater. Express **14**, 424–434, 2024”)

(H. Kawaguchi, R. Miyagawa (NITech, NIFS) and K. Sugioka (RIKEN))

Plasma Apparatus Unit

A plasma apparatus (PA) unit, as an axis of plasma science and technology, started in the fiscal year 2023 when a system of units started at NIFS. The importance of disruptive innovation as a game changer in fusion research has been pointed out. To this end, The PA unit will aspire to create innovative plasma technology by deepening scientific knowledge of the complex collective phenomena of plasma. By developing novel applications of plasma as working hypotheses, the PA unit will promote collaboration in fusion with other fields and shed light on the unexplored emergent nature of collective phenomena. The innovation of plasma science and technology will open a new horizon for various natural sciences research and science and technologies.

Toward the above end, four research topics have started in the PA unit: the neutral beam injector, anti-material and dipole plasma, muon science, and electric propulsion.

Neutral Beam Injector

A radio frequency (RF) negative ion source was applied to the Neutral Beam Injector (NBI) for ITER. One of the targets to be achieved is a smaller beam divergence than 7 mrad, which has been achieved by a filament-driven arc (FA) negative ion source for the NBI in the Large Helical Device at NIFS. It has not been clarified why the beam divergence of the RF negative source is larger than that of the FA. To compare the beam divergences of the FA and RF sources with the same diagnostics at the same ion source directly, and to investigate the physics mechanism of the beam divergence difference, collaborating with the ITER Organization (IO) and the Max-Planck Institute for Plasma Science (IPP, Germany), an FA/RF hybrid negative ion source has been developed, based on research and development of an FA negative ion source (NIFS-RNIS). The FA/RF hybrid negative ion source operations, which are only FA or RF and FA/RF hybrid discharges and beam extraction, have been accomplished [1]. Following this achievement, an international joint collaboration experiment with NIFS, IO, IPP, the National Institutes for Quantum Science and Technology, Consorzio RFX (Italy), the High Energy Accelerator Research Organization (KEK), and Doshisha University was performed for a month. The FA and RF ion source plasmas had almost the same profiles in the direction of the magnetic filter. The plasma potential in the RF ion source plasma was several times higher than that in the FA. The collaboration with KEK brought the possibility of oscillating the beam divergence by the oscillation of plasma production [Shibata]. An international collaboration, including domestic institutes in not only the fusion field but also other fields, such as the accelerator science, and collaboration with academic and development institutes will find solutions to the NBI tasks and can open new frontiers in science and technology.

[1] H. Nakano *et al.*, 29th IAEA Fusion Energy Conference (2023); K. Tsumori *et al.*, 20th International Conference on Ion Sources (2023).
[2] T. Shibata *et al.*, J. Phys.: Conf. Ser. 2743, 012007 (2024).

Anti-Material Plasma and Dipole Plasma

The levitated dipole configuration is globally analogous to planetary magnetospheres and is capable of confining high-beta plasmas suitable for an advanced fusion concept. Phenomena in fusion-oriented plasmas and geospaces share commonalities in terms of waves and transport properties. Moreover, the excellent confinement properties of a levitated dipole enable new experiments such as antimatter plasmas. We are conducting interdisciplinary studies in the dipole magnetic field configuration, focusing on the creation and understanding of electron-positron plasmas and laboratory studies on wave phenomena in geospace. Regarding electron-positron plasmas, by utilizing a linac-based pulsed positron source, we have captured 105 positrons in the dipole magnetic field, which is over 100 times the previous record. Although the captured positron cloud still does not satisfy the plasma condition, we are developing a strong magnetic field trap to accumulate up to 109 positrons in a steady magnetic field of 5 T over a 60 cm region in the axial direction. As well as a pure electron plasma experiment in this trap, we are conducting the construction of a compact levitated dipole for the confinement of positrons with electrons as pair plasmas. On plasma wave experiments, we have conducted laboratory studies on whistler-mode chorus emissions in RT-1, as a collaboration work between the Plasma Apparatus Unit and the Phase Space Turbulence Unit. By adjusting the ratio of hot-electron components in the plasma, we have demonstrated the spontaneous generation of chirping chorus emissions and investigated their appearance conditions. Through these experiments, we have shown that the presence of a simple dipole magnetic field and hot electrons are the conditions that drive chorus emissions, indicating that this is a universal phenomenon in both celestial bodies and laboratories [1].

[1] H. Saito *et al.*, Nature Communications **15**, 861 (2024).

Muon Science

The following reports the advancements in muon science achieved in 2023. Two major achievements were made using superconducting X-ray detectors with excellent energy resolution. Firstly, notable advancements were made in the high-precision X-ray spectroscopy of muonic atoms. This research involved measuring the transition energies of muonic atoms, where a muon replaces an electron, creating an environment with extremely strong electric fields between the muon and the atomic nucleus. This allowed for the verification of quantum electrodynamics (QED) under such intense conditions. The results were published in Physical Review Letters [1] (PRL130, 173001(2023)).

Secondly, groundbreaking work was accomplished with the first successful global application of high-resolution X-ray spectroscopy on the dissociation of resonant states in muonic molecules. This breakthrough helps elucidate the complex quantum mechanical dynamics involved in the muon-catalyzed fusion (μCF) process. These findings contribute significantly to the theoretical and practical understanding of μCF, which is essential for future applications.

[1] T. Okumura *et al.*, Phys. Rev. Lett. **130**, 173001 (2023).

Electric Propulsion

Fundamental studies on plasma dynamics relating to plasma production and expansion in a magnetic nozzle configuration are done via laboratory experiments. These insights are applied to an electric propulsion device in space and industrial plasma devices, e.g., plasma etching [2]. Assessment of the performance of the magnetic nozzle radio frequency plasma thruster has shown its efficiency approaching 30 percent, which is the highest to date. The key issue for the performance improvement seems to be the inhibition of the energy loss to the radial source boundary, which can be achieved with the help of a magnetically-confined fusion plasma community, where a cusp magnetic field is applied in the source tube [1]. Toward further development of an engineering model of the thruster, a permanent magnet configuration is designed to form the cusp, where the source is contiguously attached to a diffusion chamber, showing an increase in the plasma density in the magnetic nozzle region [3]. As a new type of compact electric propulsion device, a water-fueled magnetron sputtering thruster is proposed and investigated, showing the thrust generation by the sputtered materials. Since the sputtered atoms are electrically neutral, the momentum ejection from the system can be achieved with no neutralizer, providing a very compact and simple propulsion system [7]. The research on the magnetic nozzle rf plasma thruster is now extended to an international collaboration between Tohoku University and Deutsches Zentrum fuer Luft- und Raumfahrt (DLR). Furthermore, the development of the plasma etching device has been progressed over the last few years.

[1] K. Takahashi, J. Phys. D: Applied Phys. **56** , 475207 (2023).
[2] K. Takahashi *et al.*, Plasma and Fusion Res. **18**, 2501050 (2023).
[3] Y. Nakahama and K. Takahashi, AIP Advances **14**, 015059 (2024).
[4] K. Takahashi, J. Plasma Phys. **90**, 975900201 (2024).
[5] S. Sumikawa and K. Takahashi, Phys. Plasmas **31**, 034501 (2024).
[6] K. Takahashi and S. Sumikawa, Plasma Phys. Contr. Fusion **66**, 015012 (2024).
[7] S. Shimizu and K. Takahashi, J. Plasma Phys. **90**, 975900205 (2024).

(H. Nakano[1], H. Saito[1,2], S. Okada[1,3] and K. Takahashi[4] ([1]NIFS, [2]Univ. Tokyo, [3]Chubu Univ., [4]Tohoku Univ.))

Complex Global Simulation Unit

In order to understand the behavior of an entire system composed of multiple hierarchies, individual simulations of each hierarchy are not sufficient. Global simulations that consider the interactions between hierarchies are required. Such complex global simulations are an important issue that is expected to be realized not only in the field of nuclear fusion research (Fig. 1) but also in many other academic fields. However, their realization is not easy. The reason for this is that the temporal and spatial scales of a microscopic hierarchy and the entire system are often extremely different, and the capacity and capability of the computer are not sufficient to simulate the entire range of scales based on a single system of fundamental physical equations. The purpose of this unit is to develop simulation methods to solve this problem and to promote simulation research.

The Complex Global Simulation Unit aims to develop simulation methods that couple different hierarchies and physical models to realize global simulations that predict and elucidate the behavior of entire physical systems that cannot be handled by simulations based on a single system of fundamental physical equations. This unit will develop 1) global simulations of the whole of a magnetic confinement fusion plasma, including core and edge plasmas, based on kinetic-magnetohydrodynamic hybrid simulation, and 2) a methodology with broad applicability to achieve simulations that more closely reproduces real-world phenomena, beyond the severe limitations imposed by the capacity and capability of supercomputers. To develop such simulation methods, we must enhance our understanding of the physics of each different hierarchy and the interactions between them. The development of advanced theories is also crucial. Our recent studies have yielded successful results in 2023-2024, as shown in the following pages.

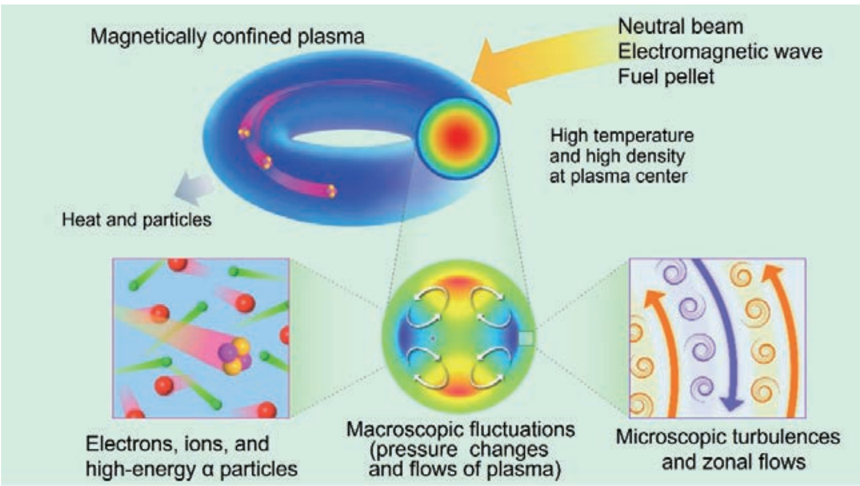

Fig. 1 Multiple hierarchies of a burning fusion plasma

(M. Toida)

Kinetic-MHD hybrid simulation of infernal modes in tokamak plasmas

For realizing a steady-state fusion reactor, high-beta plasma must be stably confined for a long time. In high-beta plasmas, non-inductive bootstrap current becomes large, and discharges with an increased proportion of bootstrap current are one of the steady-state operation scenarios in tokamak plasmas. For such plasmas, since magnetic shear is weak in the core region, infernal modes driven by the pressure gradient are considered to limit the poloidal-beta value in tokamak plasmas. Therefore, suppression of the infernal mode is one of the key issues in plasma discharges with large bootstrap currents in tokamaks. In this study, the influence of the infernal modes on the plasma confinement is investigated by simulations [1]. The simulations are performed using the MIPS code based on the MHD model and the MEGA code based on the kinetic-MHD hybrid model with kinetic thermal ions (KTIs).

Figure 2 shows the time evolution of a pressure profile on a poloidal cross-section obtained from simulations for a resistive infernal mode. In the MHD simulation without KTIs, the pressure profile is significantly deformed, which causes a significant decrease in the beta value. On the other hand, in the kinetic-MHD hybrid simulation with KTIs, deformation of the pressure profile is significantly suppressed, and the decrease of the beta value is very small, almost maintaining its initial value. This indicates that kinetic thermal ions play an essential role in suppressing the flattening of the pressure profile due to slowly growing resistive MHD instabilities.

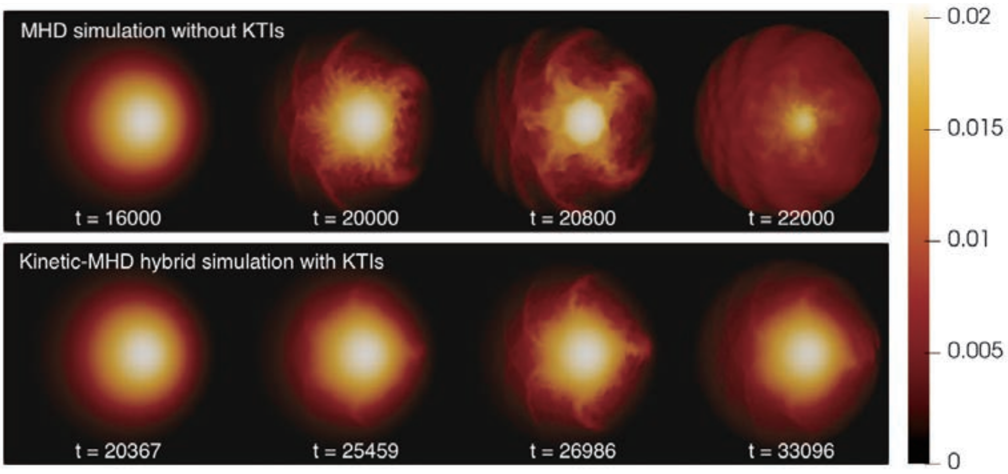

Fig. 2 Time evolution of the pressure profile on a poloidal cross section obtained from the MHD simulation without KTIs (the upper row) and the kinetic-MHD hybrid simulation with KTIs (the lower row) for a resistive infernal mode. Time is normalized by Alfvén time.

[1] M. Sato, Y. Todo, N. Aiba and M. Takechi, Nuclear Fusion **64**, 076021 (2024).

(M. Sato)

Local momentum balance in electromagnetic gyrokinetic systems

Gyrokinetics is a powerful theoretical framework based on which a large number of analytical and numerical studies on microinstabilities and turbulent processes in magnetized plasmas have been done. The Eulerian variational formulation is presented to obtain governing equations of the electromagnetic turbulent gyrokinetic system. A local momentum balance in the system is derived [2] from the invariance of the Lagrangian of the system under an arbitrary spatial coordinate transformation, by extending the previous work [3]. The gyrokinetic Poisson equation and Ampère's law, derived from the variational principle, correctly describe polarization and magnetization due to finite gyroradii and electromagnetic microturbulence. Also shown is how the momentum balance is influenced by including collisions and external sources. Momentum transport due to collisions and turbulence is represented by a symmetric pressure tensor, which originates in a variational derivative of the Lagrangian with respect to the metric tensor. The relations of the axisymmetry and quasi-axisymmetry of the toroidal background magnetic field to a conservation form of the local momentum-balance equation are clarified. In addition, an ensemble-averaged total momentum-balance equation is shown to take the conservation form, even in a background field with no symmetry, when a constraint condition representing the macroscopic Ampère's law is imposed on the background field. Using the WKB representation, the ensemble-averaged pressure tensor due to the microturbulence is expressed in detail and verified to reproduce the toroidal-momentum transport derived in previous works for axisymmetric systems. The local momentum-balance equation and the pressure tensor obtained in this work are helpful references for elaborate gyrokinetic simulation studies of momentum- transport processes.

$$\frac{\partial}{\partial t}\Big(\sum_a \int d^3v\, F_a \mathbf{p}_a\Big) - \sum_a \int d^3v\, \mathcal{K}_a \mathbf{p}_a + \nabla\cdot\mathbf{\Theta} \;=\; (\nabla\mathbf{A})\cdot\frac{\delta L_{GKF}}{\delta\mathbf{A}} - \nabla\cdot\Big(\frac{\delta L_{GKF}}{\delta\mathbf{A}}\mathbf{A}\Big)$$

$$\Theta^{ij} \equiv 2\frac{\delta L_{GKF}}{\delta g_{ij}}$$

Fig. 3 The local momentum-balance equation (upper) and the symmetric-pressure tensor derived from the variational derivative of the Lagrangian with respect to the metric tensor (lower).

[2] H. Sugama, Phys. Plasmas **31**, 042303 (2024).
[3] H. Sugama et al., Phys. Plasmas **28**, 022312 (2021).

(H. Sugama)

Harmonic structure of lower hybrid waves driven by ring-like energetic ions

Energetic ions with a ring-like distribution in velocity space perpendicular to a magnetic field are produced through various processes, such as neutral beam injection, magnetic reconnection, and particle acceleration by a shock wave. The ring-like energetic ions can drive lower-hybrid wave (LHW) instabilities. Recently, harmonic LHWs have been observed in a fusion plasma and the Earth's magnetosphere. We have studied the excitation mechanism of the harmonic LHWs through electromagnetic particle-in-cell simulations, considering the effects of the energetic-ion injection. It has been found that after the LHWs are excited with the wavenumber and frequency of (k, ω), many harmonic LHWs are generated at (mk, $n\omega$), where m and n are integers, due to nonlinear wave-wave coupling, as shown in Fig. 4 [4].

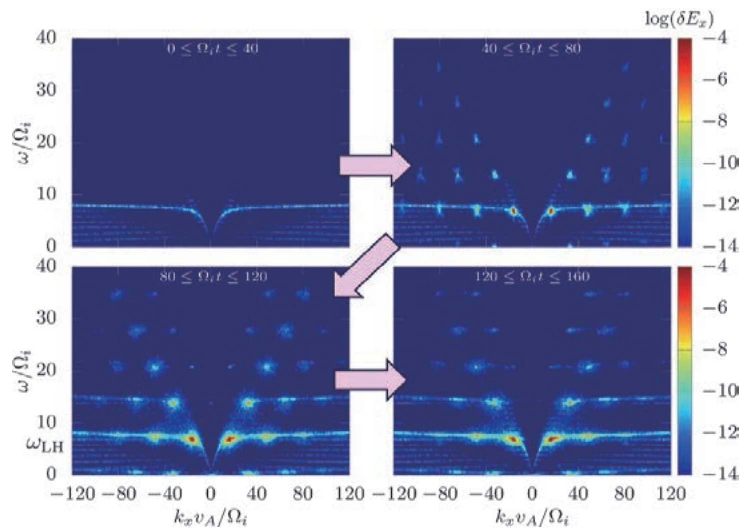

Fig. 4 Evolution of power spectrum of electric field fluctuations excited by ring-like energetic ions. The harmonic structure of LHWs is created due to nonlinear wave-wave coupling.

In addition, motivated by satellite observations of the harmonic LHWs in the Earth's polar region, we have performed simulations by setting parameter values for the observations. The results show that the energetic ions can generate the harmonic LHWs, and background ions are more strongly accelerated when harmonics with large amplitudes are created [5]. This reveals the possibility that harmonic LHWs are involved in ion-acceleration phenomena commonly observed in the polar region, which has been an unsolved problem.

The numerical simulations were performed on the Plasma Simulator of NIFS.

[4] T. Kotani, M. Toida, T. Moritaka, and S. Taguchi, Physical Review E **108**, 035208 (2023).
[5] T. Kotani, M. Toida, T. Moritaka, and S. Taguchi, Geophysical Research Letters **50**, e2022GL102356 (2023).

(M. Toida)

Non-ideal MHD growth of current interchange tearing modes at plasma edge and response to externally-imposed flow

A response of current interchange tearing modes (CITMs) to two-fluid and gyro-viscous effects is numerically studied. The CITM represents a transition phenomenon from the interchange to the tearing mode by current transport outside a last-closed flux surface (LCFS). The CITM has been proposed to explain an intermittent current eruption in the tokamak edge region. Two-dimensional numerical simulations are performed together with an effect of the current transport, modeled as a diffusive process. In a simulation without the diffusive model, the interchange modes grow as shown in the upper panel of Fig. 5. The growth of CITMs outside the LCFS is observed by applying the diffusive transport model in a single-fluid MHD simulation (middle panel) and an extended MHD simulation with a two-fluid and gyro-viscous model (bottom panel). These simulations show that the growth of CITMs significantly suppresses the deformation of magnetic field lines. A response of the CITMs to an externally imposed flow is also studied. The growth of a CITM is observed for a relatively small flow velocity (whether a flow is externally imposed or not), resulting in a suppression of the electric current outside the LCFS. It is also found that a columnar or stripe pattern is formed during CITM growth.

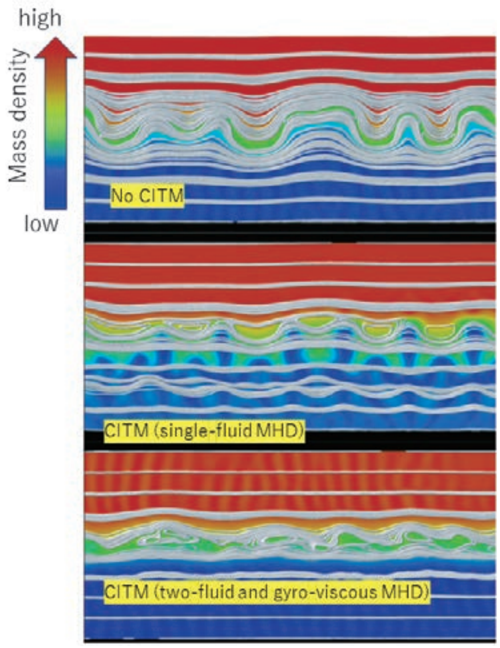

Fig. 5 Mass density (color contours) and 2D magnetic field lines in simulations in which CITM is not observed (top), CITM is observed in a single-fluid MHD simulation (middle), and CITM is deformed by two-fluid and gyro-viscous effects (bottom).

The numerical simulations were performed on the Plasma Simulator of NIFS, Oakforest-PACS (FUJITSU) of the JCAHPC, and Wisteria/BDEC-01 Odyssey (FUJITSU FX1000) of the University of Tokyo.

[6] Hideaki Miura, Linjin Zheng, and Wendell Horton, "Non-ideal MHD growth of current interchange tearing modes at plasma edge and response to externally-imposed flow", Physics of Plasmas **30**, 052503 (2023).

(H. Miura)

Ultrahigh-flux Concerting Materials Unit (UlCoMat)

Highlight

Effects of annealing temperature on microstructure and hardness changes of cold rolled high-purity vanadium alloys

Low-activation vanadium alloy, V-4Cr-4Ti, is considered a candidate structural material for blanket applications in fusion reactors. High-purity vanadium alloys containing much lower levels of high-activation impurities (Co, Ni, Nb, Mo etc.) and interstitial impurities (C, N, O) have been developed to enhance low-activation characteristics and reduce cooling periods after use in fusion reactors. Moreover, decreasing the Ti concentration enables further improvement of the low-activation property, thus shortening the recycling periods. To clarify the recrystallization behavior of the high-purity vanadium alloys with different Ti concentrations (up to 4 wt%), the microstructure and hardness changes of the cold rolled vanadium alloys after 873–1273 K annealing were investigated [1]. As shown in Fig. 1, recovery and recrystallization took place while increasing the annealing temperature. Partial recrystallization occurred at 1073 K, and recrystallization finished at 1273 K. The size of the recrystallized grains decreased with the Ti addition. Precipitation was not observed in V-4Cr-0Ti, whereas Ti(CON) particles were formed in Ti-added alloys, V-4Cr-(1~4)Ti, after annealing at 973 K and above. The particle size rose together with an increasing Ti concentration and annealing temperature. The hardness of cold rolled vanadium alloys decreased while increasing the annealing temperature up to 1173 K, which was attributed to recovery of dislocations and the recrystallization process. The hardness increased with the higher Ti concentration, indicating solid-solution hardening via Ti. Additionally, further reducing high-activation impurities and interstitial impurities did not have significant impacts on the hardness of the V-4Cr-4Ti alloy after recrystallization.

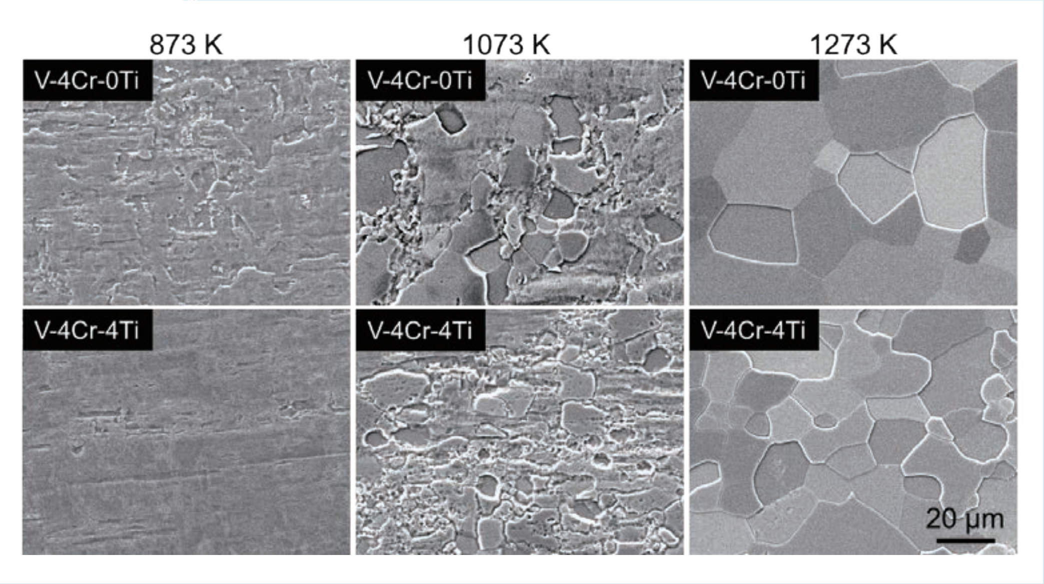

Fig. 1 Scanning electron microscope (SEM) images of cold rolled high-purity vanadium alloys after 873–1273 K annealing for 1 h.

(J.J. Shen)

Recycling of low-activation vanadium alloys within ten years after use in fusion reactors

A contact dose rate of an existing V-4Cr-4Ti alloy, NIFS-HEAT-2, alights at a remote-material-recycling level of 10^{-2} Sv/h after a radioactivity cooling of 26 years. The present study proposes much earlier material recycling, typically within ten years, leading to an extreme reduction in the volume of radioactive material storage, and reuse in the same fusion reactor because ten years are sufficiently shorter than the reactor lifespan, about 30 years. These measures accelerate innovations for economic efficiency, safety and the social acceptance of fusion reactors. Material R&D essentials are (1) purification focusing on the high-activation impurities, such as Co, Cu, Fe, Nb, Ni and Mo, (2) minimization of the Ti concentration to avoid nuclear reactions from ^{48}Ti to high-activation ^{42}K, (3) removal of ^{42}Ar, the long-lived mother for ^{42}K. (1) Purification has been examined by aqueous-solution refining for NH_4VO_3 as the precursor of vanadium metal, subsequent electron-beam refining and zone refining. The impurity levels achieved were 0.01 mass ppm for Co, <0.05 for Cu, 0.12 for Fe, 0.86 for Nb, 0.03 for Ni, and 10 for Mo [2]. They successfully satisfied the ten-year remote-recycling level. The vaporization coefficient at the gas-liquid interface in vacuum melting, and the segregation coefficient at the liquid-solid interface in zone refining were likely better for removal of Co from V, compared with Co from steels. Quantitative measurements of the coefficients are ongoing.

(T. Nagasaka)

Applicability study on photoluminescence properties of Er_2O_3 for irradiation damage and temperature monitoring in fusion reactors

In photoluminescence (PL) spectra of Er_2O_3 materials excited by an ultraviolet LED light source (365 nm), luminescence peaks were observed in the green (510–590 nm) and red (630–725 nm) ranges. Changes in the intensities of these luminescence peaks were examined for a commercially available sintered Er_2O_3 disc and Er_2O_3 powders fabricated with lower crystallinities. The results showed that the intensities of the red luminescence peaks decreased drastically compared with those of the green ones in Er_2O_3 powders with lower crystallinities. Since the crystallinities of materials irradiated with neutrons degrade due to irradiation damage, this property could be used for irradiation damage monitoring of materials in fusion reactors. Changes in the intensities of the luminescence peaks with temperature were also examined for a sintered Er_2O_3 disc. From room temperature to ~400 °C, the intensities of the green luminescence peaks decreased drastically compared with those of the red ones. Er_2O_3 materials could also be used for temperature monitoring in fusion reactors by using the property. It would be possible to perform the irradiation damage and temperature monitoring in fusion reactors during maintenance periods by using optical fibers, lenses, light sources and spectrometers [3]. The influence of induced gamma-rays emitted from radioactivated in-vessel components on the optical monitoring system is being investigated.

(T. Tanaka)

One-step fabrication of Li_2TiO_3 ceramic pebbles using pulsed YAG laser

In a fusion demonstration reactor, a large amount of Li-containing ceramic breeder pebbles will be packed in a solid breeding blanket. Several pebble fabrication technologies have been proposed in previous studies, including the wet process, the emulsion method, extrusion spheronization, additive manufacturing, and the melt process. However, a simple, energy-effective, and scalable fabrication technology remains to be developed for the automated mass production and reprocessing of used radioactive pebbles post-operation. Selective laser melting potentially enables the quick and automated fabrication of breeder pebbles. Herein, we employ a high-power density pulse laser to produce ceramic breeder pebbles [4]. A pulsed YAG laser was irradiated over a lithium metatitanate (Li_2TiO_3) powder bed in air, and the corresponding temperature was monitored using fiber-type infrared pyrometers. Spherical Li_2TiO_3 pebbles were successfully fabricated in a single step with an average diameter of 0.78 μm and a sintering density of 87.4% (input power: 7.9 J/pulse). The irradiated Li_2TiO_3 powder melted and turned spherical under surface tension and rapidly solidified, resulting in uniaxial fine grains and a decrease in the degree of long-range cation ordering.

(K. Mukai)

Simultaneous measurements method for fast-neutron flux and tritium-production rate using single crystal CVD diamond detector

The breeding blanket (BB) systems of a Deuterium-Tritium (D-T) fusion reactor have been designed using advanced and updated nuclear data libraries, although uncertainties in these calculations would impact on the BB performance such as the tritium breeding ratio. Therefore, the present study developed a simultaneous measurement method for fast neutron energy spectra and the tritium production rate, using a single crystal Chemical Vapor Deposition (CVD) diamond detector (SDD), combined with a lithium fluoride (LiF) foil, applicable for BB performance evaluation.

14 MeV neutron irradiation was carried out on the SDD [5]. Fast neutrons could be detected by the SDD through elastic collisions and (n,α)reactions, besides energetic tritons, produced in the LiF through the reaction with neutrons, could deposit the recoil energy into the SDD to be detected. We developed a code to separate pulses induced by fast neutrons and energetic tritons based on the shape, width, and height of pulses in the SDD, rejecting those induced by gamma-rays simultaneously. Subsequently, the fast neutron energy spectrum and tritium production rate were successfully deduced from discriminated-pulse data, using the response-matrix method and particle transport calculations.

(M. Kobayashi)

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[2] T. Nagasaka *et al.*, Materials Science Forum **1106**, 117–126 (2023).
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[5] M.I. Kobayashi *et al.*, Nuclear Fusion **64**, 066026, (2024).

Applied Superconductivity and Cryogenics Unit (ASC)

Highlight

FY2023 Research Results in the Applied Superconductivity and Cryogenics Unit

We have conducted thermal runaway tests in liquid hydrogen for REBCO, and have demonstrated that “cooling-stable” conditions, in which a transition to normal conduction does not lead to thermal runaway, can be met even with liquid hydrogen cooling.

We used a method (rotary magnetization) for a non-destructive, non-contact inspection of areas of Ic degradation in conductors made of laminated high-temperature superconducting wires, to measure magnetization signals and perform analysis using the finite element method. We demonstrated that it is possible to grasp the depth of deteriorated areas by changes in the magnetization-signal strength.

We developed a deep learning model to predict the ambient temperature of LHD helical coils based on measurement data accumulated during the LHD operation. We succeeded in highly accurate prediction of temperature changes that occur when helical coils are excited.

We succeeded in making an ultra-fine wire with a diameter of 50 μm using Nb3Al wire, and succeeded in making a long single wire of significantly more than 6,000 meters without breakage or abnormal deformation during processing.

We are proceeding with the development of a practical 20 kA class STARS conductor, which is a simple laminate of REBCO wire, and conducted a second cooling and excitation test on a test sample with a 600 mm diameter, a three-turn solenoid coil shape and demonstrated stable current-carrying characteristics in high-speed excitation tests up to 200 times.

Keywords:
Advanced superconducting conductor
Large scale superconducting coil
Ultra-fine superconducting wire processing
Liquid hydrogen
AI predictive maintenance
Machine learning
SDGs (power saving)
Carbon neutral

(N. Hirano)

Introduction of Machine Learning to Superconducting and Cryogenic Systems

To improve the reliability of large-scale superconducting magnet and cryogenic systems, we have been developing a system incorporating machine-learning technology. NIFS has accumulated big data on superconducting magnets and cryogenic equipment through the operation of the LHD and experiments using cryogenic test facilities. It is possible to advance system development based on these big data. The aims of system development are status monitoring and virtual measurement. In the development, the target devices are core equipment of the superconducting magnet and cryogenic systems, as shown in Fig. 1. Regarding system-status monitoring, we use principal-component analysis, which is a machine-learning technique, to reduce the dimensionality of the measurement parameters used in the system. Furthermore, we use deep learning to centralize the measurement parameters. This dimensionality reduction and centralization will simplify the system-status monitoring. Regarding the system's virtual measurement, we use soft sensors simulating the measurement sensors used in actual measurements to provide sensor redundancy. This enables the system to operate normally, even if a problem occurs with the measurement sensor.

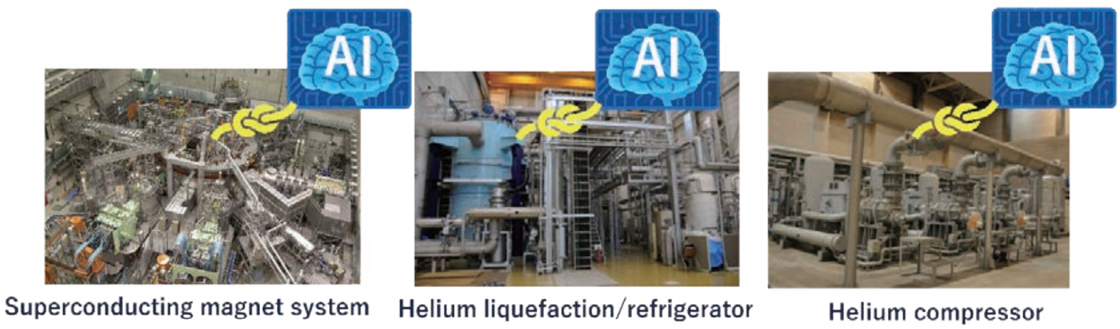


Fig. 1 Superconducting magnet and cryogenic systems with machine-learning technology.

(T. Obana)

Development of High-Temperature-Superconducting Large-Current Conductor

The High-Temperature Superconducting (HTS) magnet may become a feasible option for fusion reactors. Using HTS conductors and high cryogenic stability at an elevated temperature, the operation is expected not to consume much helium. At the National Institute for Fusion Science (NIFS), three types of large-current HTS conductors have been developed, namely, the STARS, FAIR, and WISE conductors. The STARS (Stacked Tapes Assembled in Rigid Structure) has a feature that allows rare-earth barium copper oxide (REBCO) HTS tapes to be simply stacked without twisting or transposition. This could be feasible owing to the high cryogenic stability of HTS conductors, which may allow the formation of non-uniform current distribution among the REBCO tapes. In the STARS conductor, a stack of REBCO tapes is embedded into a copper stabilizer, covered by a stainless-steel jacket with laser beam welding. This configuration primarily assures robust coil winding against intense electromagnetic forces. A 6-m sample of the 20-kA class STARS conductor was fabricated with a 600-mm diameter in a solenoid coil shape of three turns, and tested at a NIFS facility equipped with a maximum magnetic field of 13-T, 700-mm bore coil. A stable operation up to 18 kA current was confirmed at 8 T and 20 K temperature. During the experiment, a residual magnetic field was clearly observed after the transport current was ramped down to zero. A numerical calculation code has been developed for simulating the circulation currents caused by a variation of self-inductances among the simply-stacked HTS tapes, and the measured residual magnetic field was well simulated. It is shown that some of the tape currents reached the critical current at a fast ramp rate without causing an avalanche of normal-transition from tape to tape, which proves stable repetitive excitations with a 1 kA/s ramp rate. Based on these results, the applicability of the simply-stacked HTS conductor to large magnets seems plausible.

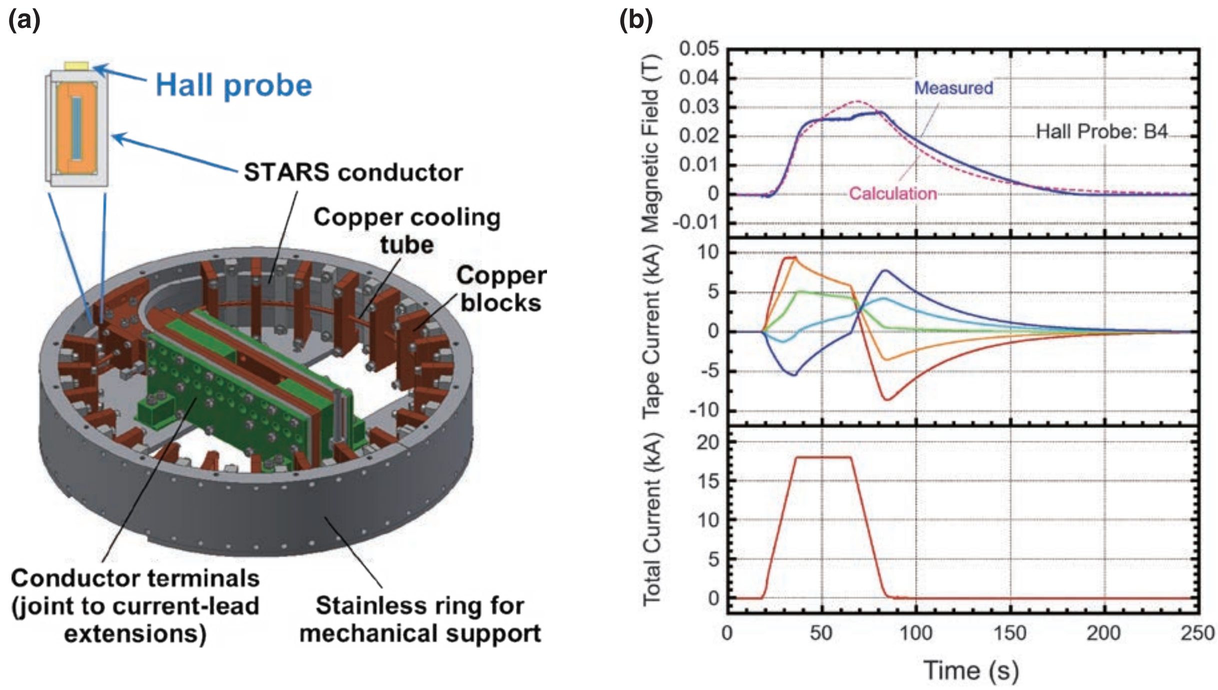


Fig. 2 (a) Schematic illustration of the 6-m, 3-turn-solenoid 20-kA-class STARS conductor sample, indicating also a Hall probe attachment for measuring the magnetic field. (b) Comparison between the measured magnetic field and the numerically calculated one. For the numerical calculation, the STARS conductor, with 15 tapes, is assumed to have five tapes, and the waveforms of the currents in each tape are shown in the middle. The waveform of the sample (total) current with a trapezoidal excitation is shown at the bottom.

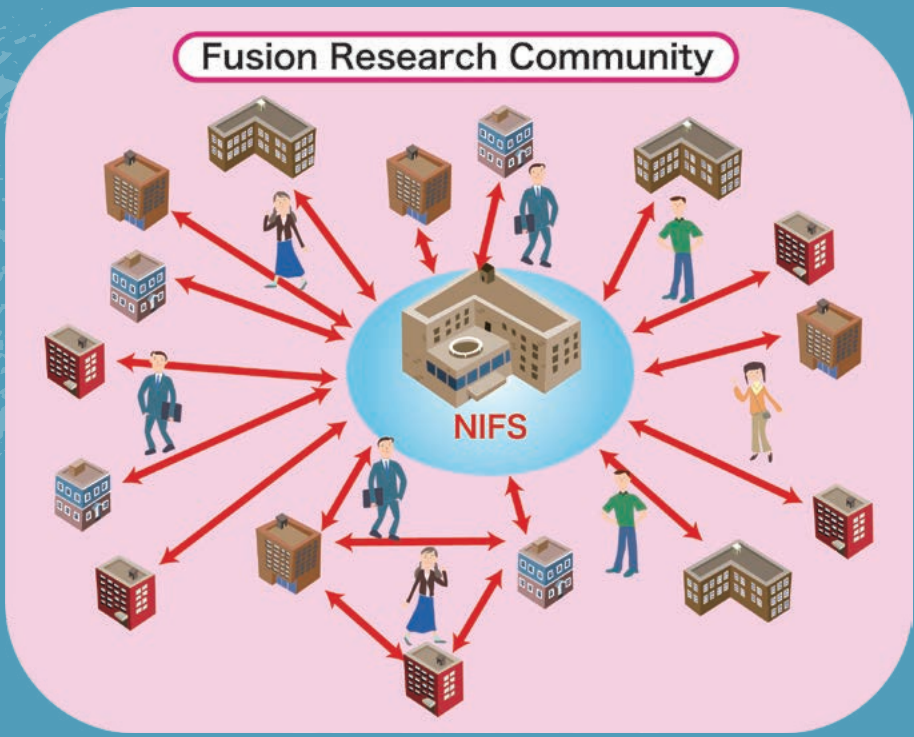
(N. Yanagi)

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.

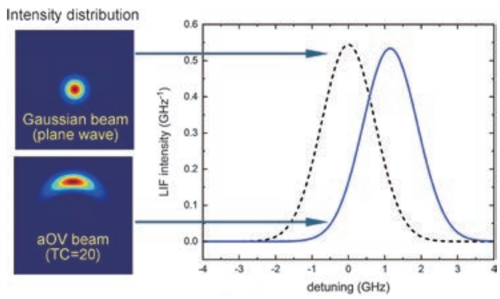


Fig. 1 Beam intensity distributions and numerically obtained LIF spectra in each beam. The figure was made with the data presented in Ref. [1].

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.

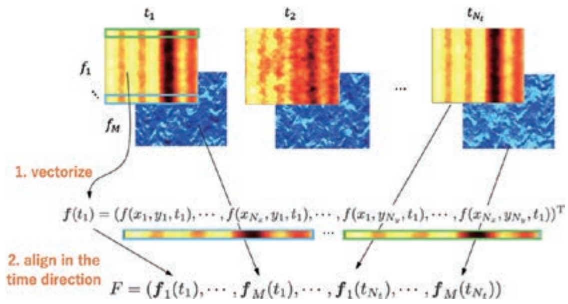


Fig. 2 Procedure of the multi-field SVD for the multi-field data F [2].

(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.

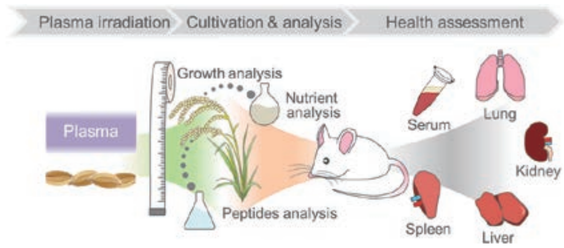


Fig. 3 Graphical overview of experimental flow in terms of harvest of plasma-irradiated rice seeds through subacute effect assessment for mice.

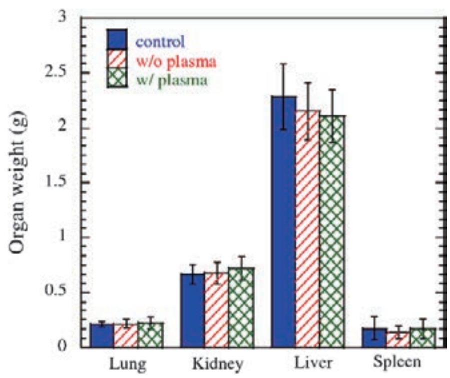


Fig. 4 Organ weight on the 28th day since the administration.

(T. Okumura, Kyushu Univ.)

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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.

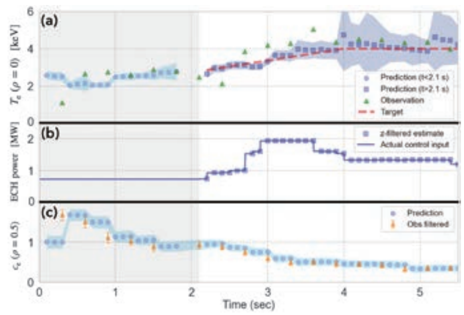

Fig. 1 Results of a control experiment (#186500); (a) control result of T_e at the plasma center, (b) ECH power adjusted using ASTI, (c) distribution (expected value and one standard deviation) of Ce at ρ = 0.5 used in the prediction step and filtered.

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(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.

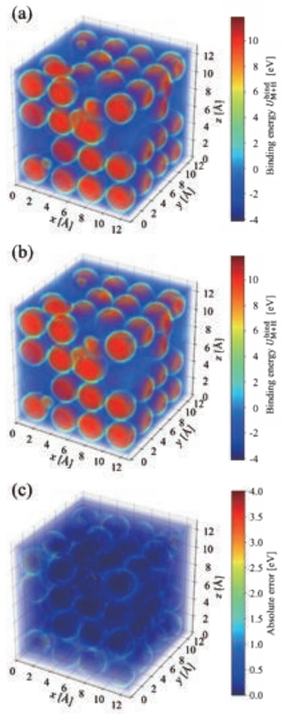


Fig. 1 An example of (a) the spatial distribution of the true values, (b) that of predicted values, and (c) the absolute error between the true and predicted values. [3] (Copyright (2024) The Japan Society of Applied Physics)

[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.

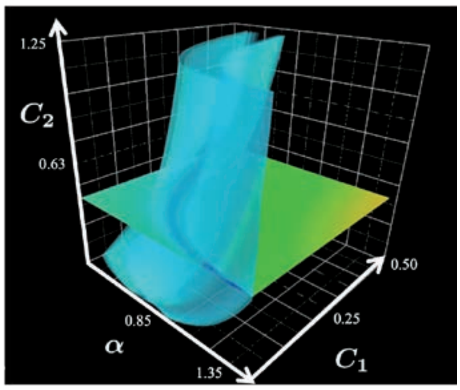


Fig. 1 Objective function for the model accuracy in parameter space of the model function.

(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.

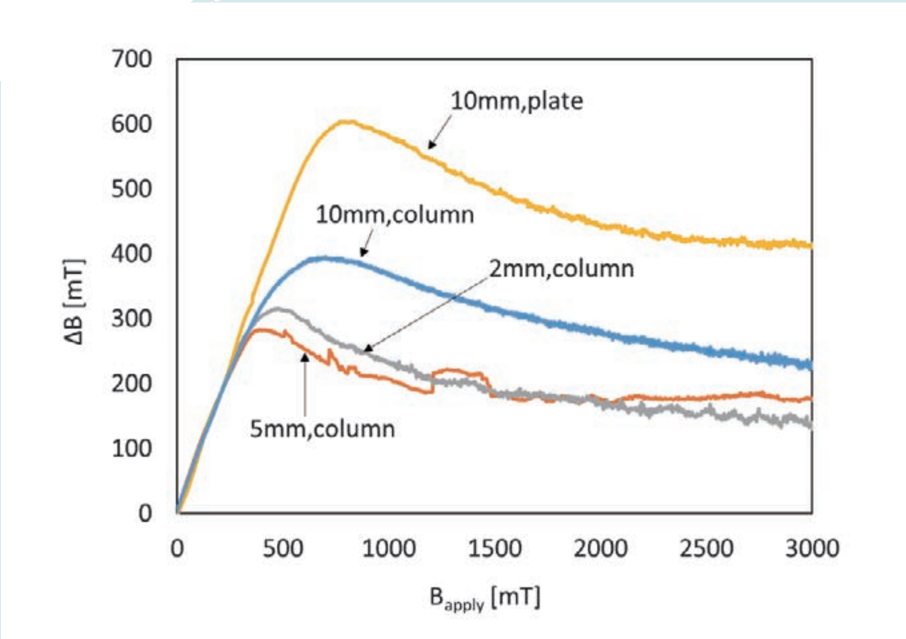


Fig. 1 Magnetic flux density (ΔB) shielded by the plate and column YBCO bulk specimens under the magnetic fields (B_{apply}) at 77 K.

(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

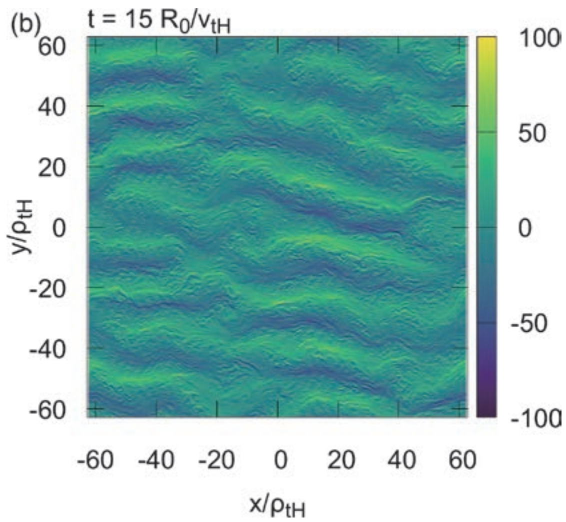
Plasma Simulator Collaboration Research promotes fusion science study using the supercomputer, Plasma Simulator. It also covers subjects that could contribute to the development of simulation science as a new academic field, as well as collaboration research on the development of new algorithms and new 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 γ_{lin} by the effective diffusion δ_{eff} caused by the ETG turbulence, such as $\gamma = \gamma_{\mathrm{lin}} - k_y^2\delta_{\mathrm{eff}}$, 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 γ_{lin}, as well as the nonlinear saturation level, has ion-mass dependence through collisionality. In contrast, the effective diffusion coefficient δ_{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.



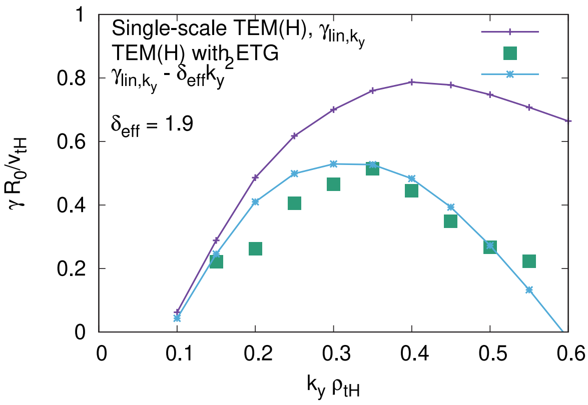


Fig. 1 (left) A snapshot of the toroidal component of an electric field in a growth phase of the trapped electron mode (TEM) in electron temperature gradient turbulence, and (right) growth rates of the TEM instability [1].

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.

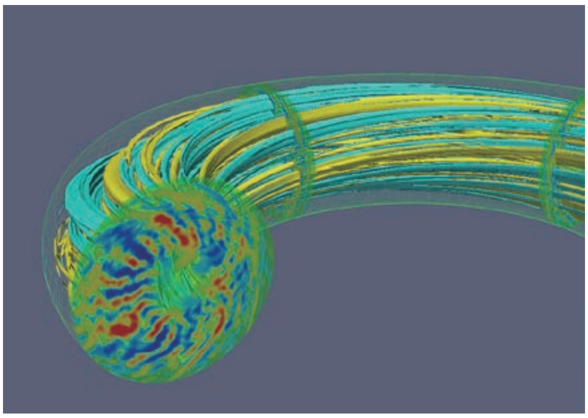


Fig. 2 Electromagnetic ITG turbulence at finite β.

[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)

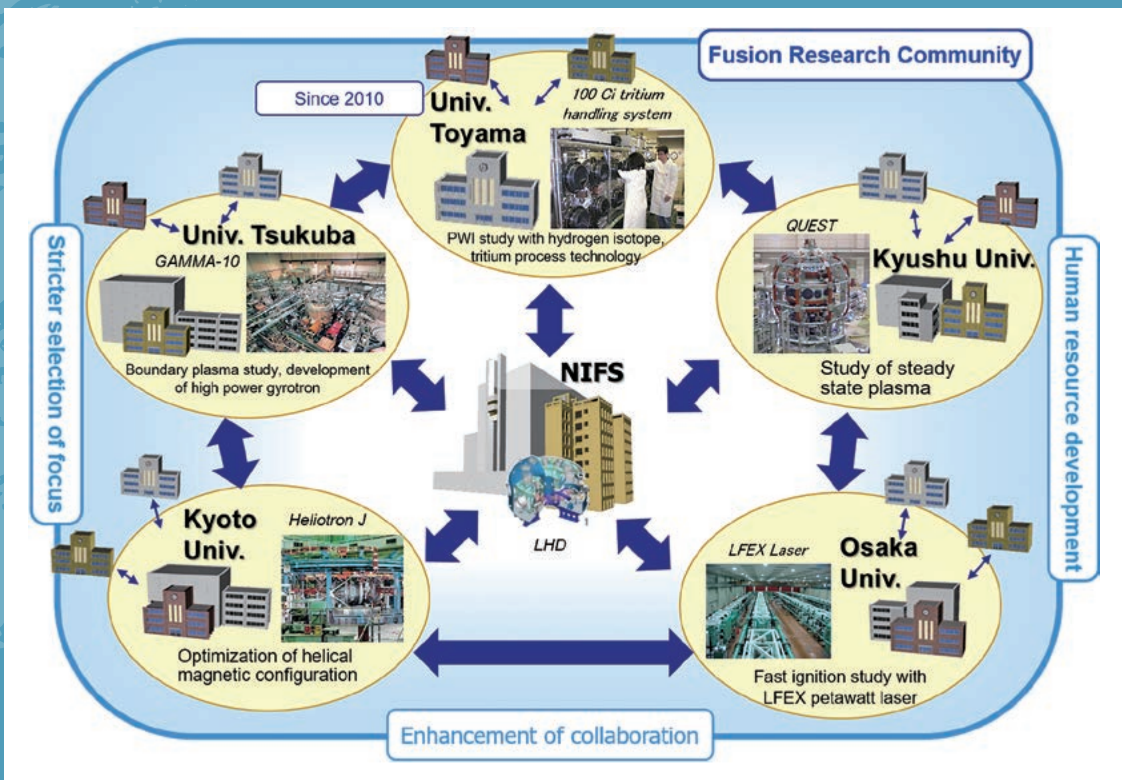
3. Bilateral Collaboration Research

The purpose of the Bilateral Collaboration Research Program (BCRP) is to reinforce the activities of nuclear fusion research in universities by using their middle-size experimental facilities of specific university research centers as joint-use facilities for all university researchers in Japan. The current program involves five university research centers as follows:

- Plasma Research Center, University of Tsukuba
- Laboratory of Complex Energy Process, Institute of Advanced Energy, Kyoto University
- Institute of Laser Engineering, Osaka University
- Advanced Fusion Research Center, Research Institute for Applied Mechanics, Kyushu University
- Hydrogen Isotope Research Center, University of Toyama

In the BCRP, each research center can have its own collaboration programs, using its main facility. Researchers at other universities can visit the research center and carry out their own collaboration research there, as if the facility belongs to NIFS. These collaboration research efforts are supported financially by NIFS as research subjects in the BCRP. They are proposed from all over Japan every year. The collaboration research committee, which is organized under the administrative board of NIFS, examines and selects the subjects.

(Y. Todo)


Fusion Research Community
Since 2010
Univ. Toyama
100 Ci tritium handling system
PWI study with hydrogen isotope, tritium process technology
Univ. Tsukuba
GAMMA-10
Boundary plasma study, development of high power gyrotron
QUEST
Kyushu Univ.
Study of steady state plasma
NIFS
LHD
Kyoto Univ.
Heliotron J
Optimization of helical magnetic configuration
LFEX Laser
Osaka Univ.
Fast ignition study with LFEX petawatt laser
Stricter selection of focus
Human resource development
Enhancement of collaboration

University of Tsukuba

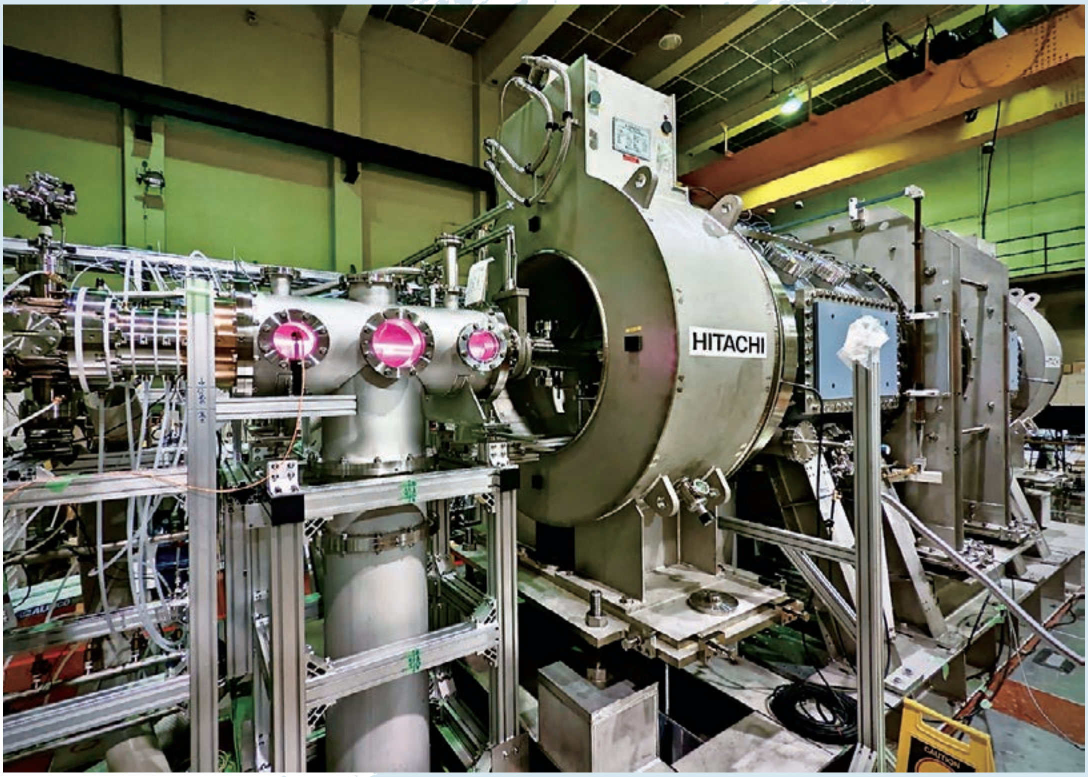


Fig. 1 Picture of the superconducting mirror machine "Pilot GAMMA PDX-SC."

Highlight

Study of boundary plasmas by making use of open magnetic field configuration and development in high power gyrotrons towards the DEMO project

In the Plasma Research Center, University of Tsukuba, studies of boundary plasma and development of high-power gyrotrons have been done under a bilateral collaboration research program. Processes of plasma detachment have been studied by introducing hydrogen and impurity gases into the end-loss plasma in a divertor simulation experimental module (D-module) installed at the west end of GAMMA 10/PDX. In FY2023, we studied the influence of gas injection positions and timings on the process of detached plasma formation, the impact of impurity ions on reducing ion-particle flux, and the spatial distribution of detached plasma due to variations in V-shaped target plate angles and the position of the plasma center axis. A new linear plasma device Pilot GAMMA PDX-SC (Fig.1) was constructed. The first plasma was successfully created in October 2022, and then ECH and ICRF antenna systems were installed. Preliminary experiments in ECH heating were conducted. ECH power of ~100 kW was applied to plasma sustained by a cascade arc plasma source, and the plasma was expanded and the density was increased.

A divertor simulation study has been carried out by using end-loss plasma of GAMMA 10/PDX. A divertor simulation experimental module (D-module) was installed in the end region of GAMMA 10/PDX to be exposed to the end-loss plasma. To clarify the effect of an impurity gas injection position on the formation and control of the detached plasma, impurity gases were injected from the inlet (Up-port) or the V-shaped target corner of the D-module and observed by a high-speed camera with a four-branch optical system (Alba prism). When nitrogen gas was introduced as an impurity, it was observed that the ratio of emission intensity from nitrogen atoms to that from nitrogen molecules was higher upstream and lower at the V-shaped target corner. Additionally, nitrogen atoms emitted weakly at the plasma axis and strongly at the periphery. It indicates that the Nitrogen Molecule Activated Reaction (N-MAR) process follows different reaction paths in space.

Measurements with an ion-sensitive probe (ISP) in the D-module were done during the injection of hydrogen and nitrogen. The ion collector current of the ISP increased and decreased with hydrogen and nitrogen gas injection. Since the ion collector current is sensitive to ions with a larger Larmor radius due to its structure, the increase in the current seems to be attributed to the formation of impurity ions with mass greater than hydrogen. Therefore, the results obtained suggest that impurity ions such as NH_x^+ are formed at multiple periods during the injection of hydrogen and nitrogen, and it is considered that the reaction between nitrogen and hydrogen is involved.

The effects of different angles of the V-shaped target plate and plasma center axis positions (strike points) on the spatial distribution of detached plasma and its formation process were investigated. The spatial distribution of the Balmer line intensity ratio $I_{H\alpha}/I_{H\beta}$ (an index of H-MAR) for different plasma center axis positions was compared, and a significant change in the distribution of the H-MAR region was observed when the strike point was moved to the upper part of the target.

As for the advanced diagnostic development, a multichannel (multi-frequency) Doppler reflectometer system has been developed to simultaneously measure turbulent fluctuation flows at different radial locations in the central cell of GAMMA 10/PDX. An azimuthal flow profile was observed when the axial current and radial potential distribution of the plasma were altered by changing the ground resistance of end plates. It was found that the flow structure during ECH was changed by modifying the ground resistance, suggesting a difference in the electric field structure is one of the factors causing the flow structure change.

Regarding fluid simulations of open-field-system plasmas, progress was made in research on kinetic effects in parallel ion conductive heat flux by using a heat-flux-limiting technique and heat-flux transport equations. Temporal simulations of pellet injection experiments in GAMMA 10/PDX were also started and reproduced experimental observations qualitatively. In addition, kinetic analyses of plasmas in mirror magnetic fields were started by using a quasi-one-dimensional particle-in-cell model.

A gyrotron with the frequency of 14 GHz has been developed to apply to a fusion reactor with a low magnetic field. Problems of this development are a large divergence of electromagnetic wave beams due to the long wavelength and a difficulty with the electron beam parameter due to the low magnetic field. To improve the efficiency of electromagnetic wave transmission at low frequencies, the distance between the mirrors (optical path length) in the gyrotron was minimized, and the design was changed so that the coupling waveguide, which had been installed in the external matching unit, was built into the gyrotron.

In order to further promote the divertor simulation study, a new linear plasma device Pilot GAMMA PDX-SC (Fig.1) was constructed and the first plasma was successfully made in October 2022, and then ECH and ICRF antenna systems and three concentric ring plates for suppression of MHD instability were installed in the main chamber. At the east end, a differential pumping system and the plasma source were installed. As the plasma source, a cascade arc plasma source and a helicon plasma source were developed.

ECH power of ~100 kW was applied to the plasma sustained by the cascade arc plasma source, and the line-averaged electron density increased by one order of magnitude to 8×10^{17} m^{-3}. Although the plasma was expanded due to ECH, the line-averaged electron density was evaluated with a line length of 7 cm, which was the diameter of the plasma before applying ECH, indicating the actual electron density during ECH was a few times lower. Even taking that into account, the ECH power was used for plasma production due to high neutral pressure in the main chamber. It is necessary to develop the differential pumping system to reduce neutral pressure in the main chamber.

(M. Sakamoto)

Kyoto University

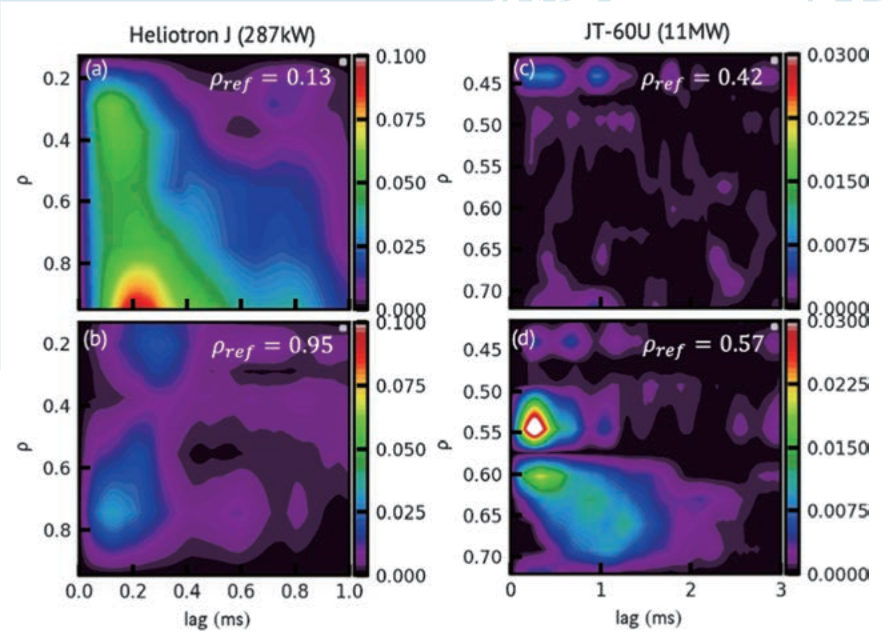


Fig. 1 The transfer entropy of electron temperature fluctuation in (a) and (b) Heliotron J and (c) and (d) JT-60U. The direction of information flow is represented as a reference location ρ_{ref}, which is indicating $T_{\rho_{ref}\rightarrow\rho_{others}}$. [F. Kin *et al.*, *Nucl. Fusion* **64**, 066023, 2024]

Highlight

Experiments utilizing magnetic field configuration and turbulence measurement

The Heliotron J device features a wide flexibility of configuration control. Rotational transform control experiments do not show a clear dependence of the energy confinement on a helical ripple, implying turbulent-dominated transport. Indeed, electron-thermal fluctuations show avalanche-type features [F. Kin *et al.*, PoP **30**, 112505 (2023)].

This fiscal year, we have reported on a comparative study of an avalanche-type of heat transport in Heliotron J with the JT-60U tokamak. We found that electron-heat propagation in Heliotron J was mainly generated from the heat-source region. Despite the increase in heating power, we observed similar temperature profiles in both devices. The electron-heat avalanches in Heliotron J were measured using an electron cyclotron emission (ECE) diagnostic. The transfer entropy analysis showed that the temperature perturbation clearly propagated from the core to the edge with one-third of the diamagnetic drift velocity. The Hurst exponent depended on total ECH power, rather than local heating power density or a local temperature gradient. In JT-60U, we observed electron and ion heat avalanches using ECE and CXRS diagnostics. The electron-heat avalanches originated from the peak of the temperature gradient, which propagated in an order of a few tenths of diamagnetic drift velocity. The Hurst exponent tended to be independent of the heating power but abruptly decreased with a rise in the temperature gradient. It was found that the large avalanche events relaxed the ion temperature gradient significantly. The different characteristics of avalanches, i.e., place of origin, propagation velocity, and dependence of the Hurst exponent, could help to understand the different profile formations observed in stellarator/heliotrons and tokamaks [F. Kin *et al.*, *Nucl. Fusion* **64**, 066023, 2024].

Research Topics from Bilateral Collaboration Program in Heliotron J

The main objectives of the research in the Heliotron J device under this Bilateral Collaboration Program are to experimentally and theoretically investigate the transport and stability of fusion plasmas in an advanced helical field and to improve plasma performance through advanced helical-field control.

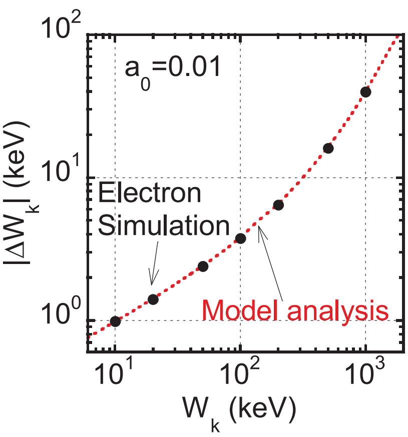
Picked up in FY2023 are the following seven research topics; (1) plasma transport control by magnetic- field coordination and related plasma structure formation control in advanced helical plasmas, (2) high-density NBI plasma generation and high-beta plasma confinement using an advanced particle supply method, (3) electron thermal fluctuation transport with self-organized criticality, (4) MHD control and a physics mechanism using ECH/ECCD, (5) boundary plasma control using ECH/ECCD, (6) generation of energetic electrons (MeV) by non-resonant microwave, and (7) development of new plasma measurement and analysis methods.

Twenty-four projects, including our baseline one, were adopted. High magnetic-field experiments were conducted for about 14 weeks, from October to the beginning of February.

Statistical acceleration using non-resonant wave heating

In Heliotron J, fast electrons exceeding 2 MeV were observed when non-resonant 2.45 GHz O-mode microwaves were injected into a vacuum magnetic-field of about 1 T [S. Kobayashi *et al.*, PPCF **62**, 065009 (2020)]. Experiments and simulations have shown that the normalized vector potential a_0 is less than 0.04, that relativistic electron production requires multiple accelerations by an electric field, that the electron energy spectrum follows the power-law, and that it exhibits a “slow heating” feature. From these points, statistical acceleration would be a possible mechanism. Simulation studies of the diffusion process of electron-energy distribution show that the diffusion coefficient is proportional to the electron energy E to the power of 3.6, and that this strong energy dependence is the essence of the power-law spectrum formation.

We performed electron acceleration simulations by changing the initial electron energy in the range of 10 keV ~ 1 MeV and investigated the amount of change in the kinetic energy of electrons as they added, subtracted, or decelerated in an electric field, and found that the model equation and the results obtained from the simulations agreed, confirming the validity of the model. On the other hand, in order to model the diffusion coefficient, it was necessary to evaluate the incremental energy determined by both the initial and final phases when exiting the electric field range, and the issue was how to incorporate the randomness of the phase, considering the electron orbit in the confining magnetic-field.



Comparison of the amount of change in electron kinetic energy added, subtracted, or decelerated in a microwave electric field, obtained from model equations and electron acceleration simulations, assuming the initial face of the electric field at the entrance of the electric field area is zero.

Many research topics have continuously made progress with collaborative researchers under the Bilateral Collaboration Program in the Heliotron J project. Progressing are (i) microwave reflectometry for zonal flow search, (ii) 320 GHz submillimeter-wave interferometry, and (iii) 2D visible high-speed spectroscopic diagnosis of pellet dissociative clouds.

(K. Nagasaki)

Osaka University

Study on Fast Ignition Scheme of Laser Fusion and Ultra-High Dense Plasma Physics

We have performed fundamental research of laser fusion with a fast ignition (FI) scheme, which enables us to separate the laser fusion process into three phases, i.e., compression, heating, and burning, using GEKKO XII and LFEX laser systems at the Institute of Laser Engineering, Osaka University. The research includes a) a high-density implosion experiment, b) a fast heating experiment using a mixed laser light of fundamental and second harmonics, and c) the effects of a kilo-tesla magnetic field on ignition burning in FI. In FY2023, the following are summary of our achievements through the Bilateral Collaboration Research Program with NIFS and other collaborators from universities and institutes (NIFS12KUGK057 as the base project).

1. High-density implosion of solid ball target with three-stage laser pulses

Laser fusion requires the generation of high-density core plasma more than 1000 times solid density. In the past, high-density plasma was generated by imploding shell targets, but in fast-ignition laser fusion, there is no need to form a hot spot in the core, so in this study, a solid ball is compressed by a three-stage shock wave driven by high-power laser lights. Solid balls are resistant to hydrodynamic instabilities, but a laser irradiation profile requires the same level of inhomogeneity as shell implosion. Last year, the non-uniformity of laser irradiation was improved by introducing a random phase plate. In FY2023, a solid ball implosion was carried out using a precisely tuned three-stage pulsed laser, shown in Fig. 1 (left). By improving the non-uniformity and the accuracy of the waveform shaping of the three-stage pulses, we were able to achieve a more uniform implosion than that in the previous year's experiment.

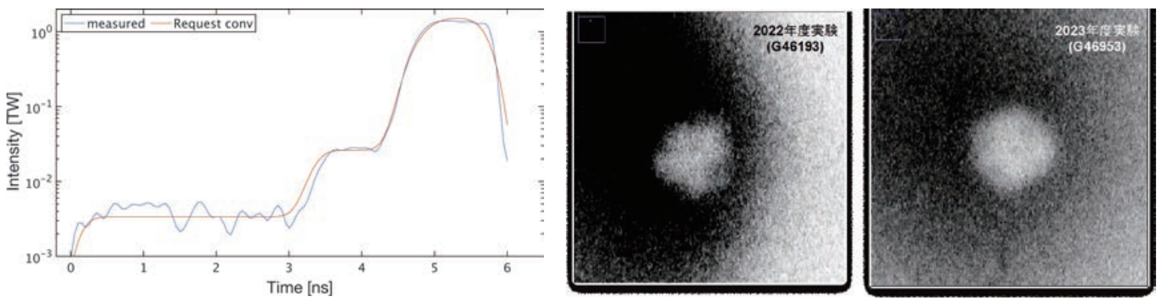


Fig. 1 (Left) Three-stage pulses are generated as requested by hydro-simulation. (Right) Backlight images of imploded plasma observed in FY2022 (Middle) and in FY2023 (Left).

2. Heating mechanism of imploding plasma by a 10 PW-class heating laser

In fast-ignition fusion, the core will be heated by a 10 PW-class laser after the formation of a high-density implosion core to drive ignition burning. The imploding core plasma is surrounded by a corona plasma of several hundred microns, and it is an important issue to elucidate the mechanism that efficiently delivers the heating laser to the core region. In the FIREX-NEO project, we used a plasma particle code (PICLS) to design fast-ignition laser fusion with 10 PW-class laser pulses.

We found that in corona plasmas, up to a critical density of several tens of times higher, the waveguide of the heating laser could be formed by a hole-boring mechanism with a 1 kJ petawatt laser. Theoretical and simulation studies for stable-waveguide formation by hole boring are underway. Calculations of core heating by

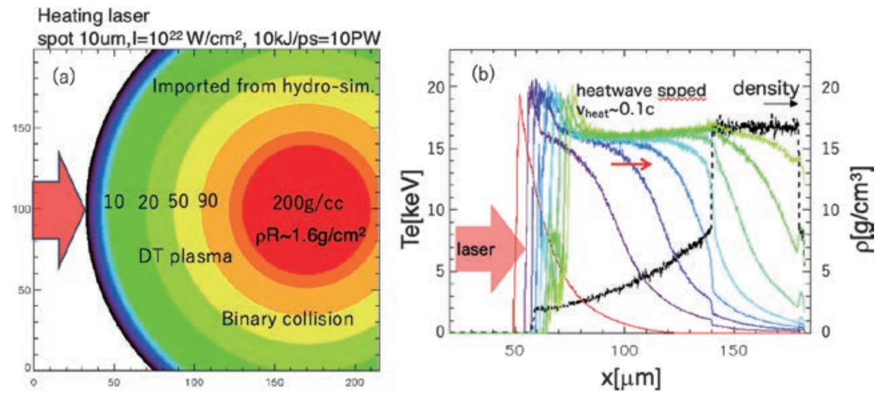


Fig. 2 (a) Initial conditions of the calculation: density profile of the detonation plasma calculated by PINOCO; (b) Time evolution of the bulk-electron temperature on the laser axis (0.5 ps intervals). Propagation of thermal waves.

a 10 PW laser after waveguide formation have also been carried out. The density profile of the imploding plasma calculated with the radiation fluid code PINOCO was loaded into the PICLS code, which incorporated Coulomb collision processes extended to relativity (Fig. 2 (a)), and a heating calculation lasting five picoseconds was carried out. Fig. 2 (b) shows the temporal evolution of the bulk- electron temperature output in every 0.5 picosecond. We found that the thermal wave propagated from left to right over a region of more than 100 microns at approximately 10% of the speed of light. Since the thermal waves are a phenomenon in the region where the mean free path is comparable to the temperature gradient, the driving conditions and propagation characteristics of thermal waves will be clarified in order to develop a more efficient fast-ignition laser fusion design in the future.

3. Development of fast neutron detectors using EO polymers

An EO polymer quickly changes its transmittance of electromagnetic waves in a certain wavelength region, as a response to induced electric voltage by radiations. We successfully created a high quality EO polymer layer with 4cm diameter and 1μm thickness on a silicon wafer (Fig. 3). A section of the EO polymer layer cut out to 1 mm × 1 mm × 0.3 mm was attached to a device. We then tested its response characteristics against energetic electrons and protons which were accelerated by irradiating the LFEX laser on a thin target. The measured data is encouraging since it is showing temporal resolution of 10 ps. The data will be verified in detail and developed for use as a fast-neutron instrument for laser fusion study.

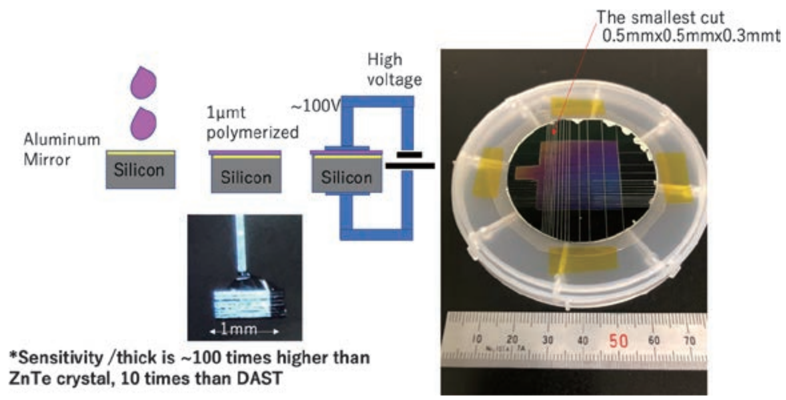


Fig. 3 Process of creation of EO polymer layer on a silicon wafer.

(Y. Sentoku)

Kyushu University

Research activities on QUEST in FY2023

We will summarize the activities of the Advanced Fusion Research Center, Research Institute for Applied Mechanics in Kyushu University during April 2023 – March 2024. QUEST experiments were executed during 13th Jun. – 14th Sep. (2023 Spring/Summer, shot no. 51226–52223) and 31st Oct. – 19th Jan. (2023 Autumn/Winter, shot no. 52224–53076). The main topics of the QUEST experiments in FY2023 are listed below.

1) Electron cyclotron plasma ramp-up with a retarding field has been conducted to suppress the growth of highly energetic electrons. When the retarding field stopped being applied, bulk-electron temperature (~150 eV) could not be maintained, and hard X-rays from the energetic electrons rapidly increased around the zero field. In coaxial helicity injection experiments, larger closed-flux surfaces were formed with high-plasma current (~90 kA) by applying higher-discharge voltage in short pulses. A pulse width with significant plasma current was extended by applying induction.
2) The Directional Material Probe (DMP) method was used in the PWI study at QUEST. DMPs were placed above and below the MH-16 port in a QUEST vacuum vessel during the 2020S/S-2 and 2021S/S-1 campaigns, respectively. There were four DMPs (top, ion- and electron-drift sides, plasma-facing side) at each position. After 2021S/S-1, visible directionality of the change of color of the surfaces of each DMP was not observed, suggesting a deposition layer was formed isotropically. The DMPs retrieved after the 2020S/S-2 campaign showed a difference between the ion- and electron-drift sides. However, with the DMPs after 2021S/S-1 this was not the case. Further investigation is ongoing to determine the cause of this difference between the campaigns.
3) Hydrogen isotope retention in the QUEST plasma wall was evaluated by ion-beam analysis. The aim of this collaboration is to understand the surface transformations and hydrogen-isotope retention of plasma-facing materials occurring in QUEST. The results quantitatively revealed that a carbon-implanted layer may suppress hydrogen diffusion.
4) Floating potential fluctuation measured by a divertor probe array in QUEST has been analyzed. Complex behavior has been found as follows. There is a strong correlation between channels near the strike point, while coherence quickly decays radially outward. The fluctuation propagates from the center channel in both inner and outward directions at an initial phase of discharge, but the propagation direction changes in a later phase.
5) EC breakdown characteristics were studied in detail with the CS (central solenoid) energized. The vertical field required for fast breakdown with the CS was found to be stronger than that without it. The shape of the plasma at breakdown was also different with the CS that led to higher electron temperature.
6) The radial profiles of T_e and n_e were measured in QUEST midplane, using the helium line intensity ratio method. The measured T_e and n_e were compared with those obtained by the Thomson scattering method, and they agreed within factors of approximately two and six, respectively.
7) Incoherent digital holography (IDH) has attracted attention in recent years due to advances in sensor and optical technologies; however, it is still far from being put to practical use. In this project, we aim to clarify the technical issues for applying IDH 3D spectroscopy to plasma measurements and to resolve them.
8) Installation of a rotation motor in an energetic particle probe (EPP) enabled rapid and reliable pitch-angle distribution measurement of fast electrons during a single discharge. The energy spectrum of fast electrons largely changed with the pitch-angle, verifying that the velocity distribution of fast electrons in the far SOL of EC driven plasma was strongly distorted.

9) Several W samples were installed in QUEST and exposed long-time plasma discharge at 320~340 °C. XPS was performed to analyze the chemical state of a sample surface, namely W-10% Re and W-K. On the top surface, C was deposited by plasma exposure. The chemical state of the sample surface was not largely different among these samples. In future, we are planning to evaluate hydrogen-retention behavior in C-deposited advanced plasma-facing materials.
10) We considered using an improved RNN method called long short-term memory (LSTM) to predict the waveform of fuel particles being fed into the plasma. Predicting values ten seconds ahead was compared, using both RNN and LSTM. It was found that LSTM did not cause any oscillation and agreed relatively well with the measured values, while RNN did so.
11) Electron cyclotron wall conditioning with argon gas (Ar-ECWC) has been performed on QUEST. Hydrogen retained in the wall was removed, and the wall pumping capability was recovered. However, many defects such as voids, bubbles, and dislocation loops were formed on the tungsten surface exposed to the Ar-ECWC plasma.
12) A direct detection of an electron Bernstein wave (EBW) in QUEST is one of the important issues to improve and optimize heating and current drive, using the wave. A hydrogen cyanide (HCN) laser is introduced as a scattering source for the direct detection of the EBW. A highly sensitive detection system at HCN laser wavelength (337 μm) is being developed utilizing a harmonic mixer system at 400 GHz. To estimate and predict the power flux of the EBW and the scattered-power flux owing to the EBW as well, an extended Quasi-optical beam tracing code (EQUASI) that can account for the structures of the medium of less than the order of the beam size is under development.
13) To determine the relationship between particle recycling and plasma performance, it is planned to implement the Non-Evaporative Getter (NEG) pump unit HV400 in QUEST. A new proposal was submitted in FY2023 to discuss the port where the HV400 will be installed.
14) In addition to the quasilinear ECH model, we have introduced a model of acceleration due to multiple resonances to the GNET code. We performed the GNET simulations assuming the QUEST magnetic configuration. It was confirmed that the fast electrons generated by the second harmonic ECH were further accelerated by the third and fourth harmonic waves.
15) A divertor biasing experiment has been conducted using four biasing electrodes installed on the upper divertor plate. Small crashes of plasma current were observed during the divertor biasing. These crashes may be attributed to the loss of energetic electrons. Whole plasma oscillation is coincident with the biasing, even though the current driven by the biasing is quite small in the scrape off layer.
16) Tomography based on visible light camera images was applied, incorporating the effect of reflected light from the inner walls of the vacuum vessel. A machine learning model based on BERT, which is one of large-scale language models, was also developed to predict the vertical positional variation of the plasma.

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MURAKAMI Sadayoshi (Kyoto University) 14)
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TSUTSUI Hiroaki (Tokyo Institute of Technology) 16)

(H. Idei)

University of Toyama

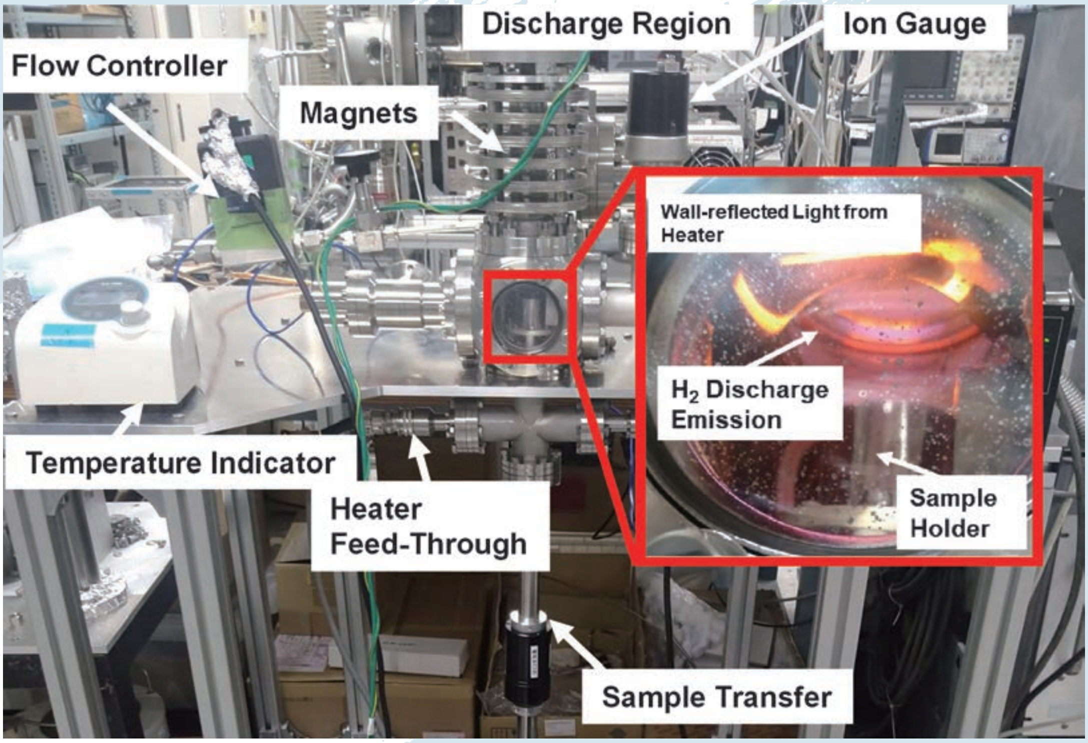


Fig. 1 Newly constructed compact plasma device to be installed in a radiation-controlled area for measurements of tritium retention and distribution in liquid and solid Sn.

Highlight

Research Activities in Hydrogen Isotope Research Center, Organization for Promotion of Research, University of Toyama

The flow of high heat flux to a divertor region is one of critical issues for magnetic confinement fusion. A liquid metal divertor has larger heat removal capability than a solid divertor plate. Tin (Sn) is a candidate for liquid metal divertor material because of low vapor pressure. However, data on the transport parameters of fuel particles such as solubility and diffusivity are scarce. The objective of this study is to evaluate transport parameters of tritium (T) in Sn in liquid and solid states. To reach this goal, a new plasma device was constructed to expose liquid/solid Sn to T plasma, as shown in Fig. 1. The uniqueness of this device is a small internal volume that realizes the plasma exposure with a relatively small amount of T. Hence, the device can be operated without a glove box. [*Precise evaluation of tritium profile in solid/liquid tin exposed to tritium plasma (H. Toyoda, Nagoya University)*]

Tritium transport in fusion reactor materials (Y. Hatano, U. Toyama): Permeation of T through steam generator piping in a fusion power station may result in the risk of uncontrolled T leakage into the environment. Hence, the T permeation must be precisely evaluated and minimized. Nickel alloys are widely used as pipe materials. In 2022, we evaluated the T permeation through Inconel 600 film under exposure to high temperature, high-pressure water and found that the permeation could be suppressed by the addition of O_2 gas in water. In 2023, we examined the effects of O_2 gas on the oxidation of Inconel 600.

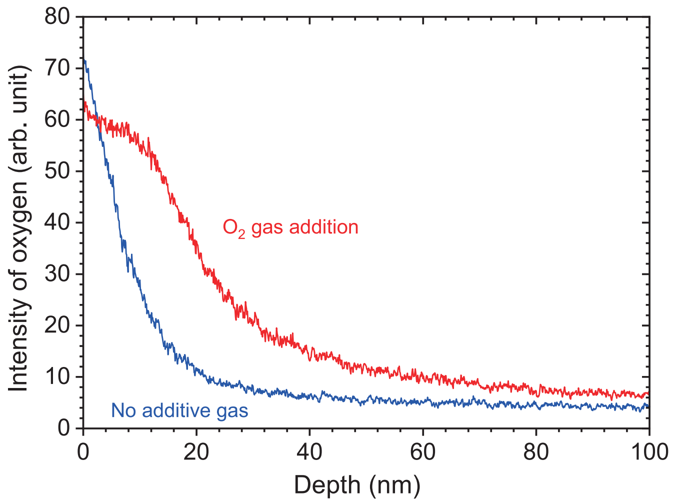


Fig. 2 Depth profiles of oxygen in oxide films formed on Inconel 600 alloy samples by exposing to steam at 280 °C and 6.4 MPa.

Plates of Inconel 600 were exposed to high-pressure water at 280 °C for 14 and 28 hours with and without O_2 gas addition. Then, the oxide films were analyzed using glow-discharge optical spectrometry. The depth profiles of oxygen obtained after oxidation for 14 hours are shown in Fig. 2. The thickness of the oxide film increased with addition of O_2 gas but it was still a few tens of nanometers. The increase in oxide thickness with the elapse of time followed a parabolic law. It meant that the oxide layer had a protective nature even under O_2 gas addition.

Other experimental studies performed in the Hydrogen Isotope Research Center in the fiscal year 2023 are listed below.

- *Nano-fiber formation on tungsten alloy by helium plasma irradiation* (Y. Ueda, Osaka U.)
- *Effect of transmutation or irradiation damage on hydrogen isotope transport dynamics* (Y. Oya, Shizuoka U.)
- *Effective tritium removal under vacuum conditions* (N. Ashikawa, NIFS and Y. Torikai, Ibaraki U.)
- *Effects of heat and particles load on hydrogen isotope retention in tungsten materials* (K. Tokunaga, Kyushu U.)
- *Release behaviors of hydrogen isotopes from tungsten materials exposed to hydrogen isotope plasma during oxidation* (T. Otsuka, Kindai U.)
- *Depth analysis of co-deposited H, He and impurity atoms on plasma exposed W by means of GDOES* (N. Yoshida, Kyushu U.)
- *Hydrogen isotope pick-up and retention in He-exposed W-Mo alloys* (E. Jimenez-Melero, The University of Manchester)
- *Suppression of tritium permeation in stainless steel by laser peening* (Y. Nobuta, Hokkaido U.)
- *Development of liquid DT fusion fuel for high repetition laser fusion reactor* (Y. Arikwa, Osaka U.)
- *Understanding and optimization of tritium absorption into titanium target for 14 MeV neutron irradiation experiments* (I. Murata, Osaka U.)
- *Correlation between hydrogen isotopes trap density and vacancy concentration in tungsten* (M. Kobayashi, NIFS)

4. International Collaboraiton

Many research activities in NIFS are strongly linked with international collaborations with institutes and universities around the world. These collaborations are carried out in various frameworks, as follows,

1) Multinational coordination in Fusion Power Coordinating Committee (FPCC) under International Energy Agency (IEA),
   - Stellarator-Heliotron Technology Cooperation Program (TCP)
   - Plasma-Wall Interactions TCP
   - Spherical Tori TCP

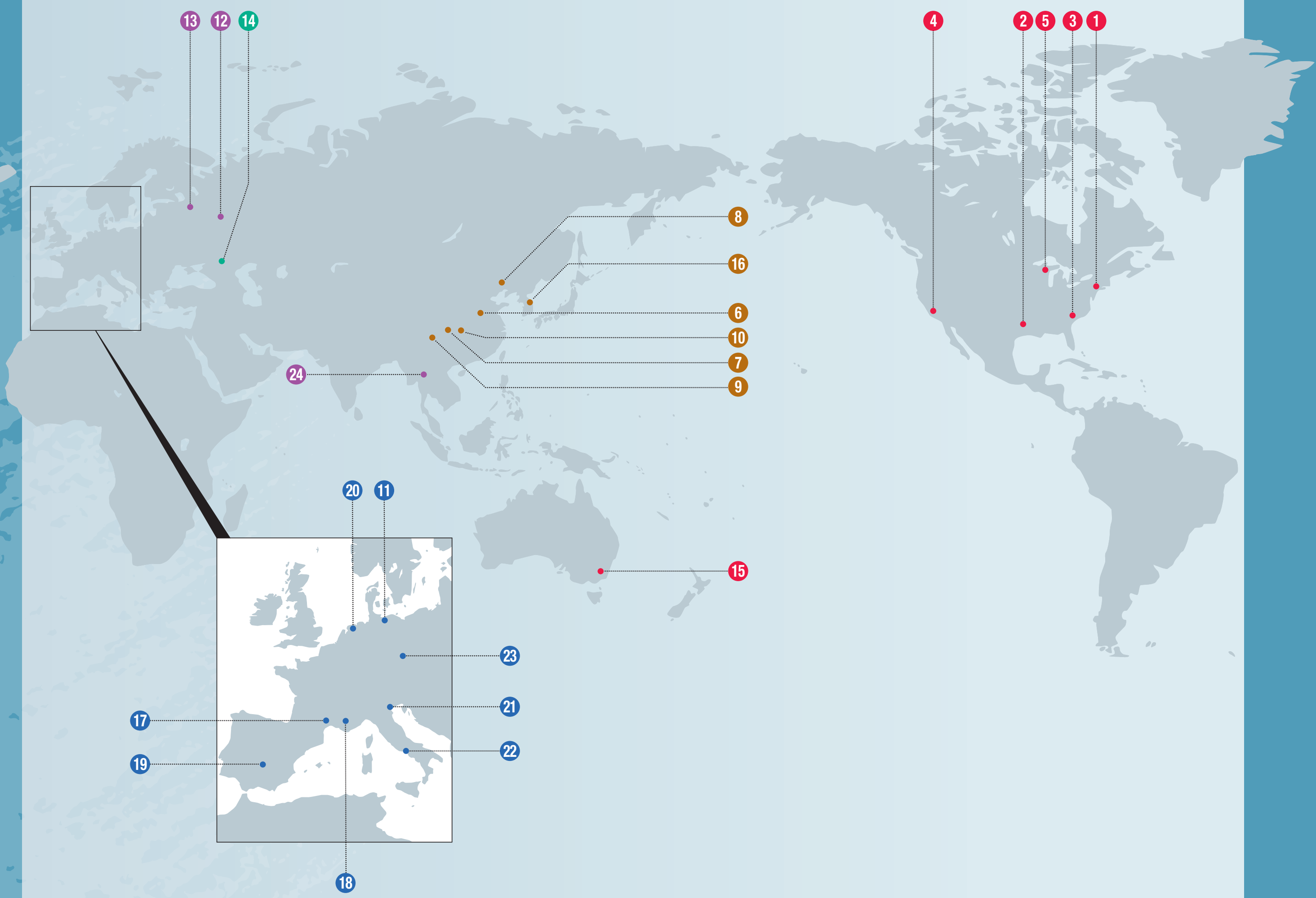
2) Binational coordination,
   - Japan-United States Collaborative Program
   - Japan-Korea Fusion Collaboration Programs
   - Japan-China Collaborative Program
   - Japan-EU Cooperation

3) Coordination with other institutions
   - 30 international academic exchange agreement

The geographical distribution of international collaborations and summary of each activity are shown in following pages.

(T. Morisaki)

Academic Exchange Agreements



U.S.A. ❶ Princeton Plasma Physics Labolatory (PPPL)
❷ Institute for Studies, The University of Texas at Austin (IFS)
❸ Oak Ridge National Laboratory (ORNL)
❹ Center for Energy Science and Technology Advanced Research, University of California, Los Angelse (UCLA)
❺ Letters & Science and College of Engineering, University of Wisconsin–Madison College (UWM)

China ❻ Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
❼ Southwestern Institute of Physics (SWIP)
❽ Peking University
❾ Southwest Jiaotong University (SWJTU)
❿ Huazhong University of Science and Technology

Germany ⓫ Max Planck Institute for Plasma Physics (IPP)

Russia ⓬ A. M. Prokhorov General Physics Institute, Russian Academy of Sciences (GPI)
⓭ Peter the Great St. Petersburg Polytechnic University

Ukraine ⓮ National Science Center of the Ukraine Khar'kov Institute of Physics and Technology Institute of Plasma Physics (KIPT)

Australia ⓯ Australian National University (ANU)

South Korea ⓰ National Fusion Research Institute (NFRI)

France ⓱ Aix-Marseille University (AMU)
⓲ Commissariat à l'énergie atomique et aux énergies alternatives (CEA)

Spain ⓳ National Research Center for Energy, Environment and Technology (CIEMAT)

Netherlands ⓴ Dutch Institute for Fundamental Energy Reseearch (FOM)

Italy ㉑ CONSORZIO RFX
㉒ Institute of Lonized Gas (IGI)

Czech ㉓ HiLASE Center, Institute of Physics CAS (FZU)

Tailand ㉔ Chiang Mai University

The ITER International Fusion Energy Organization (ITER)

US – Japan (Universities) Fusion Cooperation Program

US-Japan joint activity has continued from 1977. The 43rd CCFE (Coordinating Committee for Fusion Energy) meeting was held on April 24, 2024 via a video conference system. Representatives from the MEXT, the DOE, universities and research institutes from both Japan and the US participated. At the meeting, the current research status of both countries was reported, together with bilateral technical highlights of the collaborations. Fiscal year 2023 cooperative activities were reviewed, and FY 2024 proposals were approved.

(1) Fusion Technology Planning Committee (FTPC)

In the category of the FTPC, four personnel exchanges were performed in fiscal year 2023, including three Japan to US and one US to Japan. Three of the exchanges were in the research field of “in-vessel/high heat flux materials and components”. The linear plasma-surface interactions research facility PISCES at UCLA was used to expose tungsten samples in hydrogen and deuterium plasmas. For the US to Japan collaboration, the samples were sent to NIFS to investigate surface modification using facilities such as FIB-TEM (Fig. 1). In the category of “superconducting magnets”, current distribution in a High-Temperature Superconducting (HTS) large-current conductor fabricated at MIT was clearly evaluated from the measured magnetic field.

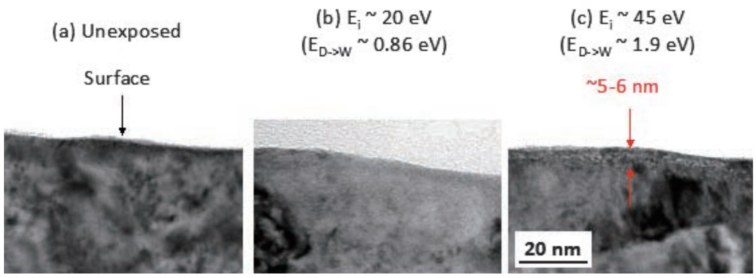


Fig. 1 TEM images of the Deuterium Supersaturated Surface Layer (DSSL). [D. Nishijima *et al.*, Nucl. Fusion **63**, 126003] (2023).

(2) Fusion Physics Planning Committee (FPPC)

In the field of fusion physics, collaborative research has been conducted in the following five categories: a steady-state operation, MHD and high Beta, confinement, diagnostics, and high energy density science. In FY 2023, one committee meeting was held, and four workshops and seven personnel exchanges were implemented from Japan to the U.S. Also, two workshops and four personnel exchanges from the U.S. to Japan were completed.

In the U.S., there was an experiment on MHD stability in an inverted triangular configuration and an optimization study on isotope ratio measurements in DIII-D. There were also experiments on the interaction between zonal flows and the phase-space vortex and on phase-space turbulence measurements in the linear plasma device LAPD at UCLA (Fig. 2). There was too an experiment on two-fluid relaxation in the reversed-field pinch device, MST, at the University of Wisconsin. Experiments on magnetic reconnection using high magnetic fields generated by lasers were done at the Princeton Plasma Physics Laboratory and the University of Rochester; and an experiment on laser-ion sources for heavy-ion inertial fusion at Brookhaven National Laboratory were conducted.

In Japan, an experiment on a non-inductive current start-up in the spherical tokamak device QUEST at Kyushu University was conducted. Discussions on plasma measurement were held at the Kyoto Institute of Technology and NIFS. At QST, plasma measurement in JT-60SA was discussed.

Fig. 2 LAPD (https://commons.wikimedia.org/wiki/File:Lapd_exterior.jpg#filelinks).

Fig. 3 Participants of the workshop on RF heating and current drive physics at UCSD.

Workshops were held on the following topics: RF heating and current drive (Fig. 3), MHD measurement and control, and inertial fusion in the U.S.; liquid metal plasma-facing walls, magnetic reconnection in Japan; and innovative and alternative confinement concepts online.

(3) Joint Institute for Fusion Theory (JIFT)

One workshop on "theory and simulation of high-field and high-energy density physics" was held at Yokohama in April 2023, and one workshop on "the progress of fusion research with extreme-scale computing and data science" was held at NIFS in November 2023. In the category of personal exchanges, one US to Japan exchange visit and one Japan to US exchange visit were successfully carried out for "collaboration on Tokamak boundary plasma turbulence simulations for divertor heat flux width," which resulted in a publication in Physics of Plasmas (Fig. 4). A JIFT discussion meeting was held at Toki in September 2023 at the Plasma Simulator Symposium. The status of JIFT activities for 2023–2024 was reviewed, and recommendation plans for 2024–2025 were discussed at Nagoya among members of the JIFT Steering Committee in November 2023.

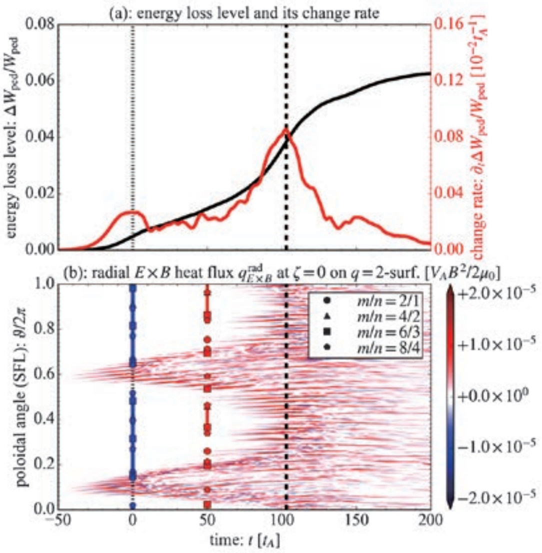


Fig. 4 Simulation results of (a) ELM energy loss level and its change rate, and (b) the spatio-temporal structure of radial heat flux at $\zeta=0$ on $q=2$ surface, where the dotted and dashed lines are the first ($t=0t_A$) and second crash ($t=103t_A$) respectively. In Fig (b), the colored solid lines represent the regions with magnetic islands (MIs), and the circle, triangle, square, and pentagon symbols are the location of X-points of $m/n=2/1$, 4/2, 6/3, 8/4 MIs [H. Seto *et al.*, Phys. Plasmas **31**, 032513 (2024)].

(4) US-Japan Joint Project: FRONTIER

The FRONTIER collaboration started in April 2019 to provide the scientific foundations for reaction dynamics in interfaces of plasma facing components for DEMO reactors. This project consists of four tasks: Irradiation Effects on Reaction Dynamics at Plasma-Facing Material/Structural Material Interfaces (Task 1), Tritium Transport through Interface and Reaction Dynamics in Accidental Conditions (Task 2), Corrosion Dynamics on Liquid-Solid Interface under Neutron Irradiation for Liquid Divertor Concepts (Task 3) and Engineering Modelling (Task 4). Regarding Task 3, liquid metal-structural material compatibility under neutron irradiation was examined. Sn capsules containing pre-oxidized FeCrAl tensile specimens (Fig. 5a) were exposed in 2022 to 0.8 Fe dpa neutrons in the High Flux Isotope Reactor at Oak Ridge National Laboratory (ORNL) for ten days at around 460 °C. The irradiated capsules were opened in 2023, and pre-oxidized Fe-Cr-Al alloy samples were successfully retrieved. Optical analyses of the specimens showed no serious corrosion (Fig. 5b). Tensile and microstructural characterization will follow. In the Safety and Tritium Applied Research (STAR) Facility at Idaho National Laboratory (INL), oxidation tests of W and W-Re alloy were successfully performed at 873–1173 K to simulate the loss of vacuum-accident conditions. Clear effects of Re on oxidation rate were observed at 1073 K and at lower temperatures (Fig. 6).

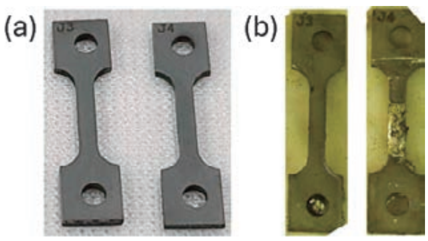


Fig. 5 Optical images of pre-oxidized FeCrAl oxide dispersion strengthened steel (ODS) samples (a) before and (b) after ten days HFIR neutron irradiation (0.8 Fe dpa) in liquid Sn environment at around 460 °C.

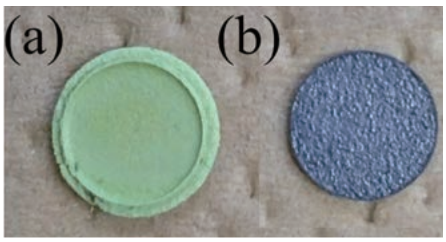


Fig. 6 Optical images of W (a) and W-10%Re alloy (b) after oxidation in Ar-20%O_2 mixture gas at 1073 K.

(T. Morisaki, S. Masuzaki, N. Yanagi, H. Sugama and Y. Hatano)

Plasma Wall Interaction (PWI) Collaboration

This collaboration is based on the IEA Technical Collaboration Programme (TCP) of the “Development and Research on Plasma Wall Interaction Facilities for Fusion Reactors” (PWI TCP) which involves Japan, Europe, the United States, Australia, and the United Kingdom. The objective of this program is to advance the physics and technologies of plasma-wall interaction research by strengthening cooperation among plasma-wall interaction facilities (in particular, by using dedicated linear plasma devices), to enhance the research and development effort related to a fusion reactor’s first wall materials and components, shown in the figure below.

NIFS collects proposals for international collaborative studies based on the PWI TCP, from domestic universities every year. The proposals are reviewed by the PWI technical committee whose members are domestic senior researchers in universities, QST, and NIFS, and some of the proposals are approved. Proponents of the approved collaborative research go to foreign institutes with support from NIFS and conduct the studies.

In the fiscal year of 2023, a collaboration on PWI experimentation was conducted.

Evaluation of D and He retention behavior in W-Re alloys and K-doped W in D+He mixed plasma irradiation

Evaluation of hydrogen-isotope retention in plasma-facing walls of fusion reactors is an important issue for the safety assessment of fusion reactors. Recently, W-Re alloys and K-doped W have been proposed as advanced plasma-facing materials, and it has been reported that irradiation-defect formation under neutron irradiation is reduced. Considering their use in plasma-facing materials, it is necessary to evaluate the hydrogen-isotope retention of these advanced plasma-facing materials to clarify He-mixing effects on the retention and to examine the applicability of the advanced plasma-facing materials from various perspectives.

In this study, deuterium plasma irradiation and mixed deuterium and He plasma irradiation of non-irradiated W-5%Ta, W-5.2%Mo, and K-doped W (40 ppm) samples were performed using a linear plasma irradiation system (DPE: Deuterium Plasma Experiment) in Sandia National Laboratories, and deuterium retention was evaluated.

As a result, it was found that the deuterium retention in W-5.2%Mo and W-5%Ta was about 1/5 of that in W, and that in W-K it was reduced by about one order of magnitude. It was shown that additive elements can significantly reduce hydrogen trapping sites. Future experiments using advanced plasma-facing materials with irradiation damage will be conducted to systematically summarize the effects of additive elements on hydrogen trapping and to study the mechanism of hydrogen trapping.

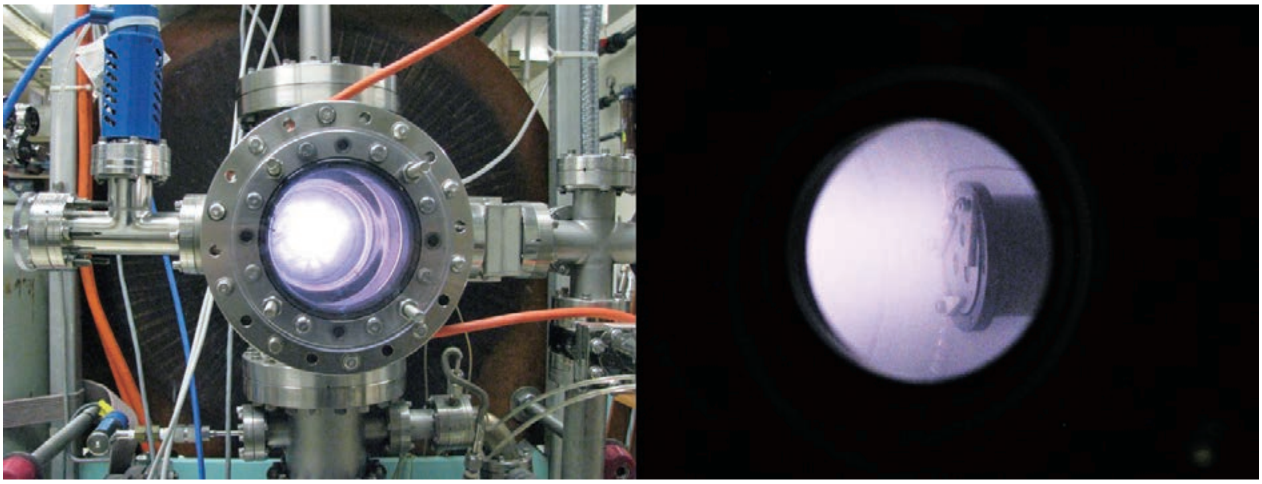


Fig. D+He mixture plasma in DPE and the material samples under the irradiation.

(Y. Oya, Shizuoka University)

IEA (International Energy Agency) Technology Collaboration Programme for Cooperation in Development of the Stellarator-Heliotron (SH) Concept ("IEA SH-TCP")

Highlight

The LHD experiment has restarted under a new budget framework.

The objective of the Stellarator-Heliotron Technology Collaboration Programme (SH-TCP) is to improve the physical basis of the Stellarator-Heliotron concept and to increase the effectiveness and productivity of research and development efforts related to that concept by strengthening cooperation among IEA Member Countries. The cooperation program will consist of the following activities: exchange of information; dispatch of experts to facilities or research groups of the Parties; joint planning and coordination of experimental programmes in specific fields; workshops, seminars, and symposia; joint theoretical design and systems studies; exchange of computer codes; joint experiments.
The LHD project ended in FY2022, supported by the Large-Scale Science Frontier Promotion Project, a budget framework for promoting large-scale projects in Japanese academic research. However, due to the high recognition of its significance and importance, a new LHD project has been launched for three years until the end of 2026, with support from another budget framework, the Academic Research Foundation Project, which also promotes large-scale projects in Japanese academic research. This new LHD project will utilize LHD as an interdisciplinary research platform to promote international joint research that seeks to elucidate the basic principles of various complex phenomena that exist not only in nuclear fusion but also in space and astronomical plasma. This three-year extension of the LHD project is expected to further invigorate the activities of the SH-TCP.

Significant achievements in 2023–2024

Significant events in the IEA SH-TCP from 2023 to 2024 are as follows: (1) As mentioned in the highlights above, the operation of LHD has been extended for three years with support from the Academic Research Foundation Project. It is now possible to conduct two more experimental campaigns (the first of which began in March 2024), and (2) the 23rd Coordinated Working Group Meeting (CWGM) was held in Kyoto, Japan, from June 5 to 8th, 2023.

As mentioned in the highlights above, the operation of LHD was extended for three years from FY2023. This extension has given us more time to consolidate the results of the comparative study of large-scale stellarator-heliotron devices. From the perspective of revitalizing SH-TCP activities, extending the LHD operation is a critical decision.

Next, the CWGM held in Kyoto, Japan, was the first multi-day CWGM since travel restrictions due to COVID-19 were eased. As explained in more detail later, from the 23rd CWGM, the strategic task force system was reorganized to realize a stellarator-heliotron-type fusion reactor, and more specific work activities were carried out. To prepare for this renewal, the CWGM Organizing Committee held many remote meetings, using

Zoom, to redefine the activities carried out by the CWGM.

In addition, the IAEA Fusion Energy Conference, the most prominent international conference on nuclear fusion, was held face-to-face in London, UK, from October 16 to 21st, 2023. At this conference, the latest research results from each stellarator-heliotron device, such as LHD, W7-X, TJ-II, and Heliotron J, were presented and attracted the attention of researchers worldwide. Moreover, the researchers gathered for the conference frequently engaged in lively discussions during the meeting about the future of international collaboration on their respective research topics. Therefore, like the International Stellarator-Heliotron Workshop (ISHW), this conference, held once every two years, significantly contributes to the revitalization of SH-TCP activities.

Summary of 52nd S-H TCP Executive Committee meeting

During the IAEA Fusion Energy Conference, the 52nd Executive Committee (ExCo) meeting of the IEA S-H TCP was held in London, UK, on October 18, 2023. At this meeting, the chair reported on preparations for an IAEA-led Workshop on Physics and Technology aspects of stellarator-based fusion power plants and the status of CICLOP, as well as confirming TCP membership, particularly about the participation of private companies. There were also reports on the preparations for the 24th ISHW and the activities of the CWGM, and the representatives from the stellarator community participating in each ITPA topical group were confirmed. The next, 53rd, meeting will be held during the 24th ISHW, which will be held in Hiroshima, Japan, in September 2024.

23rd Coordinated Working Group Meeting (CWGM)

The 23rd Coordinated Working Group Meeting (CWGM) was held in Kyoto, Japan, from June 5th to 8th, 2023, with support from the Japan Society for the Promotion of Science (JSPS) Core-to-Core Program “Advanced Core-to-Core Network for High-Temperature Plasma Dynamics and Structure Formation Based on Magnetic Field Diversity (PLADyS).” It was held in a hybrid format with in-person and remote participation. This meeting rearranged the organization into a strategic task force structure to realize a stellarator-heliotron-type fusion reactor. Specifically, the CWGM topical groups were reorganized into

- Core transport and confinement in multi-ion plasmas
  TG coordinators: M. Nunami (NIFS), D. Carralero (CIEMAT)
- Energy, particle, and impurity transport in the SOL and divertor
  TG coordinators: A. Bader (UWM/Type One Energy), V. Winters (IPP)
- Energetic Particles, MHD, and High-Beta
  TG coordinators: A. Knieps (FZJ), A. Wright (PPPL)

In each of these three reconstituted topical groups, short-term goals were set to achieve long-term objectives, and specific research results were obtained through joint activities and joint experiments while also acquiring experimental data and tools to achieve the long-term objectives. The objectives and goals of each topical group were introduced at the meeting, and future activity policy was discussed. At the meeting, there was also a discussion about the relationship with the startup companies rapidly developing fusion reactors. It was announced that the next face-to-face CWGM would be held in Japan before or after the ISHW, and it was decided that until then, the follow-up to the discussions at this CWGM would be carried out remotely.

(N. Tamura, K. Nagaoka and K. Nagasaki (Kyoto Univ.))

Japan-China Collaboration for Fusion Research

Japan-China collaboration on fusion research is motivated by (1) a joint working group (JWG) for an implementing arrangement between MEXT of Japan and MOST of China, for cooperation in the area of magnetic fusion energy research and development and related fields. (2) Collaboration on fusion research with institutes and universities in China, including the Institute of Plasma Physics, the Chinese Academy of Science (ASIPP), the Southwestern Institute of Physics (SWIP), Peking University, Southwestern Jiaotong University (SWJTU), Huazhong University of Science and Technology (HUST) and other universities. The Japan-China collaboration is carried out both for studies on plasma physics and fusion engineering. Based on the following implementation system, the Japan-China collaboration for fusion research in FY 2023 was executed.

Table 1 Implementation system of Japan-China collaboration for fusion research in NIFS

Category	① Plasma experiment				② Theory and simulation	③ Fusion engineering research
Subcategory	①-1	①-2	①-3	①-4	—	—
Operator	A. Shimizu	H. Takahashi	M. Isobe	M. Goto	G. Kawamura	T. Tanaka

①-1: Configuration optimization, transport, and magnetohydrodynamics, ①-2 : Plasma heating and steady-state physics, ①-3 : Energetic particles, and plasma diagnostics, ①-4 : Edge plasma and divertor physics, and atomic process

Primary joint research activities in FY 2023

The sixth Steering Committee meeting for the NIFS-SWJTU joint project for the CFQS quasi-axisymmetric stellarator, was held on Dec. 11, 2023 at SWJTU Jiuli campus, as shown in Fig. 1. The progress of engineering design, the current status of the construction of modular coils (MCs), and vacuum vessels (VV) were reviewed [1]. At this time, for a total of 16 MCs, most of the manufacturing processes have been finished. Coil cases/clamps, legs and other support structures were under construction. For the vacuum vessel, the manufacture of the first and second quarter toroidal sections were finished. Vacuum leak tests were perfomed on these sections, and no leaks were found. Manufacturing of the third and fourth toroidal sections on the vacuum vessel were in

Fig. 1 The sixth Steering Committee meeting of NIFS-SWJTU joint project for the CFQS held on Dec. 11, 2023 at SWJTU Jiuli campus.

progress. The first plasma will be produced in 2024 in a condition of 0.1 T operation. In additon to CFQS physics, basic research on the ion source for NBI were done joinlty with SWJTU [2,3].

Research of energetic particles, characterizations of compact neutron energy spectrometers, developed in collaboration with NIFS and ASIPP, have been utilized to measure the distribution of energetic ions in LHD and have been published [4-6]. NIFS and ASIPP performed triton burnup experiments to study alpha particle confinement ability in EAST July 2023. Also, NIFS and ASIPP have been discussing the execution of collaborative research to measure lost energetic ions for EAST and BEST. Research on energetic-ion loss due to MHD instability and runaway electron generation on the HL-2A tokamak were published as a joint outcome between NIFS and SWIP [7,8]. NIFS and SWIP have been discussing the design of neutral particle analyzers and neutron diagnostics in HL-3.

In the research of edge and divertor plasmas, we investigated the electron temperature measurement method, using the intensity ratios of impurity emission lines in relation to a steady-state operation with divertor heat load control in EAST. The main focus was on investigating the electron temperature dependence of the intensity ratio of the two emission lines of carbon ions, C IV 31.242 nm and C IV 41.971 nm, using the ADAS database. We also considered the intensity ratio of the two emission lines of neon ions, Ne VIII 10.31 nm and Ne VIII 8.809 nm, for which the neon impurity supplied for radiative cooling purposes was assumed to be used. We confirmed that it is feasible to measure electron temperature using these emission lines.

Regarding fusion engineering research collaboration, a withstand voltage test on a STARS conductor developed at NIFS was carried out at ASIPP using a mock-up sample in liquid nitrogen (temperature 77 K). The result suggested that the insulation between the copper-stabilized casing (that houses REBCO tapes) and the outer stainless-steel jacket could withstand up to ten times the required voltage.

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(M. Isobe, A. Shimizu, K. Ogawa and M. Goto)

Japan-Korea Fusion Collaboration Programs

I. KSTAR Collaboration in FY 2023

Workshop on Physics and Technology of heating and current drive

This workshop was held from 22nd to 23rd in February 2024, in Hanyang University in Seoul as a hybrid of face-to face and remote participation. There were 15 oral presentations (JA: 5, KO:10). Three people including two students traveled from Japan to Korea for on-site participation. There were 27 participants in total including eight students. The topics were electron cyclotron resonance heating/current drive, helicon wave heating/current drive, ion cyclotron range of frequency wave heating, neutral beam heating/current drive, and measurements of hard X-ray and electron cyclotron emissions related to the physics or technology of plasma heating.

KSTAR collaboration on plasma diagnostics

Thomson scattering diagnostics: Two people traveled to KFE from Japan to participate in the KSTAR experiment and a conference on diagnostics. Three people traveled to Japan to participate in the 20th International Symposium on Laser-Aided Plasma Diagnostics (LAPD20) held in Kyoto and visited NIFS. Information exchanges and discussions regarding polychromators were conducted.

Neutron and high energy ion diagnostics: Two people from NIFS and two students from SOKENDAI university traveled to KFE from Japan with a researcher from Thailand for an in-person meeting on neutron and high energy ion diagnostics.

SXCCD Camera: Work to install a soft X-ray CCD camera (SXCCD) which was previously installed in LHD and an imaging system using a beryllium filter into KSTAR was continued. One person traveled from NIFS (C. Suzuki) to KFE to conduct a status assessment. Considering that the expected results were not obtained in operational tests of the camera itself, discussions about future plans, including the possibility of replacing it with other detectors were conducted.

Japan-Korea KSTAR Diagnostics Collaboration Meeting: This meeting was held on February 6th, 2024 at KFE. Five people from NIFS traveled to Korea to participate in this meeting on-site and five people participated remotely from NIFS. Twenty-two people participated from Korea. The status of each diagnostics collaboration was reported and a discussion on JK diagnostic collaboration was conducted.

Fig. 1 Image from Japan-Korea KSTAR Diagnostics Collaboration Meeting

Collaboration of RF plasma heating in KSTAR

One person traveled to KFE from Japan (T. Seki) for discussions about improvement, and consideration of increased power capacity of the ion cyclotron range of frequency (ICRF) heating system in KSTAR. An issue with the new compact ICRF antenna (CIA) whose design was led by NIFS side arose during the experiment. The antenna strap was deformed. The investigation by KFE revealed that poor quality control during the assembly of the antenna might have led to some bolts not being properly tightened.

It is considered that the poor heating performance of the power injection system of 170 GHz GYCOM gyrotron is due to issues with beam alignment. Information about the mode content analysis was exchanged via e-mail. A preparation meeting for using a mode content analysis program that was developed in Japan was held remotely. IR images of the beam radiated from the waveguide that was connected to the matching optics unit (MOU) of the gyrotron were sent to Japanese side.

II. Human Resource Development in FY 2023

Studies on multi-scale and multi-species transport in fusion plasma

The "17th Japan-Korea Workshop on "Modeling and Simulation of Magnetic Fusion Plasmas" was held from 28th to 29th August 2023 at Seoul National University in Korea, as a hybrid of face-to face and remote participation. There were 14 participants from Japan and 16 from Korea in total. There were 11 presentations from Japan and ten from Korea. Three people traveled to Korea to participate in this workshop onsite. Transport phenomena at different space-time scales or related to impurity ions and energetic particles were focused on in this workshop. The workshop program was designed to address both aspects of anomalous transport due to waves and turbulence.

Evaluation of Tritium behavior for reactor design in fusion (V)

The "2023 Japan-Korea Tritium Workshop" was held from 30th November to 1st December 2023 at Youtree Hachinohe, in Japan, face-to face. There were six participants from Japan and six from Korea, including students. The status of the development of tritium handling technology was reported from Japan and Korea. A report was also presented on the status of the development of the Tritium Storage and Supply System (SDS) as part of ITER procurement-related technology development. Verification of fuel supply through modeling, and design activities of K-DEMO were reported from the Korean side. From the Japanese side, reports covering a wide range of research areas, such as the development of tritium recovery technology from solid tritium breeding materials, the latest status of procurement activities and BA activities for the ITER tritium removal facility at QST were presented.

Fig. 2 Image from 2023 Japan-Korea Tritium Workshop

(H. Igami, B. Peterson, T. Seki, T.H. Watanabe and Y. Oya)

5. Fusion Science Interdisciplinary Coordination Center

The Fusion Science Interdisciplinary Coordination Center was established in April 2023, to promote interdisciplinary collaboration in fusion science and development research, and social implementation of fusion technology through industry-academia-government cooperation. As a comprehensive center that leads and supports collaborative research with universities, development research institutes, and industry, the center links three new interdisciplinary fields and a group of Units to develop challenging and interdisciplinary joint research that transcends the boundaries of existing fields. In particular, in order to build a multidisciplinary research network with advanced academic research fields, promote open science, collaborate with international research projects, and implement the technologies cultivated through nuclear fusion in society, the 1) Advanced Academic Research Coordination Section, 2) Development Research Coordination Section, and 3) Industry-Academia-Government Coordination Section support various joint research in collaboration with the Units.

(I. Murakami)

Advanced Academic Research Coordination Section

The Advanced Academic Research Coordination Section supports the promotion of interdisciplinary collaboration between Units and universities in diverse academic frontier fields. It helps to establish a research network with universities and institutes at home and abroad and activates research in fusion science and joint research with a wide range of cutting-edge fields by sharing experimental data and promoting open science.

(I. Murakami)

Aurora observation project

As one of the interdisciplinary collaborative projects, researchers from the Phase Space Turbulence Unit and the Meta-Hierarchical Dynamics Unit of the National Institute for Fusion Science, the Research Institute for Sustainable Humanosphere of Kyoto University, and Tohoku University have cooperated in launching an aurora observation project. In this project, a hyperspectral camera that can acquire data in two spatial dimensions plus a wavelength and a liquid crystal filter camera that can observe images of any emission lines were installed at

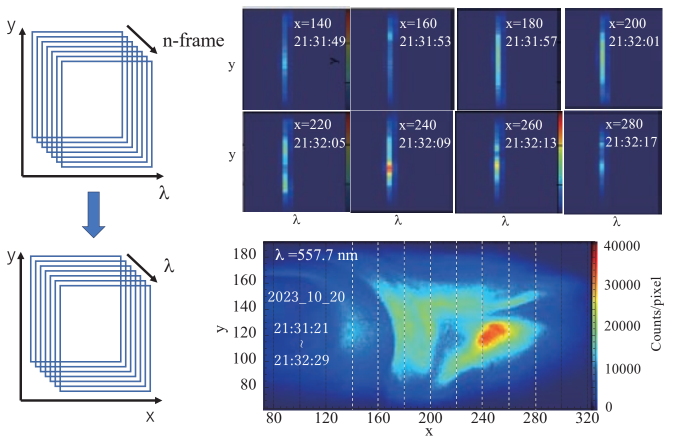

Fig. 1 (top) Original snapshots obtained by HySCAI I (y,l), and (bottom) reconstructed image (x,y) at 557.7 nm.

the KEOPS (Kiruna Esrange Optical Platform Site) of the SSC (Swedish Space Corporation) in Kiruna, Sweden (67°51′ north latitude).

The hyperspectral camera for auroral imaging (HySCAI), which can provide a two-dimensional (2D) aurora image with full spectrum, was developed to study auroral physics. HySCAI consists of an all-sky lens, monitor camera, galvanometer scanner, grating spectrograph, and electron multiplying charge coupled device (EM-CCD). The galvanometer scanner can scan a slit image of the spectrograph on the all-sky image plane in the direction perpendicular to the slit. As seen in figure 1, the several frames of the spectrum along the slit direction are converted to a two-dimensional image with different wavelength. HySCAI has two gratings; one is 500 grooves/mm for a wide spectral coverage of 400–800 nm with a spectral resolution (FWHM) of 2.1 nm, and the other is 1500 grooves/mm for a higher spectral resolution of 0.73 nm with a narrower spectral coverage of 123 nm.

As the first light results, monochromatic images of N_2^+ 1NG (0, 1) (427.8 nm), N_2^+ 1NG (0, 2) (470.9 nm), H (486.1 nm), N II (500.1 nm), N I (2 D) (520.0 nm), O I (1 S) (557.7 nm,), NaD (589.3 nm), O I (1 D) (630.0 nm), and N_2 1PG (670.5 nm) emission intensity were measured. We estimated the precipitating electron energy from a ratio of I(630.0 nm)/I(427.8 nm) to be 1.6 keV [1].

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(K. Ida, M. Yoshinuma and Y. Ebihara)

Development Research Coordination Section

Collaborating with the National Institute for Quantum Science and Technology (QST), five types of development research were carried out as a single year project; nevertheless they are to be continued.

(1) Divertor R&D for JA-DEMO

The tungsten (W) monoblock (MB) plasma facing unit (PFU) with a reduced activation ferritic/martensitic (RAFM) steel cooling pipe is one of key components for JA-DEMO divertor design. Small scale PFUs were manufactured by the Hot Isostatic Pressing (HIP) technique in order to investigate thermal and mechanical properties of the joint between W-MBs and a F82H pipe with a thin Cu interlayer. The test facility ACT2 at NIFS provided the environment for evaluating the joining performance by an iterative heat load experiment. The set-up for the experiment is shown in Figure 2. The joint sample has demonstrated its capability to withstand a maximum heat flux of 8 MW/m^2.

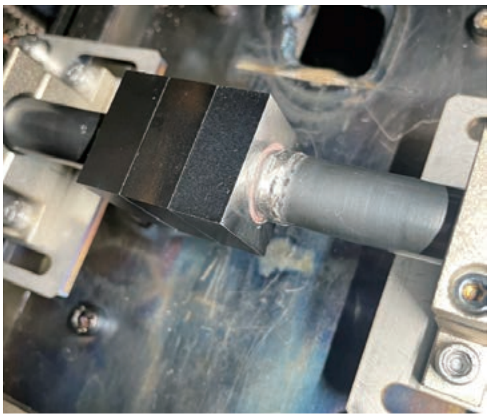


Fig. 2 Experimental set-up for heat loading test in ACT2 facility.

(2) Neutron and Gamma-ray detector development for LiPAC

Fast neutron and gamma-ray diagnostics are important for the characterization and management of an intense fusion neutron source such as the International Fusion Materials Irradiation Facility (IFMIF). The EJ-301 fast neutron scintillation detector, single crystal diamond detector and CeBr3:Ce gamma-ray detector have been used to measure neutron and gamma-ray flux in the IFMIF prototype accelerator (LIPAc).

(3) Upgrading NIFS-RNIS for DEMO NBI R&D

A giant radio frequency (RF) negative ion source for a neutral beam injector needs low beamlet (single beam of multi-beams) divergence, such as a filament-driven arc (FA) source, toward DEMO because of its long beam transport length. A research and development Negative Ion Source at NIFS (NIFS-RNIS) has been upgraded to an RF/FA hybrid source from an FA one. The RF mode operation with beam extraction was successfully performed, and the preliminary result of the beamlet divergence could be obtained with the beamlet monitor in the RF mode.

(4) Development research of bonding technique for JT-60SA divertor

In JT-60SA, the divertor component for a high-power-injection experiment has been developed, establishing a bonding technique between armor and heat sink, which is essential. The Powder Solid Bonding method (PSB) was used to test the bonding of tungsten to copper alloy, bonding tungsten to copper ally, graphite to copper alloy, graphite to molybdenum alloy, and C/C composite to copper alloy using simple test pieces.

(5) "Statistical-Mathematics" Fusion Research based on data-driven approach

It is important to incorporate data science and statistical mathematics methods as research tools to effectively utilize the large amounts of data generated by fusion-related experiments and simulations, and to link this to the development of control methods for future fusion reactors. The "QST Research Collaboration for Fusion DEMO" entitled "development of learning and estimation tools using data science and statistical mathematical methods and their utilization for control-based simulators", among researchers of the QST Rokkasho Fusion Institute, universities and NIFS, aims to develop and improve modeling methods for constructing control logic and predicting performance. Specifically, we have worked on plasma images, measurement data, and numerical simulation data such as that of turbulence and heat transport issues.

(T. Morisaki, M. Tokitani, K. Ogawa, H. Nakano and M. Yokoyama)

Industry Academia Government Coordination Section

The Industry Academia Government Cooperation Section is in charge of supporting the social implementation of fusion technology through industry academia government cooperation. Specifically, this section works on: ①Activities related to joint research with private companies, commissioned research, use of platforms, creation of opportunities for collaboration. ②Accumulation of know-how, collection of information, acquisition of external funding for industry academia government cooperation. ③Establishment of a system for industry-academia-government cooperation activities. ④AManagement and coordination of strategy for the Mission Realization Project.

(R. Yasuhara)

6. Health and Safety Promotion Center

In accordance with the reorganization of NIFS, the Health and Safety Promotion Division, which is devoted to preventing work-related accidents, to ensuring safe and sound operation of machinery and equipment, and to maintaining a safe and healthful environment for researchers, technical staff, coresearchers, and students, was changed to the Health and Safety Promotion Center. This center also ensures that research activities conducted by NIFS do not affect the surrounding environment. It consists of ten offices, and various subjects related to the health and safety are discussed by office chiefs once a month.

1. Health Management Office

The main role of this office is to keep the workers in the institute healthy, including co-researchers and students.

A) Medical checkups both for general and special purposes and immunization for influenza.
B) Mental health care services and health consultation.
C) Accompany the inspections of the health administrator and the occupational physician.
D) Maintenance of AEDs.
E) Alerts and response to infectious diseases

Various lectures were held for ensuring physical and mental health. An online stress-check was held in October 2023.

2. Fire/Disaster Prevention and Security Management Office

The main role of this office is to prevent or minimize damage caused by various disasters.

A) Making self-defense plans for fires and disasters, and implementation of various training.
B) Promotion of first-aid workshops and an AED class.
C) Maintenance of fire-defense facilities and attending on-site inspections by the local fire department.
D) Review and update disaster prevention rules and manuals.
E) Maintenance of a card-key system for gateways to buildings and controlled areas.

All workers must attend disaster prevention training held every year, and a disaster simulation exercise is also held. Figure 1 shows the disaster prevention training.

3. Radiation Control Office

The main role of this office is to maintain radiation safety for researchers and the environment. Legal procedures for radiation safety and regular education for the radiation area workers are also important roles of this office.

A) Maintain radiation safety for the workers.
B) Registration and dose control for radiation area workers.
C) Observation of emissions in the radiation-controlled area and the peripheral one.
D) Maintenance of the radiation monitor.
E) Applications for radiation equipment to national agencies and local governments.
F) Revise official regulations and establish new rules.

Fig. 1 Disaster prevention training

An educational lecture for the radiation area workers was held on February 29, 2024. We provided an opportunity for DVD viewing to absentees. Non-Japanese workers were educated and trained in English.

4. Electrical Equipment and Work Control Office

The main role of this office is to maintain electrical safety for researchers, technical staff members and students.

A) Check and control electrical facilities according to the technical standards.
B) Safety lectures for researchers and workers.
C) Annual check of electrical equipment during a blackout.

An annual inspection of the academic zone was carried out on May 14, 2023, and that of the experimental zone was carried out on May 13 and 14, 2023.

5. Crane Management Office

The main role of this office is to maintain the safe operation of cranes. The tasks of this office are as follows.

A) Inspection and maintenance of cranes.
B) Management of the crane license holders and safety lectures for the crane users.
C) Schedule management of crane operations.
D) Safety related to working at height

6. High Pressure Gas Control Office

The main role of this office is for the safety operation and maintenance of high pressure facilities with cooling system such as LHD.

A) Safety operation and maintenance of high-pressure gas handling facilities in NIFS.
B) Daily operation, maintenance, system improvement, and safety education according to the law.
C) Safety lectures for researchers and workers.

7. Hazardous Materials Control Office

The main role of this office is the management of the safe treatment of hazardous materials and maintaining safety for researchers against hazardous events.

A) Research requests about hazardous materials and storage status.
B) Management to ensure safe storage of waste.
C) Implementation of chemical substance risk assessment.

8. New Experimental Safety Assessment Office

The main role of this office is to check the safety of experimental devices except for LHD. For this purpose, researchers who want to set up new experimental apparatus must apply for a safety review. Two reviewers are assigned from members of this office and other specialists and check the safety of these devices.

A) Examine new experiments for safety problems and advise on safety measures.
B) Improve safety in each experiment and reinforce the safety culture at NIFS by annual reviews by NIFS employees.

9. Safety Management Office

The main task of this office is publication of the Safety Handbook in Japanese and English, and its update every year. The organization of regular safety lectures is also the task of this office. The lectures were held on May 26, 2023. All workers, including co-researchers and students, must attend this safety lecture every year.

10. Environmental Conservation Office

On March 28, 2013, NIFS together with the Gifu prefectural government and three local cities (Toki, Tajimi, and Mizunami), concluded an “Agreement on Environmental Conservation around the National Institute for Fusion Science” and a “Memorandum of Understanding on Environmental Conservation around Fusion Science”. The main tasks of this office are to maintain and to check environmental conservation around the NIFS according to this agreement.

(M. Osakabe)

7. Information Systems and Cyber Security Center (ISCSC)

Information network, systems and security

At NIFS, research activities generate a large amount of experimental and computational data. Some results are produced from the data by an information system that is organically connected by an information network.

From FY2023, the structure of the information systems and the information networks was reorganized from the “Division of Information and Communication Systems” to the “Information Systems and Security Center”, which consists of three groups as described below. Each group operates under the direction of a group leader. Since there is naturally some overlap in the areas for which each group is responsible, some of the members serve on more than one group at the same time.

The Information Network Group provides a stable information network environment. Information networks can be regarded as the foundation of research activities, but they are still in their infancy and cannot be a reliable foundation simply by connecting devices. It is important to examine the functions of network devices and consider security.

To ensure the stable operation of information networks, we conducted maintenance work on the necessary equipment. In FY2013, the NTP server, which receives time information from GPS satellites and distributes it to network devices, and the security system that prevents unregistered terminals from connecting to the LHD experimental LAN was updated.

In addition, in FY2023, we conducted a review of our information security equipment and installed a new DNS firewall, also known as the DNS Reputation Service. Most of the current communication uses web services, and the communication channel is encrypted with HTTPS. Previously, a targeted attack detection system installed in the communication channel detected malware and other suspicious communications, but the encryption made it difficult to verify the contents. In contrast, many communications use DNS, a service that converts host names to IP addresses, to initiate a connection, and DNS firewalls, a type of cloud service, can block malicious communications before they take place by returning invalid IP addresses when queried by known malicious hosts.

The Information Systems Group develops, operates, and maintains the various information systems that form the foundation of the Institute, as well as those related to public relations, evaluation, and research support. The efficiency of an information system depends on data design and programming methods. User comfort also depends on the quality of the user interface (UI). Therefore, at the stage of developing information systems, we conduct appropriate system development, such as clarifying requirements through interviews with relevant parties, to facilitate and improve the efficiency of research activities.

In FY2023, the NIFS Article Information System (NAIS), which is responsible for managing the Institute’s research activities, was renovated to support the latest versions of the basic software (Operating System) and the framework, Play Framework. In addition, some parts of the UI have been revised. We have reduced the number of accounts that users must manage by switching from NAIS’s own user authentication system to COLiD, a collaborative researcher authentication system. In the future, we plan to further integrate user authentication mechanisms to provide secure and convenient services.

The Cyber Security Group works with the Information Network Group and the Information Systems Group to create a strong security structure. This includes user education. In addition, members of the Information Security

Group also serve as the Computer Security Incident Response Team (NIFS-CSIRT), and in the event of a security incident, they will investigate the cause and respond to minimize the damage. Additionally, they collaborate with the institutional CISO and the Information Security Manager to address the incident. The NIFS-CSIRT is also a member of the CSIRT of the National Institutes of Natural Sciences (NINS-CSIRT), and shares information with them in regular operations.

In the 2023 fiscal year, information security training for new staff and for all offices was conducted via video on demand. Fortunately, no significant incidents occurred, and several events were responded to. In collaboration with NINS, information incident response training and targeted email training were conducted. Internal audits of information security were conducted with each other and with NINS.

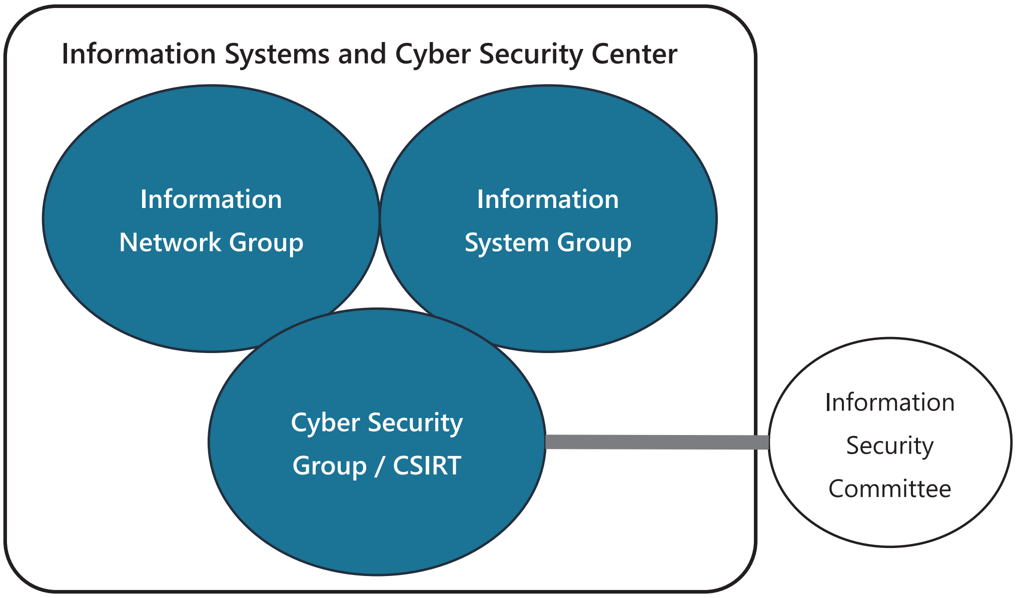


Fig. 1 Structure of Information Systems and Cyber Security Center.

(T. Yamamoto)

8. Activities of Rokkasho Research Center (RRC)

The Rokkasho Research Center (RRC, established in May 2007) promotes cooperation and joint research with the Broader Approach (BA) activities that are being undertaken in parallel with the ITER project and builds the technical foundation for the development of a prototype fusion reactor, by supporting the participation of collaborators of NIFS and universities, based on academic standpoints. Furthermore, in order to promote the interdisciplinary expansion of problems being tackled in fusion research, we are focusing on disseminating research issues to a range of academic fields, inviting interdisciplinary meetings, and promoting interdisciplinary joint efforts. As an example, the 4th mid-term strategic project of the Research Organization of Information and Systems (ROIS), “statistical-mathematical modeling for plasma data, complementary to plasma physics,” has been established and we are deepening/widening collaborations with communities in fields such as statistical-mathematics and data science. In addition, we are actively working to contribute to human resource development through establishing and deepening cooperation with neighboring educational institutions.

RRC’s Homepage: https://www.nifs.ac.jp/en/about/rrc.html

Highlighted Activities in FY2023

The RRC has been a hub for promoting the research project, the Research Organization of Information and Systems (ROIS), the 4th mid-term strategic projects, “statistical-mathematical modelling on plasma data, complementary to plasma physics”. A meeting for sharing research topics among fusion and statistical-mathematical researchers was held in Dec. 2022 at NIFS RRC/QST Rokkasho Institute (from April. 2024, QST Rokkasho Fusion Energy Institute) and Hachinohe City Public Hall. This project has pursued synergetic development of both research communities by applying/improving the statistical-mathematical approach to fusion and plasma data and has so far produced notable collaborative achievements. The report on the last symposium (March 2024 at IMS, Institute of Statistical Mathematics) was published in ISM News (No. 164, May 2024) (in Japanese).

The international conference, “Global Plasma Forum in Aomori” (October 15–18, 2023, Aomori City) was held in collaboration with the Nagoya University Low Temperature Plasma Science Research Center, with the aim of promoting communications among researchers and inviting an academic conference to Aomori Prefecture. The RRC took on the role of the local executive committee. This initiative was selected and implemented as one of the “demonstration of post-corona convention programs”, which is promoted by Japan Tourism Agency (JTA), Ministry of Land, Infrastructure, Transport and Tourism. It was further selected as an excellent initiative of the program. There were 176 registered participants, including 70 foreign residents (from 12 countries/regions). At the opening ceremony, we received a greeting from the Deputy Governor of Aomori Prefecture, and we were able to use this international conference as an opportunity to build a wide range of connections with local related authorities/organizations.

We are also working on collaboration with nearby educational institutions. In July 2023, an RRC member gave a lecture entitled “Challenges to the Unexplored, Towards the Realization of Fusion Energy” at the class of Engineering Design (ED) I for advanced-course first-year students at the National Institute of Technology (KOSEN), Hachinohe College. The contents were designed so that students could feel that their nearby area

(Rokkasho village) has been and will be further evolving as the world-leading base for fusion research. It is planned to continue lecturing in 2024 as well.

In addition, we are working to promote regional collaboration by participating in events and holding seminars related to the initiative so-called the "Aomori Prefectural College", which we joined as a partner institution in 2023.

Fig. 1 Poster for the "Global Plasma Forum in Aomori" (with a flavor of Aomori Prefecture).

Fig. 2 Group photo of the "Global Plasma Forum in Aomori" (in front of the main venue, the Aomori City Cultural Tourism Exchange Facility, Nebuta Museum WA-RASSE).

(M. Yokoyama)

9. Research Enhancement Strategy Office

The Research Enhancement Strategy Office (RESO) was established on November 1, 2013, to strengthen the research activities of the Institute by planning various support programs for researchers and conducting public relations programs for making fusion science more understandable in society. Three University Research Administrators (URAs) are working in the following five Task Groups:

(1) IR (Institutional Research)/Evaluation Task Group
(2) Collaboration Research Enhancement Task Group
(3) Human Resource Development Strengthening Task Group
(4) Public Relations Enhancement Task Group
(5) Financial Basis Strengthening Task Group

In 2023, a Self-Inspection Committee was established under the IR/Evaluation Task Group.

(1) IR/Evaluation

The task group for the IR and evaluation continued its role in making systematic analyses of the present research activities of NIFS. Statistical data of publications and scientific reports were collected using the NIFS article information system (NAIS) with complementary data obtained through SCOPUS and WoS public research resource supplying companies. Unique indicators that can demonstrate the strength of the research capabilities of NIFS were investigated.

By collaboration with the Self-Inspection Committee, the task group compiled a draft annual self-examination report for the fourth mid-term goals and assisted in compiling the materials to be submitted to the External Evaluation Committee for evaluation of the “Unit System” and the “Fusion Science Interdisciplinary Research Center, Industry-Academia-Government Coordination Section (IAGCS)”.

(2) Supporting Enhancing Collaboration Research

1) Promotion of Domestic and International Collaborative Research
   Actively facilitated and supported both domestic and international collaborative research initiatives.
2) Interdisciplinary and Collaborative Research Support
   Implemented support measures for interdisciplinary and collaborative research across different fields.
3) Support for Collaborative Research Activities
   Supported collaborative research activities domestically and internationally through the National Institutes of Natural Sciences (NINS) joint usage/research teams and international collaboration teams.

(3) Supporting Young Researchers

In activities for helping young researchers, their startup research was supported to enhance basic skills. The assistance system has been updated to a Start-up Support Program for Young Researchers. In the new system, a tutor is assigned in each program, who gives suggestions in appropriate timing. The selected programs in FY2023 are as follows:

1. *Exploration of the Principles of Laser Nano-Micro Structuring Phenomenon Induced by Topological Lightwave* (Haruki Kawaguchi), (Fig. 1)
2. *Room-temperature superconductivity in correlated systems by relativistic-plasma electric fields* (Masato Ota),

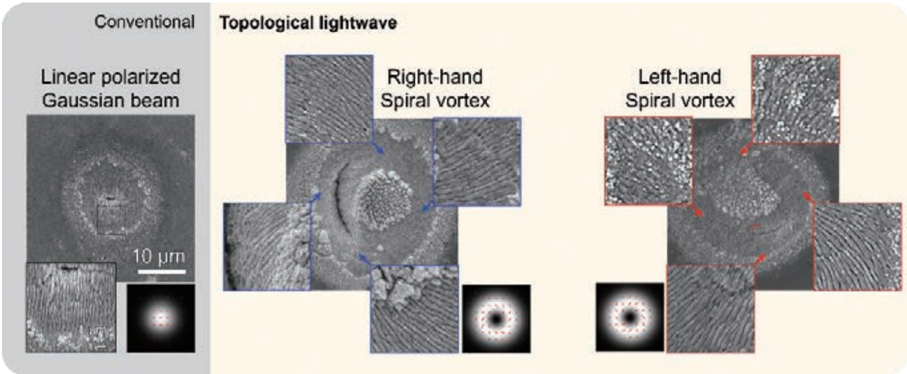


Fig. 1 Topological lightwave laser processing realized arbitrary chiral surface texturing for fusion material (tungsten), provided by H. Kawaguchi. (Reconstructed from Figs. 2 and 4 of "H. Kawaguchi *et al.*, Opt. Mater. Express **14**, 424–434, 2024").

A debriefing meeting was held in April 2023 for the three people who received support in FY2022.

RESO also assisted the applications of young scientists to the International Research Exchange Support Program of the National Institutes of Natural Sciences.

(4) Enhancing Public Relations

The policy for public relations activities was discussed at a RESO meeting. Regarding publicity events, depending on geographical spread, (1) participation in local festivals, (2) participation in events organized by Toki City, (3) holding science events in large shopping malls and (4) the Open Campus, were organized.

Altmetric indicators of press releases made by the Institute over the past year were analyzed and a policy for future press releases was considered.

Measures to make more efficient use of the Institute's official SNS (X and YouTube) were discussed. A decision was made to distribute the press releases on YouTube. In addition, it was decided to distribute photos of equipment on X and other media.

(5) Strengthening Financial Basis

1) Support for Securing Competitive Research Funds

Organized briefing sessions to obtain competitive research funds such as Grants-in-Aid for Scientific Research (KAKENHI), JST, and NEDO, and provided support for the preparation of application forms.

2) Support for the Operation of the Financial Base Strengthening Task Force

Provided operational support for the Financial Base Strengthening Task Force and supported activities of the Industry-Academia-Government Collaboration Headquarters.

3) Support for Industry-Academia-Government Collaboration Activities

Facilitated activities such as planning industry-academia-government collaboration projects at Open Campus events and organizing exchange meetings with companies as part of industry-academia-government collaboration efforts.

(T. Muroga, T. Mito, K. Ichiguchi and K. Takahata)

10. Platform Management Office

As an inter-university research institute, the National Institute for Fusion Science (NIFS) provides research equipment, including large research facilities such as the Large Helical Device (LHD) and Plasma Simulator “Raijin,” for joint usage and conducts collaborative research with domestic and foreign universities and research institutes. The Platform Management Office, which comprises three sections: the Large Helical Device (LHD) Section, the Computer Section, and Engineering Facilities Section, was established in FY2023 to manage and operate the research facilities at NIFS.

In FY2023, we started a paid platform-sharing system to make NIFSs’ facilities available for purposes other than collaborative research. First, we started the platform-sharing with academic researchers, but we are also considering expanding the system to private companies to fulfill a role appropriate to the needs of the times (https://www8.cao.go.jp/cstp/fusion/index.html).

Large Helical Device Section

The Large Helical Device (LHD) Section is composed of the Experiment Planning Task Group (TG) and the Device Planning TG. It is responsible for managing and operating the LHD and provides the support necessary for carrying out LHD experimental research. The Experiment Planning TG plans experiments in response to experimental proposals from collaborators, manages machine times and schedules, and plans the personnel required to carry out the experiments. The Device Planning TG plans the maintenance and operation of the device required to carry out LHD experiments.

The LHD has been conducting experimental research as the world’s largest superconducting plasma confinement device for a quarter century since it made its first plasma in March 1998 and has achieved many results. Although the LHD project was completed in FY2022, in order to utilize the legacy of the LHD project so far, such as high-precision diagnostics and various heating devices, the LHD will operate for three years as an academic research platform from FY2023. In the Academic Research Platform LHD, which can stably generate high-temperature plasma, we will conduct international collaborative research to address the principles of various complex phenomena common not only to fusion plasma but also to space and astronomical plasmas, by investigating the internal structure of plasma using a variety of high-precision diagnostics in the LHD.

The first experiment campaign of the Academic Research Platform LHD was held from 13 May 2024 to 20 June 2024. Prior to the experimental campaign, 165 experiment proposals were received, including 118 from domestic collaborators and 47 from overseas. In December 2023, the LHD Research Forum was held online to introduce the experimental proposals. Each of the 165 experimental proposals plans experiments under various conditions, and allocating all the proposals to the limited experimental period is a challenging problem. The Experiment Planning TG have arranged an experimental schedule that allows more researchers to produce fruitful results. During the plasma experiment campaign, 6,335 shots of plasma experiments were performed over 55 operational days, and 140 research themes were carried out. In addition, the deuterium plasma experiments performed in the LHD from 2017 to 2022 have ended, and the Academic Research Platform LHD now performs experiments without deuterium. Therefore, there is no further generation of neutrons or tritium during the plasma experiment campaign.

The LHD promotes open science. It is the only fusion research facility in the world that publishes experimental data in real-time (https://www-lhd.nifs.ac.jp/pub/Repository_jp.html). It also uses an online meeting system to facilitate communication with collaborators in distant places, and it is possible to participate in LHD experiments via the Internet without visiting NIFS. The results of each day’s experiments are reported promptly in an online meeting the morning after the experiment and published on a web page (https://www-lhd.nifs.ac.jp/rails/dspp_plan/).

(R. Sakamoto)

Computer Section

The Computer Section is composed of the Plasma Simulator Task Group (TG), Database TG, and Data Analysis Equipment TG.

The Plasma Simulator “Raijin” is a massive parallel supercomputer system utilized to promote academic-simulation research on nuclear fusion science and to support research and development that can contribute to progress in simulation science. The Plasma Simulator “Raijin” consists of 540 computers, each of which is equipped with one scalar processor for controlling the system and eight “Vector Engine” accelerators for high-speed computing. The 540 computers are connected with each other by a high-speed interconnect network. The computational performance of the system with Vector Engines is 10.5 petaflops. The capacities of the main memory and the external storage system are 202 terabytes and 32.1 petabytes, respectively. The supercomputer system is capable of large-scale simulation of fusion and other complex plasma phenomena. The Plasma Simulator was operated for 351 days and supplied 27 million VE hours of computational time on 82 subjects to 271 users in FY2023. The Plasma Simulator TG supports usage of the Plasma Simulator through operation scheduling and maintenance of the network, support of users’ simulation code development, running the code, and other matters.

The Database TG provides the NIFS Atomic and Molecular Numerical Database at http://dbshino.nifs.ac.jp/ for researchers all over the world, which contains numerical data, such as cross-sections, for collision processes between electrons, atoms, and molecules in plasmas. The amount of stored data, which is 1,765,059 pieces in total as of Apr. 4, 2024, increased from 1,629,876 (Apr. 3, 2023), is the largest among the databases of collision cross-sections provided anywhere in the world. Many researchers access our database for their research. We are also making databases, e.g. the Atomic Data and Analysis Structure (ADAS), available for domestic collaborators, which are provided under international collaborations.

Data analysis equipment includes the experimental data acquisition and analysis system, the SNET research collaboration network, and the CompleXcope immersive virtual reality system. The experiment-data system accumulates over three petabytes of diagnostic and analyzed data from NIFS LHD and other universities’ devices via SNET. The amount of plasma diagnostic data acquired by LHD experiments still continues growing even after 25 years of operation, exceeding 70 GB per short-pulse plasma discharge of less than ten seconds duration. The LHD project makes the entire research resources, including hundreds of analysis programs, available to the public at the same level as local and remote collaborative researchers. This is a research project to develop and build a “Plasma and Fusion Cloud.” The world’s largest nuclear fusion database is expected to be used for fusion energy developments and for “data science” and other fields, to promote the “Open Science” of the nuclear fusion research. CompleXcope enables observers to enter 3-D data space and observe plasma from various directions, thereby facilitating the study of plasmas with complex structures.

(Y. Todo, H. Miura, I. Murakami and H. Nakanishi)

Engineering Facilities Section

The Engineering Facilities section manages and operates experimental facilities in the Superconducting Magnet System Laboratory, the Fusion Engineering Research Laboratory, the Radiation Controlled Area in the LHD building, the Development Laboratory, and the Diagnostics Laboratory. A task group is assigned to each experimental building to coordinate the dates and systems of experiments. In FY2023, we established and implemented rules for collecting equipment usage fees and electricity usage fees. As a result, annual electricity usage was reduced to less than half of what it was before, and it was concluded that this was largely due to the reduction of usage of air conditioning systems.

(S. Imagawa)

11. Research and Education Innovation Office

The Research and Education Innovation Office comprises the six committees shown in Figure 1. It implements activities to deal with various problems related to research and education at NIFS and raise the research and education level. Two crucial activities in the 2023 fiscal year of this office are reported below.

Fig. 1 Composition of the Research and Education Improvement Office and the committees positioned within it.

<Fusion Science Seminar and NIFS Colloquium>

The Fusion Science Seminar (FSS) is a scientific seminar with distinguished lecturers in a wide scientific research field. The NIFS Colloquium is an opportunity to learn about topics in which research communities are interested. Three FSSs and four NIFS Colloquiums were held in a hybrid format, and many scientists, students and staff (almost 100 participants on average) participated in them and discussed topics deeply and widely (Fig. 2). The information of these seminars and colloquiums can be seen on the NIFS webpage (https://www.nifs.ac.jp/about/reio/all/index.html).

Fig. 2 Picture at NIFS-Coll-3.

FSS-1 “Quantum materials dynamics at the nexus of exascale computing, AI, quantum computing, and X-ray scattering”, Aiichiro Nakano (Professor, University of Southern California)

FSS-2 “90 years in Elementary Particles and 21 century in Physics”, Hikaru Kawai (Professor, National Taiwan University)

FSS-3 “Solid-state physics and atomic/molecular physics experiments in large facilities”, Toshio Hyodo (KEK)

NIFS-Coll-1 “Logic behind venture capital investment in Western nuclear fusion ventures, and key points for implementing research results in society”, Kenichi Hattori (venture capitalist)

NIFS-Coll-2 “Recapturing the Big Questions: Communicating cutting-edge research to outside the field and weaving the “story of academia”, Tetsuya Suzuki (Editor-in-Chief, Kyoto University Press)

NIFS-Coll-3 “Fusion Energy Innovation Strategy: Expectations for Academic Research”, Daisuke Baba (Director for Research and Development Strategy, Research and Development Bureau, Ministry of Education, Culture, Sports, Science and Technology (in charge of nuclear fusion and international nuclear cooperation))

NIFS-Coll-4 “Data creation and utilization for open science”, Kazuyoshi Yoshimi (The Institute for Solid State Physics, The University of Tokyo)

<Diversity of researchers at NIFS >

To Improve research capabilities, increasing the diversity of researchers is an urgent issue at NIFS. The Human Resources Development Committee has addressed this issue and has actively reached out to female researchers and students outside NIFS through the Workshop for Women in Plasma Physics at the 7th Asia-Pacific Conference on Plasma Physics, NIFS collaboration- research programs and other events (Fig. 3). In addition, this committee has made efforts to support young researchers. In the framework of the Young Researcher Start-up Support Program, the committee assigned research grants for two researchers in FY2023.

Fig. 3 Flyer for the open recruitment of female researchers in FY2023.

12. Public Relations Office

The Public Relations Office, as the core organization responsible for public relations and outreach activities, promotes the disclosure and sharing of research achievements with society, including the local community, through a variety of activities. Since the restructuring of this organization in FY2023, there now are four committees: the Scientific and Public Relations Committee, the Social Engagement Committee, the Archives Committee, and the Educational Collaboration Committee. A summary of the committees is depicted in the following illustration (Fig. 1).

Many NIFS staff are active as members of the office. Principal activities include issuing press releases (Fig. 2), publishing public relations magazines, holding scientific events (Fig. 3), providing tours of NIFS facilities (Fig. 4), scientific classroom activities (Fig. 5), organizing and storing historical materials related to fusion science research in Japan, and educational collaboration activities with high schools.

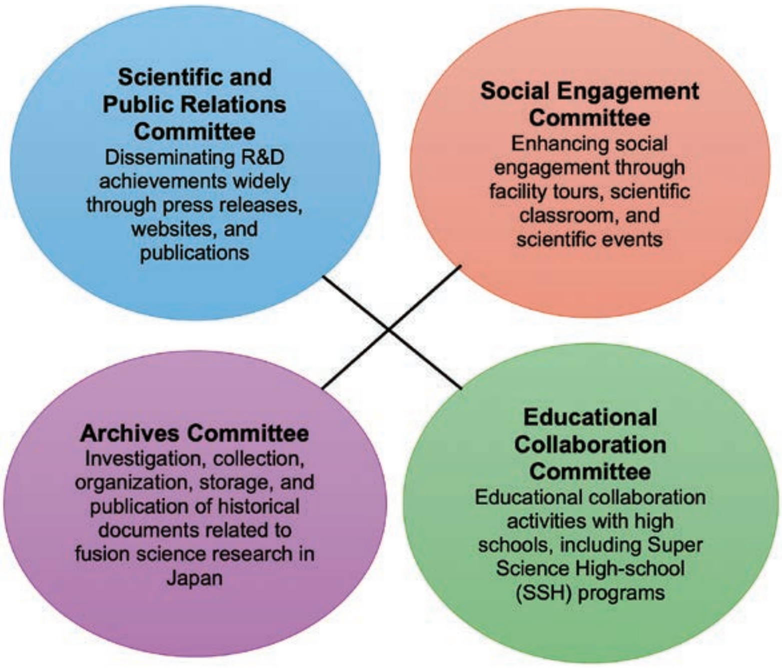


Fig. 1 Organization chart of Division of External Affairs

Activities held in 2023 include the following.

- Tours of NIFS facilities (any time) held 403 times; 3,033 people participated
- Science classroom activities, held 24 times
- Release of information through web pages, mailing lists, and SNS (X and Facebook)
- Publication of NIFS official pamphlet (in Japanese and English)
- Publication of public relations magazine: NIFS News (4 issues)
- Publication of public relations magazine: Letters from Helica-chan (4 issues)

Fig. 2　Press release

Fig. 3　Scientific events in shopping malls, “Machikado (street corner) Science Lab”

Fig. 4　Tour of the NIFS facilities

Fig. 5　Scientific classroom

13. Fusion Science Archives (FSA)

The Fusion Science Archives (FSA) were established in 2005 to learn lessons from preserved past fusion science archives and to maintain collections of historical documents and materials that are related to fusion research in Japan. These activities are important from the viewpoint of the historical evaluation of fusion research, its social accountability, and making references for seeking future directions. Since then, historical materials on fusion research and/or organizations related to it have been collected and preserved at the FSA. They are stored in acid-free folders and boxes. Catalogs of registered items are available to the public through the Internet in a hierarchical structure. In FY2023, the FSA office was moved to Research Building I and the archives were relocated to the second floor in the library building. The cataloged database of about 28,500 items is stored in FileMaker for internal use. Among these, catalogs of about 6,000 items are available through a web page from outside NIFS.

The following are summaries of selected collaborative works performed this fiscal year.

- **Studies on the history of the establishment of the Institute of Plasma Physics, Nagoya University**

T. Amemiya (CST Nihon Univ.) *et al.*

The Institute of Plasma Physics, Nagoya University (IPPJ) was established in 1961 as the first Inter-University Research Institute of plasma physics and controlled fusion research in Japan. The IPPJ is one of the predecessor bodies of today's NIFS. This collaborative research aims to find new historical interpretations by the IPPJ and a discussion about institutes at the dawn of fusion research in Japan, based on historical documents in NIFS FSA and other science archives. This collaborative research of FY2023 consists of the following subjects: 1) History of a discussion about the new institute in the fusion researcher community before the establishment of the IPPJ. 2) A discussion at the Ultra High Temperature Research Society, related to the establishment of the "Institute for Ultra High Temperature" of Osaka University.

- **Analysis of Husimi Kodi Documents on Early Stage Nuclear Development in Japan**

H. Iguchi (NIFS, FSA) *et al.*

Historical documents left by Kodi Husimi on the development of nuclear technology in Japan are reserved in the NIFS Fusion Archives. We investigated those materials in detail, especially for the latter half of the 1950s. The Japanese policy on nuclear development started with importing foreign advanced technology. The key events were the passage of the nuclear budget in 1954 (ID: 503-03-12) and the "Agreement for Cooperation Concerning Civil Uses of Atomic Energy Between the Government of Japan and the Government of the United States of America" (539-09-02). The first step was to import the British Calder-Hall Nuclear Reactor. The Japan Atomic Power Company was established as an operating institution. The Science Council of Japan stated that discussion on safety, such as on earthquake resistance, was not enough, but the Japan Atomic Energy Commission gave permission for its establishment (504-12-03).

- **Historical Study of Nuclear Energy Development and Utilization Policies in Japan**

S. Kobori (Kyoto University) *et al.*

This study aims to clarify the history of nuclear power development policies in Japan in conjunction with the organization and analysis of historical materials held in the Fusion Science Archives. In FY 2023, we organized the Kazuhisa Mori Papers over three days and analyzed the documents regarding the following themes: (1) nuclear power plant location measures by the government and the Japan Atomic Industrial Forum, (2) the reorganization of the Japan Atomic Energy Commission in the 1970s, and (3) the planning of energy and global environmental policies.

- **Organization, registration and analysis of historical documents and materials of Tihiro Ohkawa**

S. Kubo (Chubu Univ.) *et al.*

Tihiro Ohkawa's materials which had been left in the study of his home after his death were transferred to NIFS Fusion Science Archives (FSA) in 2016. These materials include notes, manuscripts, memos, papers, and his book collections in a wide range of fields. Although a well organized memorial reflections web site is already open (https://fusion-holy-grail.net/), it mainly relies on personal remembrances, and should be supplemented by archival materials. On the occasion of the relocation of the FSA library, these materials, which have been restored in conservation boxes, are now under classification and registration to be archived.

- **Investigation on the trend of light sources for plasma spectroscopic research in Japan from the chronicle of collaborative research meeting on plasma spectroscopy**

N. Yamaguchi (Comprehensive Research Organization for Science and Society (CROSS)) *et al.*

A collaborative meeting on plasma spectroscopy has been hosted by the Institute of Plasma Physics, Nagoya University (IPPJ) and NIFS for over half of a century from 1969. Keywords relevant to light sources for spectroscopic research have been extracted from about 1300 papers presented in meetings from 1969 to 2017. The accumulated number of keywords is 552. The three types of light source which are "laser-plasma", "tokamak" and "LHD" have been analyzed. The count of each keyword is 89, 69 and 68, respectively. The appearance frequency of the three keywords reflects the trend of plasma spectroscopic research in Japan.

14. Industry-Academia Collaboration Laboratory

The Industry-Academia Collaboration Laboratory is an innovation research center focused on fusion energy, where industry, academia, and government collaborate to advance the practical application of fusion energy—widely regarded as the world's next-generation energy source. The center also aims to create new social value through partnerships with external organizations.

The National Institute for Fusion Science has long fostered cooperative relationships with private companies and industries to promote the social implementation of fusion energy, anticipated to become a sustainable and environmentally friendly energy source. To further strengthen these initiatives, the Fusion Energy Industry-Academia Collaboration Laboratory was established in 2023.

In addition, we are actively collaborating with emerging fusion start-up companies, which have gained significant momentum in recent years. To support these efforts, we have formed an internal "HF Collaborative Research Group" to conduct joint research with Helical Fusion, Inc (Fig. 1). This group is doing joint research on superconducting magnets, etc., with the aim of commercializing helical fusion reactors.

Fig. 1 Simplified schematic diagram HF Collaborative Research Group

(R. Yasuhara)

15. Department of Engineering and Technical Services

The Department of Engineering and Technical Services (DETS) is involved in the operation and maintenance of research platforms such as the Large Helical Device (LHD) and information facilities such as the research infrastructure network, as well as the design, development, and fabrication of equipment, radiation control, and safety promotion.

The Platform Management Office, which consists of the LHD Section, Computer Section, and Engineering Facilities Section, was established in FY2023. The DETS was reorganized from five divisions in technical fields to 12 teams for each research task, to support the platforms including the LHD which held the 25th experiment campaign from 13 March to 20 June, 2024.

The following is a report on the activities of the DETS.

(H. Hayashi)

Mechanical Systems Technology Division

The main work of this division is the fabrication of experimental equipment. We also take care of technical consultation and experimental parts supplies related to LHD experiments. The number of machined requests was 78, and the production parts total number was 300 in this fiscal year (FY). We also perform maintenance and modification of LHD-related equipment. The main equipment includes: utilities (compressed air, cooling water, GN2), water leak detection equipment, the Local Island Divertor (LID), Boronization, ECH, ICH and NBI.

In addition, we manage the administrative procedures of the department.

The details of some of this division's activities follow below.

(M. Yokota)

(1) 154 GHz notch filter

We have fabricated a notch filter (Fig. 1) for ECH. It has four cavities and a waveguide in an internal space. In order to decide the parameters of the cavities, we have analyzed the electromagnetic field. The cavities are 1.5 mm in diameter and 1.265 mm deep. The rectangular waveguide is 1.651 mm long and 0.826 mm wide.

(T. Shimizu)

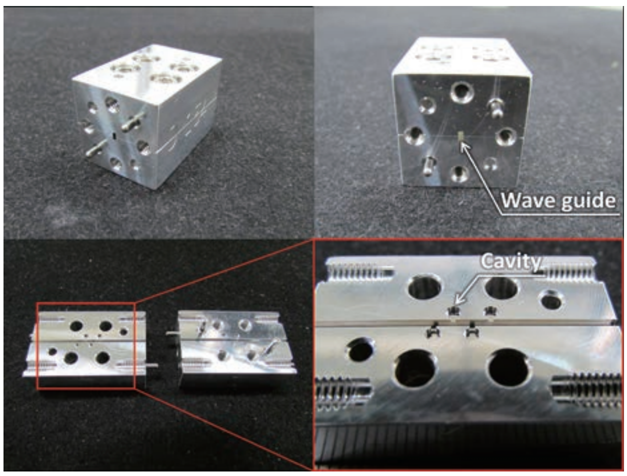


Fig. 1 154 GHz notch filter

(2) Modification of the ECH#4 transmission line

A modification of the ECH#4 transmission line was performed for the 25th LHD experimental campaign. Three aluminum mirrors were newly set in the middle of the transmission line to receive an electron cyclotron emission (ECE) signal from LHD plasmas. This modification made it possible to adjust the polarization of the ECE signal because it can be received through λ/4 and the λ/8 polarizers. A picture of the new transmission line is shown in Fig. 2.

(T. Takeuchi)

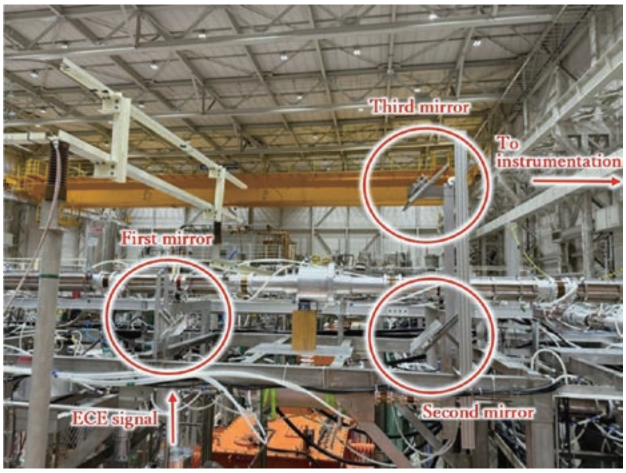


Fig. 2 ECH#4 transmission line

Design and Development Technology Division

This Division provides support for the operation, improvement, and maintenance of LHD, as well as support for collaborative and commissioned research.

(N. Suzuki)

(1) Development of activated carbon derived from unutilized biomass

A cryo-sorption pump equipped with activated carbon as an adsorbent of gas particles has been used in LHD. We have developed activated carbon derived from unutilized biomass suitable for a cryo-sorption pump [1,2].

In this study, we used a Spark Plasma Sintering (SPS) method to sinter powdered activated carbon. SPS is a method to sinter powdered materials, e.g., metals and carbon, by applying pressure and pulsed current heating. Using SPS, we aim to sinter activated carbon without a binder which would inhibit the performance of activated carbon.

In order to investigate the effect of the sintering temperature, we sintered activated carbon derived from rice husks by SPS at various temperatures. The sintering succeeded at each temperature from 650 °C to 1600 °C. As shown in Fig. 3, we found that a specific surface area, which was the principal parameter of activated carbon, became larger as the sintering temperature was reduced. Especially, the specific surface area of the activated carbon sintered at 800 °C or below

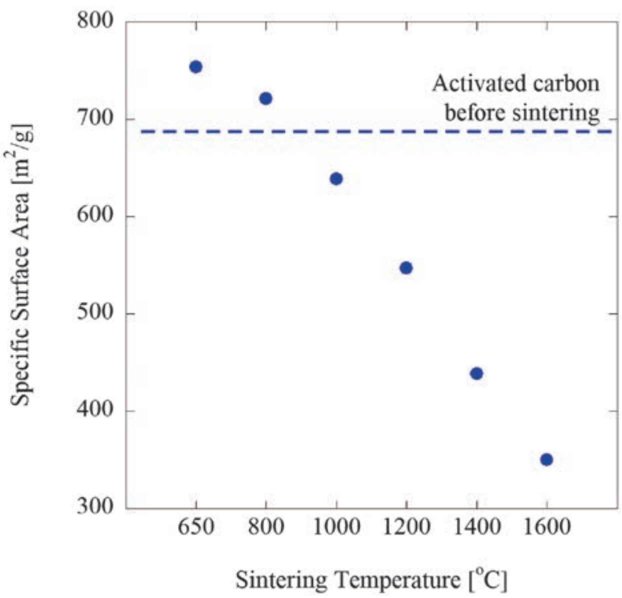


Fig. 3 Specific surface area of activated carbon at each sintering temperature by SPS

and was larger than that of the activated carbon before sintering. We obtained a patent based on this achievement [3].

[1] Y. Yanagihara *et al.*, Plasma Fus. Res. **19**, 1205012 (2024).
[2] Japanese Patent 7301300.
[3] Japanese Patent 7501845.

(Y. Yanagihara)

(2) Developing 3D display functionality for temperature-monitoring application using LabVIEW

The surface temperature inside the vacuum vessel (VV) of LHD is monitored by thermocouples at more than 200 measurement points. Identifying immediately which locations are exposed to severe heat loads during a plasma experiment is greatly important.

Conventional temperature-monitoring systems are limited to displaying measuring points on a two-dimensional diagram. Such a display method is not always appropriate for showing the locations of temperature- measuring points. For example, in the case of the LHD VV with a complicated helical shape, it is difficult to understand the measuring points, since the location displaying image has no alternative but to show an unfolded figure.

To address this issue, we recently updated the temperature-monitoring application using LabVIEW and added a function that can display the location and temperature of each measuring point on a 3D model of the LHD VV (Fig. 4). An auxiliary function to search the TC location with a TC identification number and a feature of the specific view storing were also implemented. Developing 3D displaying functionality with LabVIEW was quite challenging because the software is not suitable for such usage.

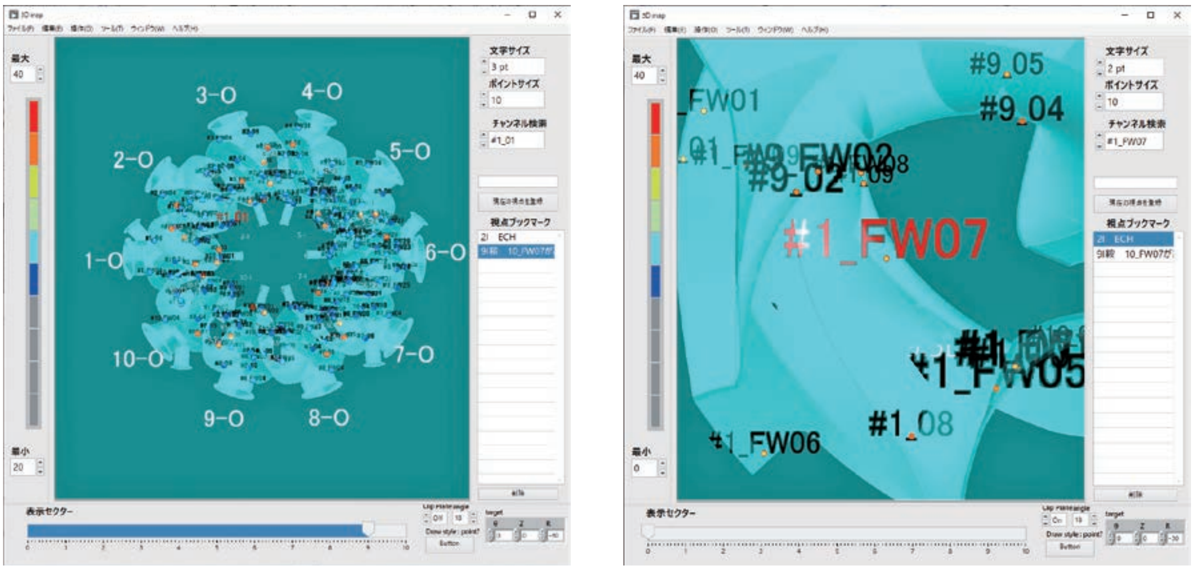


Fig. 4 3D displaying function of the temperature monitoring application

(S. Nakagawa)

Electrical and Electronic Technology Division

The main tasks of this division are the operation and maintenance of plasma-heating devices using high-voltage and high-frequency power supplies and their common facilities. We have also provided technical support for experimental equipment, including electrical and electronic circuits. The details of these activities are as follows.

(T. Kondo)

(1) Electrical and electronic work for experimental equipment

(a) Repair of the impedance matcher

The control circuit of the impedance matcher for the NBI's RF ion source had a malfunction. However, it could not be repaired because its manufacturer had already gone out of business. And so, we developed a new control circuit which has a microcomputer board (STMicroelectronics NV, model STM32) and tested it (Fig. 5).

(Y. Ito)

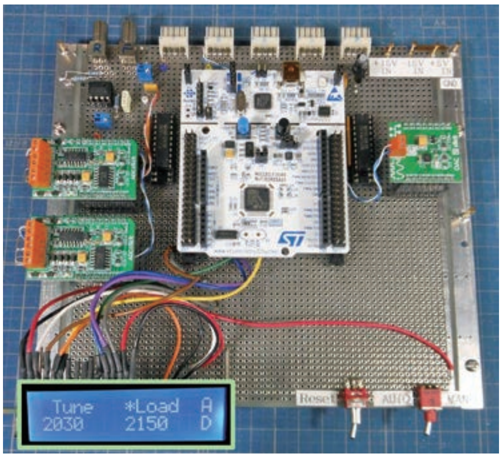


Fig. 5 New control circuit of the impedance matcher for the NBI's RF ion source

(b) Modification of the pump control panel

We modified the control panel of cooling water pumps in the R & D Laboratories to save electric power. The manual operation function of the existing control panel for eight cooling water pumps was retained (Fig. 6) but additional timers and relays to supply cooling water only at set times were built in (Fig. 7).

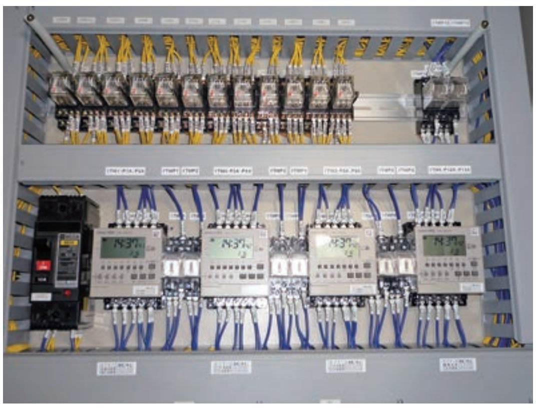


Fig. 6 Additional 2ch timers and relays (8 systems)

Fig. 7 Cooling water pump control panel on/off button (8 systems)

(K. Yasui)

(2) The Operation and maintenance of plasma heating devices for LHD

(a) ECH

We repaired a 28 GHz gyrotron that we uninstalled due to its poor condition in the 24th experimental campaign and operated it for about six months as a joint research project. A 77 GHz gyrotron that had been dormant since 2019 was operated again and worked well too. Before this fiscal year's experimental campaign, the microwave beam-focus location at the plasma-vacuum vessel of LHD was measured and had no significant deviation. In this fiscal year's experimental campaign, we injected power up to 4 MW to assist the plasma experiments of LHD.

(Y. Mizuno)

(b) ICRF

In the ICRF heating system, the output of the amplifier can be switched to an antenna or dummy load by using a coaxial switch. An indicator showing the direction of the amplifier output was fabricated to reduce errors in checking the connection destination of the coaxial switch (Fig. 8). Since its introduction, this system has successfully prevented injection errors. In the future, we plan to integrate this indicator with the amplifier control system and activate an interlock if the switching destination is not correct.

(M. Kanda)

Fig. 8 Indicator of the direction of amplifier output attached to the coaxial switch

(c) NBI

The cooling tower has a risk of freezing cooling water during the winter, and so has been run continuously for 24 hours. We modified the control system of the cooling tower to run the pump only when the outside air temperature drops below near freezing, and to save electric power. This new system has an outside air temperature sensor, and repeats pump runs for ten minutes, stopping for 50 minutes when the outside air temperature at the pump yard dropps below 2 °C. This winter, from December 25 to March 31 (2,352 hours), the outside air temperature fell below 2 °C for 406 hours (17 %). In other words, the pump's operating rate was reduced by one-sixth, which resulted in a 97% reduction in power consumption (50,000 kWh/year, 1 million yen/year Less).

(M. Shibuya)

(d) Motor-Generator (MG)

The MG is used to supply pulsed power for NBI and ECH in the LHD. The MG has supplied power for 5,273 shots in this fiscal year and 715,531 shots since its construction. The operation time was 269 hours.

(Y. Mizuno)

Diagnostics and Analysis Technology Division

We are engaged in the maintenance and improvement of plasma diagnostic devices and a data acquisition system for the LHD. We also conduct radiation measurements and are responsible for radiation control. Regarding the diagnostic devices, until FY2022, the operators performed inspections and maintenance. However, since the contract has ended, all tasks have been taken over by the technical staff. We have been preparing for the LHD experiments scheduled to start at the end of the FY2023 by confirming the startup procedures of the diagnostic devices and organizing manuals.

The improvements implemented in the Heavy Iron Beam Probe (HIBP), the activities related to the data acquisition system, and radiation control are described below.

(H. Hayashi)

(1) Improvement of beam transport from HIBP negative-ion source to tandem accelerator injection

Until FY2022, the beam intensity was insufficient for measurement in high plasma density, due to beam attenuation. Therefore, we developed a new ion source to increase the beam current. When we measured the current of the newly developed ion source at the test stand, it was around 40 μA near the center of the beam. However, when we installed this ion source into the actual HIBP device and measured the current, it was only 25 μA near the center, just before the tandem accelerator. We have optimized the beam transport by adjusting the resistance division of the multi-stage accelerator tube and changing the shape of the equipotential surface to provide an electrostatic lensing function (Fig. 9). As a result, the beam current has increased to about twice its previous value.

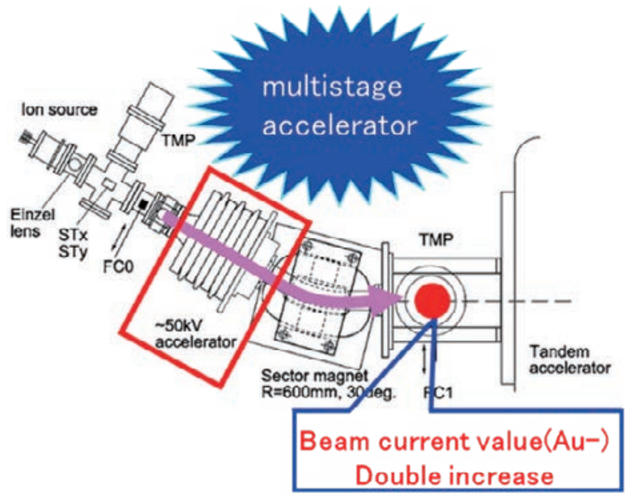


Fig. 9 Beam loss due to multistage accelerator

(H. Takubo)

(2) LHD data acquisition (DAQ) system

In the 25th LHD experimental campaign, the LHD DAQ system acquired data from 6,334 plasma shots, and the total generated data was approximately 232 TB after compression. During this campaign, the communication between the DAQ PC and the digitizers was often abnormal, mainly in the NBI data acquisition. This required the digitizers to be turned off and on again. The long distance of the optical fiber path between the PC and the digitizers may have affected the results, which will be addressed by the next campaign. For long-term storage, we have switched to free-cloud storage using Amazon Web Services.

(M. Ohsuna)

(3) Radiation measurement

To monitor the tritium concentration in the exhaust gas generated in the radiation control area, tritium was collected in water form and measured with a liquid scintillation counter. So far, no tritium exceeding the standard has been confirmed. One of three sampling systems has been measuring tritium concentration in chemical form (HTO, HT, CH3T). Following the completion of the deuterium experiment in December 2022, the system was modified in October 2023 to stop collecting tritium in chemical form. As a result, the work time for monitoring tritium concentration in exhaust was reduced by about 40%.

(M. Nakada, H. Miyake and C. Iwata)

(4) Activation evaluation

In order to evaluate the degree of activation of the LHD torus hall and its basement due to the deuterium plasma experiment, NIFS have conducted a survey in collaboration with the High Energy Accelerator Research Organization (KEK) since 2022. In FY2023, concrete cores were extracted to investigate the degree of activation of the concrete in the floor and walls of the LHD torus hall. Furthermore, to investigate the amount of tritium produced in the concrete by the deuterium plasma experiment, concrete core samples were analyzed, and it was confirmed that the amount of tritium was below the detection limit for all samples.

(S. Kurita and T. Kobuchi)

Control and Information Technology Division

The Control and Information Technology Division is in charge of important engineering tasks in the LHD project, such as system development, project management, and system operation, which are mainly targeted at central control systems, cryogenic systems, coil power supply, and super-conducting coils.

We are also responsible for IT infrastructure, e.g., the LHD experiment network, the NIFS campus information network, and internet servers, in every phase of the project, including requirements analysis, system design, implementation, operation, and user support.

The essential topics of the activities for the last fiscal year are described below.

(S. Takami)

(1) Technical Support for Research Using Liquid Helium (LHe) and Liquid Hydrogen (LH2)

We received a request for technical support for research on understanding the phenomena and detection methods of degradation of the vacuum insulation layer for long-term storage of LHe and LH2. This year, we designed a flange and a frame to be attached to a glass dewar containing liquid hydrogen (Fig. 10). The newly designed flange and frame were sent to the Noshiro

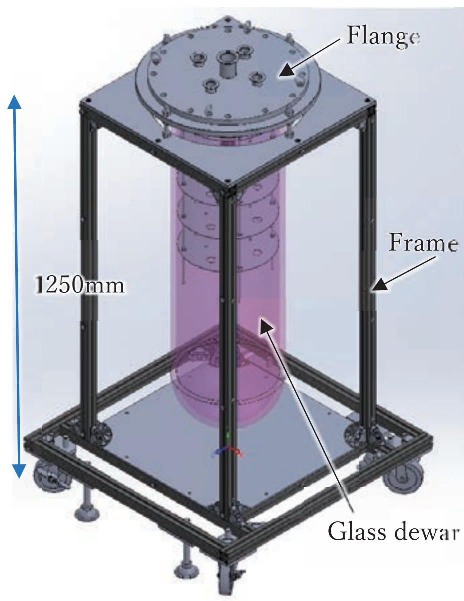


Fig. 10 Assembly drawing of designed flange and frame

Rocket Testing Center in Akita Prefecture, where the experiment was to be conducted, and assembled with the glass dewar on site. The designed parts were assembled without any problems. In the next fiscal year, we plan to provide the necessary equipment and support for experiments.

(S. Takami)

(2) Development of TESPEL Control System for JT-60SA on QST

In the LHD Experiment, a Tracer-Encapsulated Solid Pellet (TESPEL) injector is used for impurity injection. NIFS' engineering department has developed remote-control software for this equipment, and the current LHD has two sets of equipment and software. Also, the JT-60SA experiment system at the National Institutes for Quantum Science and Technology (QST) has a project to introduce a similar TESPEL injector. The NIFS engineering department is also going to develop remote-control software for that injector (Fig. 11). Based on the remote-control software in LHD, we have changed some view and memory addresses of the connected Programmable Logic Controller (PLC). Although JT-60SA is currently in preparation, we have confirmed the operation of the main part, on site. An easily comprehensible operation view was also well received by QST researchers.

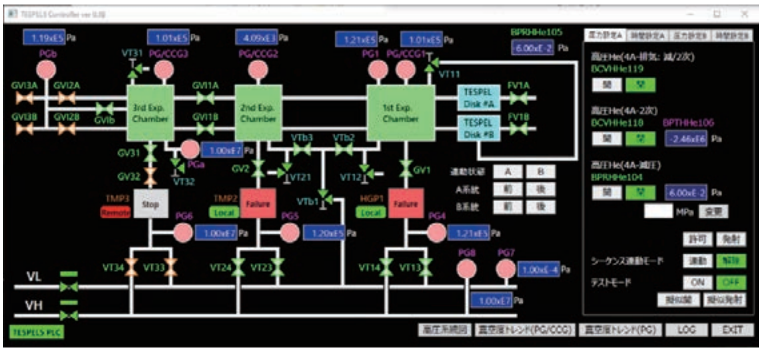


Fig. 11 TESPEL remote-control software operation view

(H. Maeno)

(3) Network Management

The NIFS campus information networks consist of several clusters. We manage the Research Information Cluster (NIFS-LAN) and the LHD Experiment Cluster (LHD-LAN).

The achievements in FY 2023 are as follows:

(a) Introduction Akamai Secure Internet Access Enterprise

Communication by malicious domains and IP addresses during DNS name resolution were prevented by changing the reference source of NIFS DNS servers to Akamai's (Fig. 12). Installation trials began in late June 2023, with the official operation starting in September.

Fig. 12 SIA Block Page

(b) Firmware update for SSL-VPN system

An extremely high severity vulnerability of CVE-2023-46805 was announced in January 2024, and a temporary countermeasure, XML, was applied in January and February. It appears that many institutions were attacked and tampered with, but fortunately, NIFS, which was quick to respond, did not suffer from any tampering. A permanent countermeasure to CVE-2023-46805 was completed with firmware update to 22.3R1.1 in March 2024.

(c) LHD-LAN

It is required in our security policy that network management staff be present when connecting a new device to LHD-LAN. In FY2023, 24 new devices were connected to LHD-LAN, 79 devices were updated, and 23 IP addresses were made available due to device removal.

(T. Inoue and O. Nakamura)

Technical Exchanges

Sixth technical exchange meeting: “computational technology using finite element method”

On February 16, 2024, we held a technical exchange meeting to discuss numerical computational technology based on the finite-element method. This meeting, which was the seventh held hitherto, was attended by six presenters and 24 participants, including those who used a remote web conference application (ZOOM), as shown in Fig. 13. In this meeting, two invitees presented talks under the titles of “Progress of 3D design technology by AI and its industrial application” and “Evaluation of Contact Thermal Conductance of ITER Poloidal Polarimeter Retroreflectors”. In addition, four general talks were presented, all of which resulted in lively discussions.

Fig. 13 Group photos of the technical exchange meeting

(T. Murase)

Internship

We accepted internships from three high schools as part of the institute's outreach activities. One example is shown below.

The Mechanical Systems Technology Division receives two senior high school students for internship every year. They are students of the Tajimi Technical High School. They manufacture experimental devices with us for three days. It helps them to learn machine-tool operation techniques (Fig. 14). We gave lectures on the basics of mechanical drafting, TIG* welding and how to make NC programs.

*TIG: tungsten inert gas

Fig. 14 Internship

(K. Okada)

16. Department of Administration

The Department of Administration handles planning and external affairs, general affairs, accounting, research support, and facility management work.

The major operations of this department are to support the promotion of the Institute's regular research and the development of the collaborative research.

The department consists of the following four divisions, namely, the General Affairs Division, the Financial Affairs Division, the Research Support Division, and the Facilities and Safety Management Division. Details of these divisions are described below.

General Affairs Division

The General Affairs Division handles administrative work and serves as the contact point with the outside. This Division consists of four sections. The General Affairs Section is in charge of secretarial work for the Director General and the Deputy Director General, support for the Advisory Committee meetings, and enacting rules and regulations. The Planning and Evaluation Section is in support for assessment of the institution's performance including scientific achievement and management efficiency. The Personnel and Payroll Section is in charge of general personnel affairs, salary, and public welfare. And the Communications and Public Affairs Section focuses on outreach and publicity activities.

Number of Staff Members

Director General	1
Researchers	104
Technical and Engineering Staff	44
Administrative Staff	42
Employee on Annual Salary System	17
Research Administrator Staff	3
Visiting Scientists	0
Total	211

Financial Affairs Division

The Financial Affairs Division consists of six sections: The Audit Section, the Financial Planning Section, the Accounts and Properties Administration Section, the Contracts Section, the Procurement Section, and the Purchase Validation Section.

The major responsibilities of the division are to manage and execute the budget, to manage corporate property, revenue/expenditure, and traveling expenses of staff, and to purchase supplies and receive articles.

The budget is 7,000,000,000 yen. (JFY 2023)

Research Support Division

The Research Support Division consists of four sections and one center. These are the Graduate Student Affairs Section, the Academic Information Section which includes the Library at NIFS, the Research Support Section and the International Collaboration Section, which is in charge of inter-university coordination and arranging international cooperation. The Visitor Center assists collaborating researchers and visitors.

Collaboration Research Programs

	Applications Applied	Applications Accepted	Researchers Accepted
Network-Type Collaboration Research	4	4	100
Interdisciplinary Fusion Science Collaboration Research	100	100	870
Fusion Plasma Collaboration Research	66	65	768
Fusion Technology Collaboration Research	87	86	459
Plasma Simulator CollaborationResearch	81	81	511
Workshops	29	28	836
Bilateral Collaboration Research	100	99	1,512
Total	467	463	5,056

Number of Graduate School Students
(SOKENDAI: The Graduate University for Advanced Studies)

Doctoral Course					
Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
2	3	5	8	4	22

(The Joint Program of Graduate Education)

Graduate course education is given in NIFS apart from SOKENDAI in joint programs with the Department of Energy Science and Engineering of the Graduate School at Nagoya University, Division of Particle and Astrophysical Science of the Graduate School of Science at Nagoya University, Division of Quantum Science of the Graduate School of Engineering at Hokkaido University, Department of Energy Science of the Graduate School of Science and Engineering at University of Toyama, Interdisciplinary Graduate School of Engineering Science in Kyushu University and the Graduate School of Engineering at Tohoku University. In total, 31 graduate students are involved in the programs as of March 31, 2024.

The Special Research Collaboration Program for Education

Affiliation \ Degree	Bachelor's Course	Master's Course	Doctoral Course	Total
National Graduate School	5	14	12	31
Public Graduate School	0	0	0	0
Private Graduate School	0	0	0	0
Total	5	14	12	31

Books and Journals

Books in Japanese	20,895
Books in Other Languages	51,343
Total (volumes)	72,238
Journals in Japanese	283
Journals in Other Languages	844
Total (titles)	1,127

Facilities and Safety Management Division

The Facilities and Safety Management Division consists of three sections: The Safety and Health Management Section, the Facilities Planning Section, and the Facilities Maintenance Section. They are in charge of planning, designing, making contracts, supervising the construction and maintenance of all facilities at NIFS, such as buildings, campus roads, electricity, telephone, power station, air conditioning, water service, gas service, elevators, and cranes. The Facilities and Safety Management Division submits a budget request and administers the budget for those facilities.

The Safety and Health Management Section also arranges medical examination and disaster drills. These three sections promote facilities' environment better for all staff.

Site and Buildings

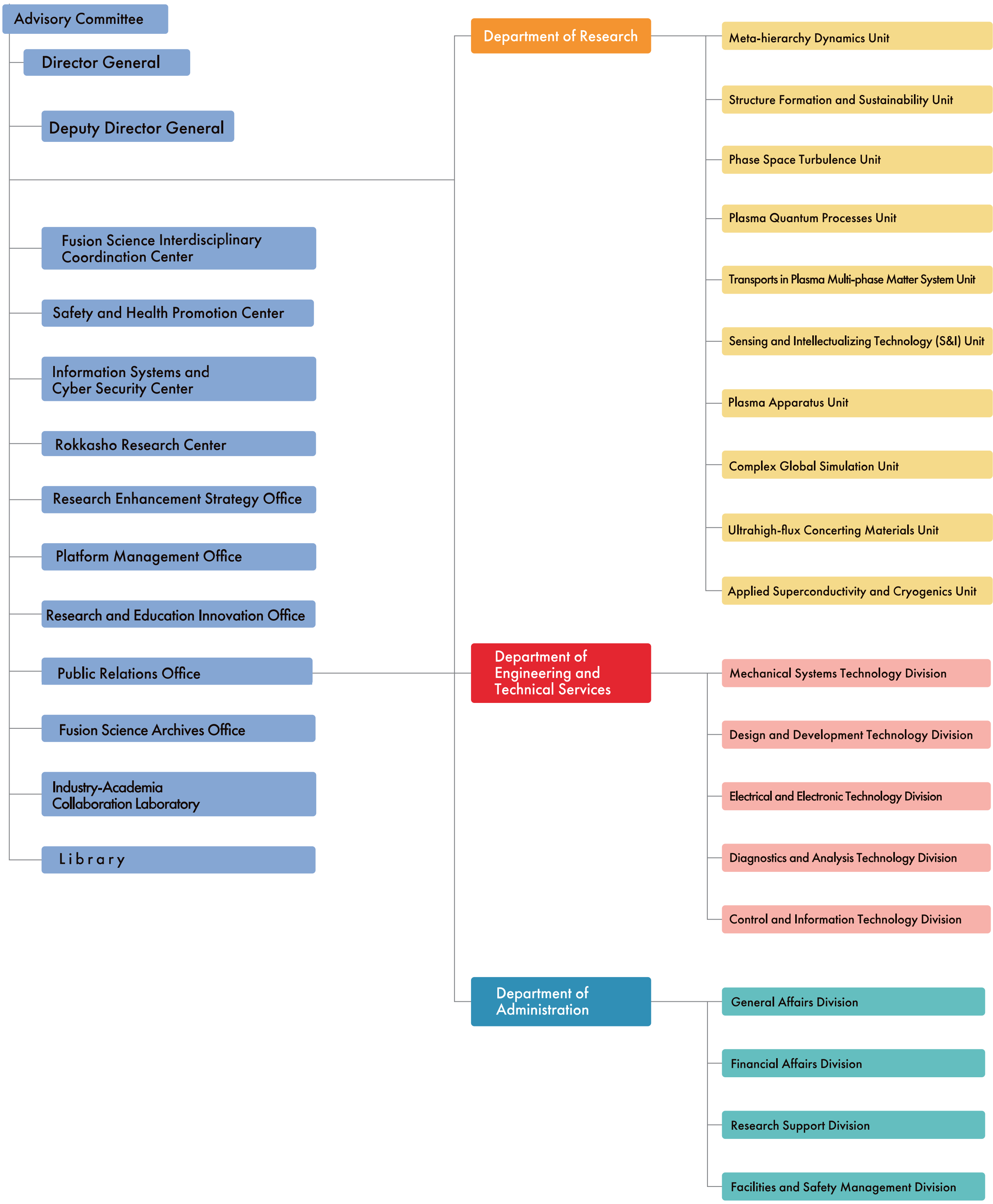
Toki	
Site	464,445 m^2
Buildings	
Total Building Area	39,557 m^2
Total Floor Space	71,830 m^2

※ All statistical data is as of March 31, 2024

APPENDIX

APPENDIX 1. Organization of the Institute

April 2024



APPENDIX 2. Members of Committees

Advisory Committee

ISHIDA, Shinichi	Deputy Director National Institute for Quantum Science and Technology
UEDA, Yoshio	Professor Graduate School of Engineering, Osaka University
OZAWA, Tohru	Professor Faculty of Science and Engineering School of Advanced Science and Engineering, Waseda University
KANEKO, Toshiro	Professor Graduate School of Engineering , Tohoku University
FUJISAWA, Akihide	Professor Research Institute for Applied Mechanics, Kyushu University
FUJITA, Takaaki	Professor Graduate School of Engineering, Nagoya University
MATSUOKA, Ayako	Professor Graduate School of Science, Kyoto University
MORII, Takashi	Director Institute of Advanced Energy, Kyoto University
YAMADA, Hiroshi	Professor Graduate School of Frontier Sciences, The University of Tokyo
YONEDA, Hitoki	Professor Institute for Laser Science, The University of Electro-Communications
WATANABE, Tomohiko	Professor Graduate School of Science, Nagoya University

※ This list was compiled as of March 31, 2024

APPENDIX 3. Professor Emeritus

Professors Emeritus

ICHIKAWA, Yoshihiko (1993)
MIZUNO, Yukio (1994)
FUJITA, Junji (1996)
KURODA, Tsutomu (1997)
AMANO, Tsuneo (1998)
MOMOTA, Hiromu (1998)
IIYOSHI, Atsuo (1999)
HATORI, Tadatsugu (1999)
TANAHASHI, Shugo (2000)
KAWAMURA, Takaichi (2000)
SATO, Tetsuya (2001)
FUJIWARA, Masami (2002)
KAMIMURA, Tetsuo (2003)
HAMADA, Yasuji (2007)
KATO, Takako (2007)
NODA, Nobuaki (2008)
WATARI, Tetsuo (2008)
MOTOJIMA, Osamu (2009)
SATOH, Kohnosuke (2010)
OHYABU, Nobuyoshi (2010)
MATSUOKA, Keisuke (2010)
TOI, Kazuo (2012)
NARIHARA, Kazumichi (2012)
KUMAZAWA, Ryuhei (2012)
UDA, Tatsuhiko (2012)
SATO, Motoyasu (2012)
YAMAZAKI, Kozo (2013)
KAWAHATA, Kazuo (2013)
OKAMURA, Shoichi (2014)
KOMORI, Akio (2015)
SUDO, Shigeru (2015)
SKORIC, Milos (2015)
MUTO, Takashi (2016)
NAGAYAMA, Yoshio (2017)
NAKAMURA, Yukio (2017)
SAGARA, Akio (2017)
ITOH, Kimitaka (2017)
HORIUCHI, Ritoku (2017)
HIROOKA, Yoshihiko (2018)
MORITA, Shigeru (2019)
NISHIMURA, Arata (2019)
TAKEIRI, Yasuhiko (2021)
KUBO, Shin (2021)
MITO, Toshiyuki (2021)
NISHIMURA, Kiyohiko (2021)
KANEKO, Osamu (2022)
MURIGA, Takeo (2022)
ISHIGURO, Seiji (2022)
NAKAJIMA, Noriyoshi (2022)
SHIMOZUMA, Takeshi (2022)
IDA, Katsumi (2023)
SAKAGAMI, Hitoshi (2023)

※ This list was compiled as of March 31, 2024

APPENDIX 4. List of Staff

Director General
YOSHIDA, Zensho

Deputy Director General
TODO, Yasushi

Department of Research
Prof. SAKAMOTO, Ryuichi (Director)

Meta-hierarchy Dynamics Unit
Prof. NUNAMI, Masanori (Chief)
Prof. SAKAMOTO, Ryuichi
Prof. NAGAOKA, Kenichi
Assoc. Prof. IGAMI, Hiroe
Assoc. Prof. ITO, Atsushi
Assoc. Prof. KASAHARA, Hiroshi
Prof. GOTO, Motoshi
Assoc. Prof. SATO, Naoki
Assoc. Prof. SEKI, Tetsuo
Assoc. Prof. TODA, Shinichiro
Assoc. Prof. NAKATA, Motoki
Assoc. Prof. MAEYAMA, Shinya
Assist. Prof. ISHIKAWA, Ryohtaro
Assist. Prof. KAWATE, Tomoko
Assist. Prof. KAWAMURA, Gakushi
Assist. Prof. TAKAYAMA, Arimichi
Assist. Prof. HASEGAWA, Hiroki
Assist. Prof. MATSUOKA, Seikichi
COE Researcher LIN, Keren
COE Researcher YANG, Shudi
Visiting Professor REITER, Detlev

Structure Formation and Sustainability Unit
Assoc. Prof. YAMAGUCHI, Hiroyuki (Chief)
Prof. ISOBE, Mitsutaka
Prof. ICHIGUCHI, Katsuji
Prof. OSAKABE, Masaki
Assoc. Prof. OGAWA, Kunihiro
Assoc. Prof. SATAKE, Shinsuke
Assoc. Prof. TAKAHASHI, Hiromi
Assist. Prof. ITO, Atsushi
Assist. Prof. KAWAMOTO, Yasuko
Assist. Prof. GOTO, Takuya
Assist. Prof. SHIMIZU, Akihiro
Assist. Prof. NISHIMURA, Shin
Assist. Prof. NUGA, Hideo

Phase Space Turbulence Unit
Assoc. Prof. KOBAYASHI, Tatsuya (Chief)
Project Prof. IDA, Katsumi
Assoc. Prof. TAMURA, Naoki
Assoc. Prof. TOKUZAWA, Tokihiko
Assoc. Prof. NISHIURA, Masaki
Assoc. Prof. YAMADA, Ichihiro
Assoc. Prof. KENMOCHI, Naoki
Assist. Prof. YANAI, Ryohma
Assist. Prof. YOSHINUMA, Mikiro
Project Researcher NASU, Tatsuhiro

Plasma Quantum Processes Unit
Prof. KATO, Daiji (Chief)
Prof. HOSHI, Takeo
Prof. MURAKAMI, Izumi
Assoc. Prof. IWAMOTO, Akifumi
Assist. Prof. SAKAI, Kentaro
Assist. Prof. SAKAUE, Hiroyuki
Assist. Prof. SUZUKI, Chihiro
Assist. Prof. FUNABA, Hisamichi
Assist. Prof. MUTO, Sadatsugu
Assist. Prof. MORITAKA, Toseo
Assist. Prof. YAMAGISHI, Osamu
Project Researcher GUPTA, Shivam

Transports in Plasma Multi-phase Matter System Unit

Prof. MASUZAKI, Suguru (Chief)
Prof. NAKAMURA, Hiroaki
Prof. MORISAKI, Tomohiro
Assoc. Prof. USAMI, Shunsuke
Assoc. Prof. KANNO, Ryutaro
Assoc. Prof. KOBAYASHI, Masahiro
Assoc. Prof. SHOJI, Mamoru
Assoc. Prof. TOKITANI, Masayuki
Assoc. Prof. MOTOJIMA, Gen
Assoc. Prof. YOSHIMURA, Shinji
Assist. Prof. GOTO, Yuki
Assist. Prof. HAMAJI, Yukinori
Assist. Prof. HAYASHI, Yuki
Assist. Prof. YAJIMA, Miyuki
Specially Appointed Prof. NAGATA, Daisuke
Visiting Professor KOVTUN, Yurii

S&I: Sensing and Intellectualizing Technology Unit

Assoc. Prof. UEHARA, Hiyori (Chief)
Prof. SAKAKIBARA, Satoru
Prof. TANAKA, Kenji
Prof. PETERSON, Byron
Prof. YASUHARA, Ryo
Prof. YOKOYAMA, Masayuki
Prof. WATANABE, Kiyomasa
Assoc. Prof. OHTANI, Hiroaki
Assoc. Prof. SAZE, Takuya
Assoc. Prof. TANAKA, Masahiro
Assoc. Prof. NAKANISHI, Hideya
Assist. Prof. EMOTO, Masahiko
Assist. Prof. OHTA, Masato
Assist. Prof. KAWAGUCHI, Haruki
Assist. Prof. TAKEMURA, Yuki
Assist. Prof. MUKAI, Kiyofumi
Research Fellowship SAKAI, Hikona
Project Researcher ZHAO, Mingzhong
Project Researcher YU, Linpeng

Plasma Apparatus Unit

Assoc. Prof. NAKANO, Haruhisa (Chief)
Prof. TSUMORI, Katsuyoshi

Complex Global Simulation Unit

Prof. TOIDA, Mieko (Chief)
Prof. SUGAMA, Hideo
Prof. TODO, Yasushi
Prof. MIURA, Hideaki
Assoc. Prof. MIZUGUCHI, Naoki
Assoc. Prof. YAMAMOTO, Takashi
Assist. Prof. ISHIZAKI, Ryuichi
Assoc. Prof. SATO, Masahiko
Assist. Prof. SEKI, Ryosuke
Assist. Prof. WANG, Hao
Assist. Prof. WANG, Jialei
COE Researcher WEI, Shizhao
COE Researcher KANG, Byungjun

Ultrahigh-flux Concerting Materials Unit

Prof. NAGASAKA, Takuya (Chief)
Assoc. Prof. TAKAYAMA, Sadatsugu
Assoc. Prof. TANAKA, Teruya
Assoc. Prof. MUKAI, Keisuke
Assoc. Prof. KOBAYASHI, Makoto
Assist. Prof. SHEN, Jingjie
Assist. Prof. NOTO, Hiroyuki

Applied Superconductivity and Cryogenics Unit

Prof. HIRANO, Naoki (Chief)
Prof. IMAGAWA, Shinsaku
Prof. TAKAHATA, Kazuya
Prof. YANAGI, Nagato
Assoc. Prof. TAMURA, Hitoshi
Assoc. Prof. CHIKARAISHI, Hirotaka
Assoc. Prof. HAMAGUCHI, Shinji
Assoc. Prof. HISHINUMA, Yoshimitsu
Assist. Prof. ONODERA, Yuta
Assoc. Prof. OBANA, Tetsuhiro
Assist. Prof. TAKADA, Suguru
Assist. Prof. NARUSHIMA, Yoshiro

Fusion Science Interdisciplinary Coordination Center
Prof. MURAKAMI, Izumi (Director)

Safety and Health Promotion Center
Prof. OSAKABE, Masaki (Director)

Information Systems and Cyber Security Center
Assoc. Prof. YAMAMOTO, Takashi (Director)

Rokkasho Research Center
Prof. YOKOYAMA, Masayuki (Director)

Research Enhancement Strategy Office
Prof. YOSHIDA, Zensho (Chief)
Project Professor MITO, Toshiyuki
Project Professor MUROGA, Takeo
Specially Appointed Senior Specialist CARR, Stephen

Platform Management Office
Prof. SAKAMOTO, Ryuichi (Chief)

Research and Education Innovation Office
Prof. NAGAOKA, Kenichi (Chief)

Public Relations Office
Prof. TAKAHATA, Kazuya (Chief)

Fushion Science Archives Office
Prof. MURAKAMI, Izumi (Chief)

Industry-Academema Collaboration Laboratory
Prof. YASUHARA, Ryo (Chief)

Library
Prof. MURAKAMI, Izumi (Chief)

※ This list was compiled as of March 31, 2024

Department of Engineering and Technical Services

	HAYASHI, Hiromi	Director
Mechanical Systems Technology Division	YOKOTA, Mitsuhiro	Manager
Design and Development Technology Division	SUZUKI, Naoyuki	Manager
Electrical and Electronic Technology Division	KONDO, Tomoki	Manager
Diagnostics and Analysis Technology Division	KOBUCHI, Takashi	Manager
Control and Information Technology Division	MORIUCHI, Sadatomo	Manager

※ This list was compiled as of March 31, 2024

Depertment of Administration

	IINO, Michiko	General Manager
General Affairs Division	ASANO, Masahiro	Manager
	ARAI, Masanori	Deputy Manager
	MATSUBARA, Tomohisa	Senior Specialist
	SHIMIZU, Kazuma	Leader/General Affairs Section
	UESUGI, Kohtaro	Leader/Planning and Evaluation Section
	INAGAKI, Tomoko	Leader/Employee Section
	MURASE, Itaru	Leader/Personnel and Payroll Section
	HOSOE, Tsunenari	Leader/Communications and Public Affairs Section
Financial Affairs Division	HIROI, Noriaki	Manager
	OHBA, Ryo	Deputy Manager
	HIBINO, Atsushi	Leader/Audit Section
	SUZUKI, Takayuki	Leader/Financial Planning Section
	KONDO, Takahiko	Leader/Accounts Section
	IWASHIMA, Itsuki	Leader/Procurement Section
Research Support Division	SHOJI, Madoka	Manager
	OHKAWA, Jun	Deputy Manager
	SOGA, Shihoko	Leader/Research Support Section
	FUKUOKA, Miwa	Leader/International Collaboration Section
	KAWAI, Sanae	Leader/Graduate Student Affairs Section
	OHKAWA, Jun	Leader/Academic Information Section
	OHKAWA, Jun	Director/Visitor Center
	HAYASHI, Tomomi	Leader/Visitor Center
Facilities and Safety Management Division		
	YASUE, Akihito	Manager
	WAKASHIMA, Masahiro	Deputy Manager
	IKEDA, Katsumi	Leader/Facilities Planning Section
		Leader/Facilities Management Section

※ This list was compiled as of March 31, 2024

APPENDIX 5. List of Publications I (NIFS Reports)

NIFS-DATA-116
Calculation of electronic excitation cross sections and rate coefficients for boron monohydride (BH)
Tomoko Kawate, Izumi Murakami, Motoshi Goto
Aug. 24, 2023

NIFS-MEMO-93
Overview of tokamak devices in universities in Japan
Study Group on Experimental Research for Advanced Tokamaks
Sep. 1, 2023 (In Japanese)

NIFS-MEMO-94
Report on Administrative Work for Radiation Safety From April 2022 to March 2023
Radiation Control Office / Division of Health and Promotion
National Institute for Fusion Science
Mar. 11, 2024 (In Japanese)

NIFS-PROC-126
NIFS-SWJTU JOINT PROJECT FOR CFQS –PHYSICS AND ENGINEERING DESIGN–
VER. 5.1 2023. AUG.
CFQS Team
National Institute for Fusion Science, National Institutes of Natural Sciences
Institute of Fusion Science, School of Physical Science and Technology,
Southwest Jiaotong University
Hefei Keye Electro Physical Equipment Manufacturing Co. Ltd.
Jan. 26, 2024

※ This list was compiled as of March 31, 2024

APPENDIX 6. List of Publications II (Journals, etc.)

1. Adulsiriswad P., Todo Y., Sato M., Aiba N., Narita E., Wang H., Idouakass M., Wang J.
Simulation study of interaction between energetic particles and magnetohydrodynamic modes in the JT-60SA inductive scenario with a flat q≈1 profile
Nuclear Fusion 63 12 126030 -2023

2. Adulsiriswad P., Todo Y., Yamamoto S., Kado S., Kobayashi S., Ohshima S., Okada H., Minami T., Nakamura Y., Ishizawa A., Konoshima S., Mizuuchi T., Nagasaki K.
Effects of the Resonance Modification by Electron Cyclotron Current Drive on the Linear and Nonlinear Dynamics of Energetic Particle Driven Magnetohydrodynamics Modes in Heliotron J
Nuclear Fusion 64 1 016036 -2024

3. Akata N., Okada K., Kuwata H., Kheamsiri K., Hosoda M., Tazoe H., Yasuhara R., Sugihara S., Yamada R., Tanaka M.
Tritium Concentration in Natural Spring Water Collected at Hirosaki, Japan
Plasma and Fusion Research 18 Special Issue 1 2405030 -2023

4. Anirudh R., Archibald R., Asif S., Becker M., Benkadda S., Bremer P., Budé R., Chang C., Chen L., Churchill R., Citrin J., Gaffney J., Gainaru A., Gekelman W., Gibbs T., Hamaguchi S., Hill C., Humbird K., Jalas S., Kawaguchi S., Kim G., Kirchen M., Klasky S., Kline J., Krushelnick K., Kustowski B., Lapenta G., Li W., Ma T., Mason N., Mesbah A., Michoski C., Munson T., Murakami I., Najm H., Olofsson K., Park S., Peterson L., Probst M., Pugmire D., Sammuli B., Sawlani K., Scheinker A., Schissel D., Shalloo R., Shinagawa J., Seong J., Spears B., Tennyson J., Thiagarajan J., Ticoş C., Trieschmann J., Dijk J., Essen B., Ventzek P., Wang H., Wang J., Wang Z., Wende K., Xu X., Yamada H., Yokoyama T., Zhang X.
2022 Review of Data-Driven Plasma Science
IEEE Transactions on Plasma Science 51 7 1750 -2023

5. Emoto M., Ida K., Imazu S., Yoshida M.
Application of container technology in LHD analysis system
Fusion Engineering and Design 196 113992 -2023

6. Engrhyt R., Osakabe M., Masaki S., Tsumori K., Nakano H., Nagaoka K., Ikeda K., Takeiri Y.
New Method to Evaluate Negative-Ion Density Using Conventional Langmuir Probe
Plasma and Fusion Research 18 Regular Issue 1401020 -2023

7. Engrhyt R., Osakabe M., Tsumori K., Nakano H., Nagaoka K., Ikeda K., Takeiri Y.
Langmuir-probe measurement through the plasma grid aperture of hydrogen negative ion source
Journal of Instrumentation 19 C02037 -2024

8. Feng S., Kajita S., Yasuhara R., Tokitani M., Shi Q.
Formation of corrugated nano-fuzz tungsten thin film on silicon via helium plasma irradiation
Japanese Journal of Applied Physics 63 1 010904 -2024

9. Feng S., Natsume H., Kajita S., Yasuhara R., Tokitani M., Tanaka H., Ohno N.
Fabrication of tungsten-based optical diffuser using fiberform nanostructure via efficient plasma route
Optics Express 31 16 25438-25445 -2023

10. Funaba H., Yasuhara R., Uehara H., Den hartog D., Yanai R., Kenmochi N., Yamada I.
Improvement of electron temperature and density accuracy in Thomson scattering diagnostics by an accumulation of 100 laser pulses within 5 milliseconds
Journal of Instrumentation 18 C11015 -2023

11. Goto Y., Garmon S., Petrosky T.
Enhanced classical radiation damping of electronic cyclotron motion in the vicinity of the Van Hove singularity in a waveguide
Progress of Theoretical and Experimental Physics 2024 3 033A02 -2024

12. Goya K., Sasanuma H., Ishida G., Uehara H., Tokita S.
Fusion splicing of plastic optical fibers using a mid-IR fiber laser
Applied Physics Express 16 5 052006 -2023

13. Gupta S., Oishi T., Murakami I.
Study of Electron Impact Excitation of Na-like Kr Ion for Impurity Seeding Experiment in Large Helical Device
Atoms 11 142 142 -2023

14. Hasegawa H., Ishiguro S.
Analysis of plasma particle orbits in boundary layers with the efficient electrostatic particle-in-cell simulation code
102-105 -2023

15. Hirano N., Onodera Y., Mito T., Motoki Y., Kawagoe A.
Basic research on a magnetic refrigeration system for cooling to liquid hydrogen temperature
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Assessing the variability of tissue-free water tritium and non-exchangeable organically bound tritium in pine needles in Fukushima using atmospheric titrated water vapor
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17. Hirooka Y., De Castro A., Goto T., Maingi R., Morgan T., Ono M., Shimada M.
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Nuclear Fusion 63 9 097001(11pp) -2023

18. Hishinuma Y., Kikuchi A., Taniguchi H., Oguro H., Awaji S., Muroga T.
Improvement of mechanical properties by internal matrix reinforcement in bronze processed Nb3Sn wire — Internal matrix reinforcement by solid solution strengthening mechanism —
低温工学 (Journal of the Cryogenic Society of Japan) 58 3 108-115 -2023

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Surface and Coatings Technology 480 130563 -2024

20. Ida K.
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Cryogenics 132 103673 -2023

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Generation and measurement of low-temperature plasma for cancer therapy: a historical review
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23. Ito A., Takayama A., Nakamura H.
Tungsten Nanostructure Growth by Sputtering and Redeposition in BCA-MD-KMC Hybrid Simulation
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Improved Variable-Reduction Method and Its Variant for Solving Asymmetric EFG-Type Saddle-Point Problem
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28. Kasahara H., Saito K., Seki T., Mutoh T.
The design of a slit ICRF antenna in EU-DEMO
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Wave Absorption Profile during ICRF Heating in Mixed Plasma in Large Helical Device
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31. Kawaguchi H., Yasuhara R., Yang H., Hori C., Miyagawa R., Sugioka K., Ota M., Uehara H.
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Optical Materials Express 14 2 424-434 -2024

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Fusion Engineering and Design 193 113799 -2023

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43. Kovtun Y., Kasahara H., Moiseenko V., Kamio S., Seki T., Saito K., Seki R., Dinklage A., Hartmann D., Laqua H., Stange T., Lazerson S., Alonso A., Wauters T., Kazakov Y., Ongena J., Garkusha I.
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45. Koyama H., Okumura H., Ito A., Nakamura K., Otani T., Kato K., Fujimori T.
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50. Liao L., Ogawa K., Isobe M., Sangaroon S., Kawamoto Y., Zhong G., Fan T.
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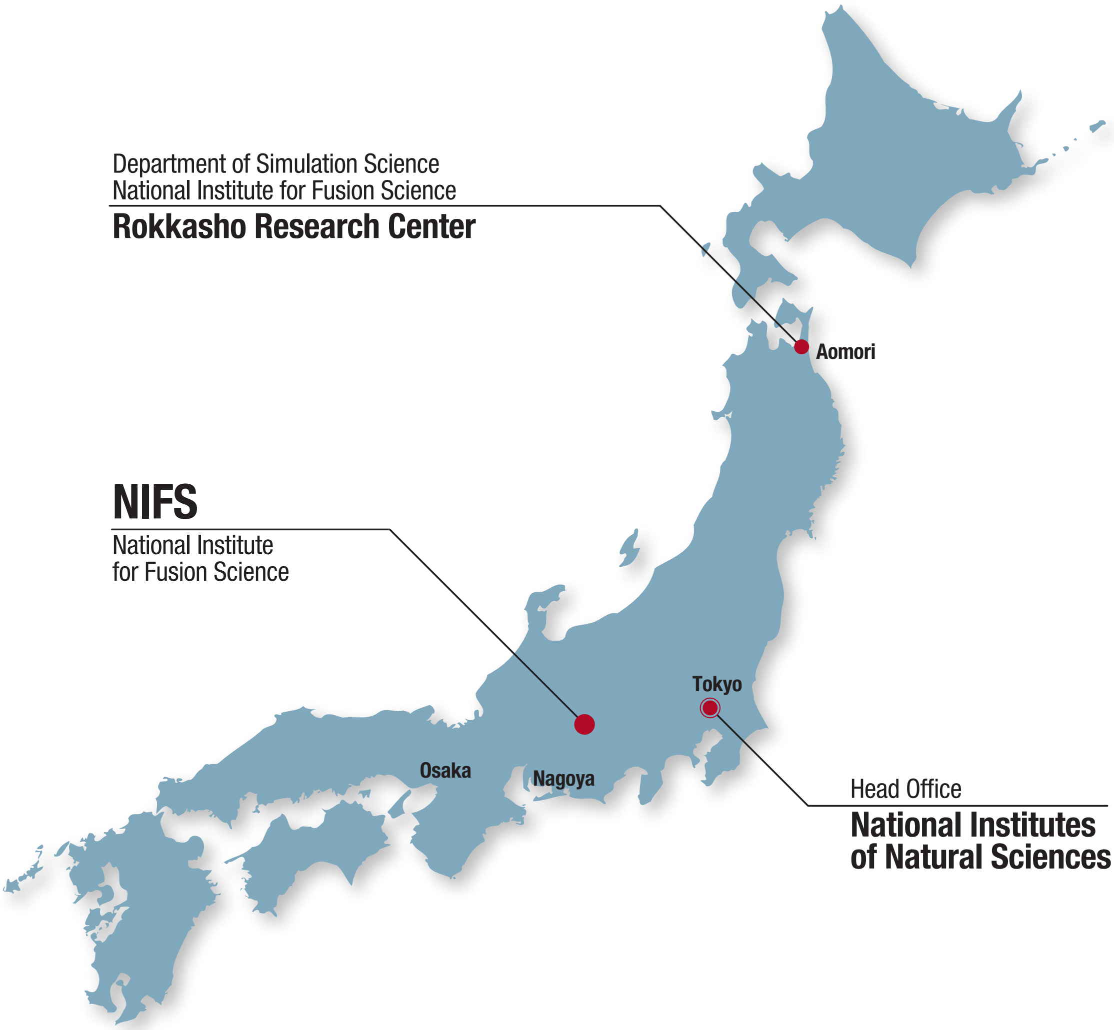

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How to Reach National Institute for Fusion Science

☐**ACCESS**
When you use the public transportation facility

◇**from Centrair** (Central Japan International Airport)

Centrair–(μ-sky)–**Meitetsu Kanayama Sta. (36km)**
about 25min

JR Kanayama Sta.–(JR Chuo Line)–**JR Tajimi Sta. (33km)**
about 33min (express)

JR Tajimi Sta.–(Totetsu Bus)–**Kenkyuugakuentoshi (7km)**
about 15min

◇**from JR Nagoya Sta.**

JR Nagoya Sta.–(JR Chuo Line)–**JR Tajimi Sta. (36km)**
about 22min (limited express) / about 30min (lapid) / about 40min (local)

JR Tajimi Sta.–(Totetsu Bus)–**Kenkyuugakuentoshi (7km)**
about 15min

◇**from Nagoya Airport**

(Obihiro•Akita•Yamagata•Niigata•Kouchi• Matsuyama•Fukuoka•Kumamoto•Nagasaki)

Nagoya Airport–(Taxi)–**JR Kachigawa Sta. (4km)**
about 10min

Nagoya Airport–(Meitetsu Bus)–**JR Kachigawa Sta. (4km)**
about 19min

JR Kachigawa Sta.–(JR Chuo Line)–**JR Tajimi Sta. (21km)**
about 20min

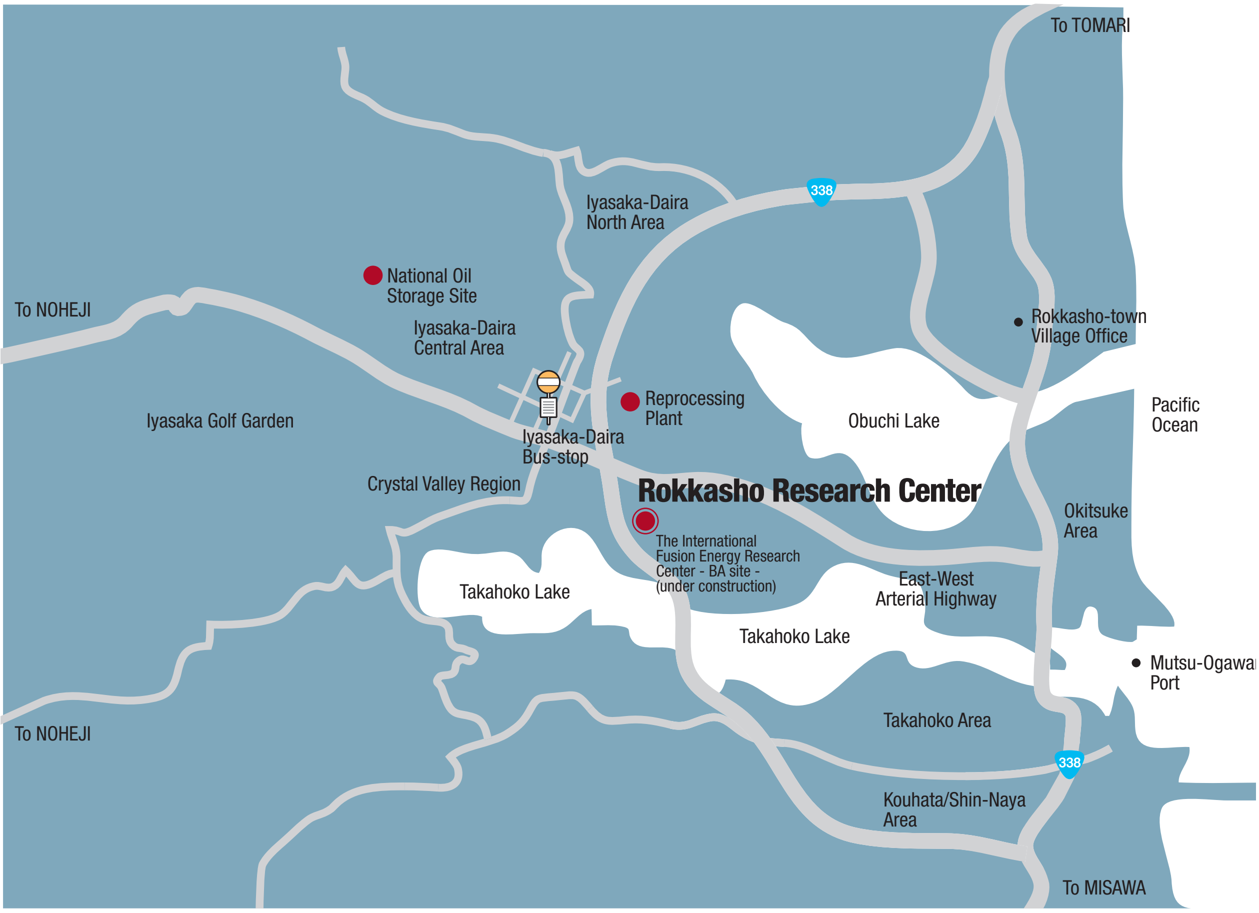
JR Tajimi Sta.–(Totetsu Bus)–**Kenkyuugakuentoshi (7km)**
about 15min

When you use a car

from Chuo Expressway Toki I.C. or Tajimi I.C. (8km)
about 20min

from Tokai-Kanjo Expressway Tokiminami Tajimi I.C. (2km)
about 5min

How to Reach Rokkasho Research Center



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When you use the public transportation facility

◇**from Tokyo**

Tokyo–(Tohoku-Shinkansen)–Hachinohe Sta. (630km)
about 3hr

Hachinohe Sta.–(JR Tohoku Limited Express)–Noheji (51km)
about 30min

Noheji–(Shimokita Koutsu Bus)–Iyasaka-Daira (10km)
about 40min

Iyasaka-Daira .....on foot..... Rokkasho Research Center (0.7km)
about 8min

◇**from Misawa Airport**

Misawa Airport–(Bus)–Misawa (2km)
about 13min

Misawa–(JR Tohoku Limited Express)–Noheji (30km)
about 20min

Noheji–(Shimokita Koutsu Bus)–Iyasaka-Daira (10km)
about 40min

Iyasaka-Daira .....on foot..... Rokkasho Research Center (0.7km)
about 8min

◇**from Aomori Airport**

Aomori Airport–(Bus)–Aomori (12km)
about 40min

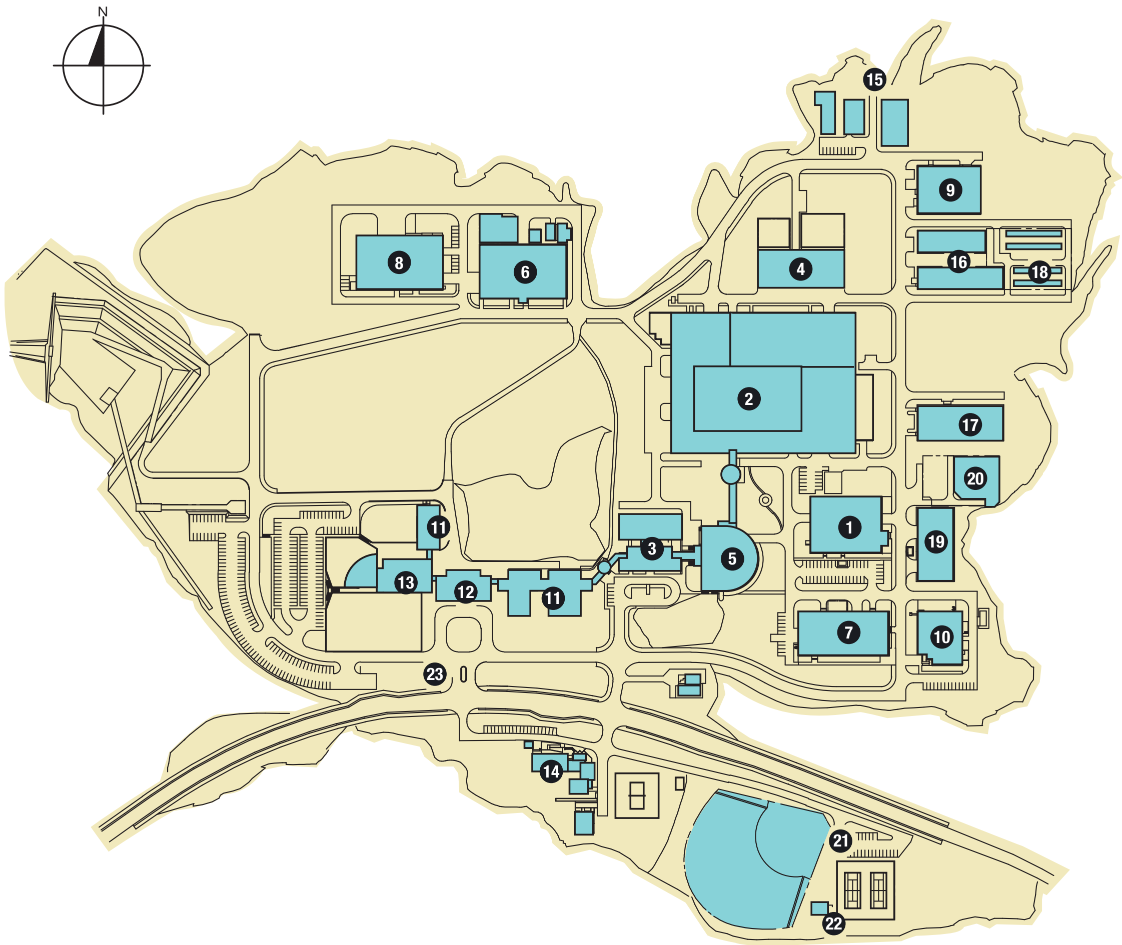
Aomori–(JR Tohoku Limited Express)–Noheji (45km)
about 30min

Noheji–(Shimokita Koutsu Bus)–Iyasaka-Daira (10km)
about 40min

Iyasaka-Daira .....on foot..... Rokkasho Research Center (0.7km)
about 8min

National Institute for Fusion Science

Building Arrangement



NIFS plot plan

1. Superconducting Magnet System Laboratory
2. Large Helical Device Building
3. Simulation Science Research Laboratory
4. Heating and Power Supply Building
5. LHD Control Building
6. Fusion Engineering Research Laboratory
7. Plasma Diagnostics Laboratories
8. R & D Laboratories
9. Motor-Generator Building
10. Central Workshops
11. Research Staff Building
12. Library Building
13. Administration Building
14. Helicon Club (Guest Housing)
15. High-Voltage Transformer Station
16. Cooling Water Pump Building
17. Helium Compressor Building
18. Cooling Tower
19. Equipments Room
20. Helium Tank Yard
21. Recreation Facilities
22. Club House
23. Guard Office