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National Institute for Fusion Science

NIFS Peer Review Reports in FY2021

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National Institute for Fusion Science

Advisory Committee External Peer Review Committee

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Executive Summary
of the External Review Report in FY2021

The FY2021 NIFS External Peer Review Committee (hereafter referred to as “the committee”) held its meetings and hearings from Oct.12, 2021 to Feb.4, 2022 to evaluate the Large Helical Device Project (LHDP), the Numerical Simulation Reactor Research Project (NSRP), and the Fusion Engineering Research Project (FERP) during the 3rd Medium Term Target Period (FY2016-2021). Three sub-committees were organized and compiled their reports for each project in charge, and then the committee worked out the review report from their reports. Overall the committee was impressed by extensive scientific achievements and physical findings in these three projects. In consideration of the extraordinary circumstances due to the COVID-19 pandemic, the committee would like to emphasize its appreciation of outstanding support to collaborative research by NIFS. The committee also seriously takes the situation that the budgetary support for the full operation of LHD will end in FY2022 and expects that this review would be helpful to make provision for the coming years of NIFS.

This review responds to the evaluation perspectives provided below,

Perspective 1 Were the goals set appropriate from the perspective of the National Institute for Fusion Science, and have they been appropriately updated in light of research results and research trends, and have the corresponding measures been taken accordingly?

- It is appropriate that the specific plans related to the LHDP were made to improve plasma control, heating, diagnostics, and safety management facilities to realize high-performance plasmas, and to carry out deuterium experiments as academic research.

- Incorporated with the LHDP, the NSRP was organized to accelerate reactor design using numerical simulations. The basic design of the plan is meaningful and then adequate as a whole. They have advanced integration of the research activities of theory and simulation group at NIFS, and promotion of organized research program to achieve the goal of the NSRP.

- Along with newly added research objects in the FERP, the refinement of reactor design was conducted, and efforts were made toward the design of a full-scale prototype of the large high-field superconducting magnet and the advanced blanket system. Then, the prospect for establishing the academic research roadmap for a helical reactor has been summarized, reinforcing the interaction between reactor design and R&D as an outcome of the reactor design studies.

- The committee recommends that NIFS integrates the research results accumulated in the LHDP as basic physics insights, which should provide the international community with guidance for the next steps in the research of fusion science. It is also recommended that NIFS seeks for measures to resolve remaining important scientific issues posed in the LHDP.

- The committee recommends that targets of the FERP should move to more fundamental fusion engineering applicable to various types of reactor concepts based on excellent research results in NIFS so far.
- The scientific targets seem to have been too much focused on LHD-related science. Such focusing may have unintentionally excluded wider interests in the plasma and fusion science community, including ITER project, plasma physics in astrophysics or particle-hadron physics, fluid dynamics, mathematical science, etc. The committee recommends NIFS to consider this point for the next step.

Perspective 2 Have sufficient results been produced as an inter-university research institute in the academic field?

- A large number of outstanding physics results have been obtained from the LHDP over the past several years. They cover important aspects of plasma physics and operations relevant to fusion reactors, including isotope effect, confinement and transport, control, and plasma-wall interactions. They impact greatly the ongoing research around the world. The results were enabled by the comprehensive set of diagnostics, the controllability of the LHD plasmas, and the excellent research team.
- The NSRP has developed state-of-the-art codes spanning the plasma core to the edge including the plasma facing wall. The NSRP has accepted a wide variety of cross-disciplinary studies through the collaboration research programs. The NSRP could have played more active role in cultivating diverse research fields to promote interdisciplinary researches as a leading institute of fusion-plasma sciences.
- The committee confirmed that the collaborative use of the main facilities for fusion engineering was positively promoted and that research activities using the facilities have produced many results and papers. NIFS made an outstanding contribution to research activities in the academic fields of fusion engineering from the viewpoint of the role as an inter-university research institute.
- The committee recommends that NIFS should promote international-level experimental research which is difficult to be conducted at universities and strengthen cooperation and interactivity with exploratory and original research in universities.
- For more open and flexible collaboration research programs, the scope of the collaboration researches needs to be extended from the current framework centering at the LHDP to more diversified areas covering the whole plasma and fusion sciences.

Perspective 3 Were sufficient results obtained from the viewpoint of the following special notes in the Third Medium-Term Plan?

3-1 for LHDP Deuterium experiments are carried out by upgrading plasma control, heating, diagnostics, and safety control facilities to further improve the performance of the Large Helical Device (LHD) for systematization of physics and engineering of helical systems and comprehensive understanding of torus plasmas.

- Excellent execution of the planned operation of the superconducting coils is highly commended and 92% of the planned discharges has been completed. Outstanding progress in the LHDP has been recognized over the past years on key aspects of reactor-relevant plasma physics and performance, and the understanding of toroidal plasmas from various perspectives is commendable.
- The knowledge of the heating and diagnostics system developed for the deuterium experiments in the LHDP is expected to contribute to the next fusion devices. Furthermore, as for the systematization of physics and engineering of helical systems, further comparison with W7-X is highly recommended. There are many results for comprehensive physics understanding in toroidal plasmas and NIFS should seek new paradigm to resolve unresolved issues in this direction.

3-2 for LHDP Achievement of 120million degrees by the end of the third mid-term target period and realize ultra-high performance plasmas that can be extrapolated for use in a fusion reactor.

- The realization of high-temperature plasmas with an ion temperature of 120 million degrees in the helical device, and the generation of high-temperature plasmas with both ion and electron temperatures reaching 100 million degrees are highly regarded.
- In terms of the realization of ultra-high-performance plasmas that can be extrapolated to fusion reactors, the direction to reach more reactor relevant conditions from either the high-density region or the high-temperature region, which are currently realized in the LHD, is not clear in the Lawson diagram. The experimental research to identify the approach to high performance plasmas that can be extrapolated to a fusion reactor in a helical system should be promoted by making full use of the availability of the LHD and accelerating the international collaboration with W7-X.

3-3 for LHDP Hydrogen isotope effects on the formation of internal transport barriers of ions and particle recycling characteristics in deuterium discharges is verified through academic research based on collaboration.

- Favorable experimental results on isotope effects on confinement and transport have been obtained. New excellent results have been obtained for the isotope effects on the ion and electron transport in discharges exhibiting internal transport barriers, which are important for the extrapolation to the fusion reactor conditions.
- Further research is recommended to clarify the underlying physics mechanism of isotope effect through the comparison with theory.

3-1 for NSRP Effectively using the supercomputer system, the Plasma Simulator, for construction of the Numerical Simulation Reactor, research for development, extension, high precision, and the integration of the simulation codes for the whole device from the core plasma to the peripheral plasma and plasma facing wall is advanced. During FY2019, the performance of the Plasma Simulator is improved more than four times compared to the current system, and various three-dimensional simulation codes for the improved system are optimized.

- Plasma Simulator (NIFS supercomputer system) was upgraded in July 2020 as it was delayed one year from the original schedule due to achieving the target performance, and the new system was then fully utilized in the development and operation of the various simulations, achieving its original purpose.
- Development, extension and integration of various simulation codes for reactor-relevant research have been achieved in most target areas. In particular, notable achievements are seen in a hybrid code MEGA, a gyro-kinetic code GKV, a suite of codes for edge plasmas EMC3-EIRENE and an integrated transport code TASK-3D.
- The top 10% paper rate of the NSRP is 6.7%, which is below the international average. Also, the average international co-authorship rate is 39.1%, which is not high enough for an international research institute. The committee recommends that the NSRP extends the study by advancing the cooperation with wider disciplines and more activating international joint research.

3-2 for NSRP Modeling of turbulent transport in core plasma and the application of the model into the integrated transport code are completed by the end of FY2019, and the incorporation of multiple ion species effects into various transport codes is done by the end of the third mid-term target period. Furthermore, by the end of the third mid-term target period, molecular dynamics simulation techniques are developed by improving programs and building new models necessary for

evaluating the physical properties of plasma facing materials such as tungsten.

- The NSRP has made several important achievements in studies of turbulent transport. It is noteworthy that quantitative evaluation of transport for non-axisymmetric devices with three-dimensional field configuration, such as LHD, is accompanied with qualitatively different difficulties compared with those for axisymmetric (tokamak) systems. This is because the three-dimensional field configuration complicates the numerical modeling. In spite of these difficulties, the NSRP successfully promoted the state-of-the-art in the transport research for helical systems, and produced internationally visible research outcomes.

- A multi-hybrid simulation technique was developed on the basis of binary collision , kinetic Monte-Carlo, and molecular dynamics methods. As a result, formation process of tungsten “fuzz” nano structures caused by helium plasma irradiation was realized by simulation. Moreover, a recycling model was constructed for hydrogen plasma-wall-interaction on tungsten wall on the basis of molecular dynamics, which also produced a remarkable progress in the analysis of LHD plasmas.

- The strength in the field of turbulent and neo-classical transport should be maintained. A successful balance and synergistic cooperation between flux tube codes (GKV) with high resolution of phase space dynamics and global codes (such as GT5D and FORTEC-3D) addressing self-organization of mesoscopic structures as well as the edge turbulent transport should be one of the high priority items in reorganizing the future research efforts.

3-3 for NSRP As supporting research to achieve the above goals, the code accuracy by comparison with the experimental results on the three-dimensional equilibrium, transport, instability and nonlinear evolution of magnetically confined plasmas, including LHD plasmas, is improved while conducting simulation research on related basic physics.

- The simulation research activities, leading to fruitful collaborations between the NSRP and the LHDP, are highly regarded, which has identified and interpreted key physics processes regarding equilibrium, MHD, neo-classical and turbulent transport etc. by comparing to experimental results.

- Basic physics studies have been also promoted by simulations of the magnetic reconnection, Hall MHD turbulence, magnetic reconnections based on multi-scale kinetic model, turbulence simulations of high Reynolds number based on large eddy model, etc., which are evaluated as excellent results.

- The committee recommends that NIFS should play more active role in cultivating diverse research fields to promote interdisciplinary research and to keep the NIFS’s leading status in wider areas in the fusion and plasma sciences. It is a time to consider how to proceed this direction in the balance with those of more fusion oriented world-wide urgent problems including ITER toward the next Mid-Term Target Period.

3-1 for FERP Aiming for the early realization of fusion reactors, the conceptual design of helical fusion reactors is summarized, and the numerical targets of each development issue is concretely defined in 2016.

- In 2016 the conceptual design and the R&D activities were summarized in detail in a ~450 pages report (in Japanese) with numerical targets of each development issues included in the appendix. The summarized report clearly clarifies the roadmap, design policy, technology gap, R&D and simulations for the Helical Fusion reactor with the numerical targets of each development issue were embodied.
- The visualization tool developed in the FERP should be utilized effectively to develop a targeted academic roadmap and to establish a systematization of fusion engineering from broader perspective.

3-2 for FERP By promoting refinement of reactor design, and the interrelated enhancement of performance and reliability of core equipment, and by progressing development research for establishment of standards and criteria, the engineering design of a full-scale prototype of the large high-field superconducting magnet and the advanced blanket system are summarized, and the academic research roadmap for helical fusion reactor development is summarized in the report.

- The refinement of reactor design was conducted, and efforts were made toward the design of a full-scale prototype of the large high-field superconducting magnet and the advanced blanket system, including the cryogenic system design and the in-vessel component design. Then, the prospect for establishing the academic research roadmap for the helical reactor has been summarized, reinforcing the interaction between reactor design and R&D as an outcome of the reactor design studies.
- NIFS should promote fundamental research for advanced blanket design and adopt these results to DEMO TBM. R&D of HTS design and fabrication technologies should also be promoted, not only for magnetic confinement fusion reactors, but also the other applications to expand their research toward fields outside of fusion reactor development.

3-3 for FERP **The functions of domestic and international collaborations are strengthened by expanding performance and establishing collaboration centers for largescale facilities such as "heat/mass flow loop" and "the large-diameter high magnetic field conductor test facility" that were launched in the second phase. The systematization of fusion engineering and its contribution to interdisciplinary research by accumulating knowledge for the establishment of standards and criteria are promoted, and the expansion and promotion of related technologies to industry are planned.**

- NIFS has many characteristic large devices related to fusion engineering, and contributes to strengthening the functions of universities and other institutions and to the development of the community through their joint use and joint research. The collaborative activities have covered research areas in SC Magnets, Liquid Blanket, High Heat Flux Component, Tritium and Advanced Materials. NIFS made an outstanding contribution in these areas.
- As for the accumulation of knowledge for the establishment of standards and criteria, there remain many issues that need to be addressed. Expansion and contribution to interdisciplinary research and industry activities based on accumulated knowledge in NIFS are also seen in BNCT (Boron Neutron Capture Therapy) and the cryogenic technology applied to KAGRA (Kamioka Gravitational wave detector, Large-scale Cryogenic Gravitational wave Telescope).
- More efforts should be placed on expansion and promotion of related technologies to interdisciplinary research and industrial applications in addition to the contributions to BNCT and KAGRA.

Perspective 4 **Was contribution made to the enhancement of the functions of the universities and the development of the community as a domestic and international core research center in this field?**

- The commendable contributions of NIFS are recognized as a domestic and international core institute in fusion science. The contributions to the plasma and fusion science community are obvious through three existing frameworks for collaboration researches, i.e., LHD Project Collaboration Research, Bilateral Collaboration Research, and General Collaboration Research. It should be emphasized, in addition to these three frameworks, that the DEMO R&D Collaboration Research has been newly established since 2019. The establishment of this new framework is highly regarded since it is regarded as that NIFS starts to bear the substantial responsibility as the core institute in the new phase of the fusion science, that is, in the era of burning plasmas research to realize a fusion reactor.

- NIFS has many characteristic large devices strengthening the functions of universities and other institutions through their joint use and joint research. Results from broad and intense collaboration demonstrate the core role of NIFS and clearly show the extending function of universities.

- As an inter-university research institute, NIFS plays an excellent role by conducting more than 500 joint research projects per year. In the COVID-19 pandemic, it is outstanding that NIFS has provided a system that allows domestic and international collaborators to participate in LHD experiments remotely.

- The committee notes that the termination of the present budgetary support to the LHDP would lead to the termination of LHD Project Collaboration Research which cause significant damage to the plasma and fusion science community. It is recommended that NIFS should make efforts to find an alternative to the present framework to support activities in universities.

- Facing budgetary difficulty, it is needed to pursue the external funds such as JSPS Grant-in-Aid Scientific Research much more than before. The committee recommends that NIFS should make a systematic analysis of the reason of limited adoption rate and take measures. The action of planning out a strategy of raising funds up to sufficient amount for excellent research programs is one of the most important issues of NIFS.

- It is time to enter a new phase of nuclear fusion research to realize burning plasma and reify DEMO project, therefore, the committee recommends that NIFS should be a hub to connect the universities in the coming nuclear fusion research and promote related activities in universities.

Perspective 5 Was internationalization promoted through exchanges of researchers and joint research with overseas research bases, based on international exchange agreements?

- It is commendable that NIFS has proceeded with the research projects under the agreements with 33 institutes in 15 countries. International collaborations were promoted either under many bilateral or under multilateral frameworks.

- In conjunction with developing the concept of open science for LHD data, the number of overseas proposals in the LHDP has tremendously increased in spite of the COVID-19 pandemic. This is an excellent implementation.

- International research collaborations are actively promoted under the NSRP as well, such as research exchanges and workshops through the US-Japan Joint Institute for Fusion Theory (JIFT) program, which makes NIFS internationally visible as a leading institute of fusion-plasma science in the world.

- A large number of fusion engineering topics have been also tackled ranging from magnet research, cryogenics, negative ion hydrogen sources, materials research, to plasma wall interaction and the fusion neutron source. These collaborations supported quite strongly the internationalization of Japanese research.

- The committee recommends that NIFS should assess effectiveness of each agreement and should better activate selectively the substantial number of exchanges of researchers and collaboration research based on the assessment.

Perspective 6 Was human resource development tackled together with universities and other organizations to achieve results?

- NIFS has instituted an educational system that contributes toward developing human resources in the plasma and fusion science community. In addition to Department of Fusion Science in *SOKENDAI*, NIFS has formed cooperative laboratories based on the agreements with partner graduate schools of Nagoya University, Kyushu University, and the University of Tokyo, which provide the graduate students in these universities with the opportunity to study under the excellent environment of NIFS.

- The special research fellowship/postdoctoral programs are expected to make a significant contribution to the development of the next generation of researchers in fusion-related fields and are highly regarded.

- The committee notes that the activities of postdocs do not reach the commendable level. The number of JSPS research fellows (the PD levels) has been zero in the last few years. These facts show that NIFS has failed to provide attractive career paths to the young scientists compared with well-known scientific institutes overseas. To maintain the high-level standards and the vitality of the institute in the plasma-fusion research field, it is essential to keep the constant entry of new talented researchers into the community. The committee recommends that NIFS should take measures to improve the situation.

- The committee recommends that NIFS implements education and human resource development responding the demands of the future fusion science activities.

Annex A. List of Members of External Peer Review Committee

Main Body of the External Review Report in FY2021

In the external peer review of the "Large Helical Device Project, the Numerical Simulation Reactor Research Project and the Fusion Engineering Research Project" in FY2021, the perspective of the evaluation is set as follows for the 3rd Medium-Term Plan (April 2016 – March 2022). Each item of the perspective is based on the evaluation of the validity and achievement of research and other activities carried out by the National Institute for Fusion Science (NIFS) as an inter-university research institute.

Perspective 1 Were the goals set appropriate from the perspective of the National Institute for Fusion Science, and have they been appropriately updated in light of research results and research trends, and have the corresponding measures been taken accordingly?

Findings/Evaluation

- Goals of the LHD project (LHDP) and its validity to perspective of NIFS

In the 3rd Mid-Term Plan, NIFS has set two major goals: 1) realization of high-performance plasmas and 2) comprehensive understanding of toroidal plasmas. These are absolutely necessary to realize D-T fusion reactions. It is appropriate that the specific plans related to the LHDP were made to improve facilities of plasma control, heating, diagnostics, and safety management to realize high-performance plasmas and to carry out deuterium experiments as academic research. This is in line with the goals stated in the 2003 report of the Fusion Working Group of the Academic Committee
[https://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu4/toushin/1213875.htm]
(Chair: Yoichi Suematsu)
(https:// (www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu4/toushin/attach/1337713.htm).

Furthermore, the plans of the LHDP were set appropriately for NIFS to advance fusion science on core plasma physics, together with the other two projects of NIFS; the Numerical Simulation Reactor Project (NSRP) and Fusion Engineering Research Project (FERP). The LHDP serves as the core of the NIFS research enterprise to advance the frontiers of helical plasma performance and reactor-relevant plasma physics, while the other two projects build bridges needed between the current LHD regimes and future fusion reactors.

The committee seriously notes that the budgetary support for the full operation of LHD will end in FY 2022.

- Achievements in LHD plasma performance

  On the LHDP, outstanding progress has been recognized over the past years on key aspects of reactor-relevant plasma physics and performance in terms of plasma parameters, which shows the feasibilities of a helical fusion reactor. This research portfolio is consistent with the vision of a path towards helical type reactors, whose issues are closely related to that of tokamaks, although some of the aspects are different.

  In the past years, the expansion of the neutral beam injection system and other heating devices to enlarge the plasma operation area, the expansion of the vacuum pumping system to improve the neutral particle recycling function, and the implementation of appropriate measures such as the development of neutron measurement is also commendable. As a result, high-performance plasmas with ion temperatures of 120 million degrees were achieved in deuterium plasmas, and a variety of operating regimes were developed, and the understanding of toroidal plasmas from various perspectives is commendable.

  On the other hand, although the goal of realizing ion temperatures of 120 million degrees has been achieved, it is necessary to elucidate the reason of degradation of ion temperature above moderate density compared to the experimental results of the other similar size helical device, W7-X. Such research is essential for the realization of an attractive fusion reactor and is one of the important tasks of NIFS. In addition, the most important parameter of D-T fusion is well-known as triple product and its sustainment. The compatibility between high ion temperature T_i and high electron temperature T_e is a target for fusion reactor. In that sense, the theoretical and numerical research to understand the region of $T_e / T_i > 1$, which may help to provide a route, that involves a form of highly nonlinear self-organized process, to reach such a regime.

- Change in research strategy of the LHD Project (LHDP)

  The focus of research to the science of realizing a fusion reactor is highly regarded while promoting collaborative research, especially the hydrogen isotope effect in deuterium experiments, in view of the era of burning plasmas, when fusion research is directly related to the reactor. It is also highly regarded to start open access of LHD data since the participation of the international research community in NIFS collaborations is extremely important. It is also highly appreciated that NIFS is promoting interdisciplinary collaborative research with fields other than fusion and space plasma, expanding the scientific activities of the LHDP, and contributing to a wide range of academic fields.

- Numerical Simulation Reactor Research Project (NSRP)

  The NIFS has set a strategy to systematize nuclear fusion under the title of “comprehensive understanding of toroidal plasma” by promoting the reach of a helical system using LHD as the primary project and associated scientific and engineering bases of a helical reactor incorporated with NSRP (Numerical Simulation Reactor Research Project), which is based on simulations using a supercomputer through collaboration with universities and related institutes. Under this strategy, the main goal of NSRP for the 3rd Mid-Term Plan is to advance the simulation studies for the whole device by developing various simulation codes from core to edge plasmas and plasma facing wall and to construct the numerical simulation reactor (NSR). To achieve them, NSRP organized following subjects, 1) updating the Plasma Simulator (supercomputer system) and developing various three-dimensional simulation codes mentioned above, 2) constructing models of turbulent transport in the core plasma and applying them to the integrated transport code with including multiple ion species effects, 3) developing the molecular dynamics (MD) simulation techniques for evaluating the physical properties of complex plasma facing materials, 4) improving code accuracy by verifying and validating with the experimental results, and 5) conducting various simulation studies on related basic physics.

The basic design of the plan is meaningful and then adequate as a whole, which integrates the research activities of theory and simulation group at NIFS and promotes an organized research program to achieve the goal of the NSRP. Actually, it covers a wide range of relevant research areas consistent with the perspective of the NIFS. The NSRP has gotten visible results for evaluating and predicting key physics processes in toroidal plasmas incorporated with the development of various theoretical models, which include gyro-kinetics theory, multi-species collision modeling, methodologies for representing multi-scale interaction, key numerical schemes, etc. One of excellent key works is a recent result comparing characteristics of neo-classical and turbulent transport in LHD and W7-X, which could affect the selection of the optimal magnetic structure for future helical reactors. They have been appropriately updated in light of their own research results and research field trends, and the corresponding measures have been taken accordingly. More specific targets are summarized in item 3-2 for the NSRP, such as modeling of turbulent transport in core plasma, application of the model into the integrated transport code, incorporation of multiple ion species effects, and improvement of MD simulation techniques for plasma-material interactions, which are also highly regarded.

It is also an important mission for NIFS to collaborate with other academic science fields by generalizing results obtained in fusion plasma research as theoretical-numerical research center within NIFS. In item 3-3 for the NSRP, the describes accuracy improvement of each code and conducting simulation researches related to basic physics. It is commendable for the NSRP to have performed these efforts continuously by taking science-oriented approach in the requirement and gotten results through the collaboration with domestic universities and institutions (see item 4) also through various international collaboration programs (see item 5).

Meanwhile, NSR aiming at evaluation and designing future reactor as the whole device is very ambitious project. However, some goals are too generic, and some others too specific but narrow. Therefore, it is not so clear if the mentioned specific areas of higher priorities or area for urgent improvement with respect to the number of research staffs (30 researchers) involved in the project. Namely, a tendency can be seen that the problem setting is too large, so that the project timeline and/or milestones to achieve the goal is hardly related or matched to individual research levels and situations, while it is understandable under the requirement for promoting a variety of scientific researches being based on ideas of individual researchers.

- Fusion Engineering Research Project (FERP)

It was confirmed that at the beginning of the 3rd Mid-Term Target Period (FY2016) the following emphases were placed:

(a) Collaborative use of the facilities, started in 2015, was of high priority for enhancing activities in universities.
(b) Summary of reactor design and definition of numerical targets were scheduled.
(c) Engineering designs of prototype of superconducting magnet and liquid blanket were targeted, based on the tests to be carried out using the newly installed facilities.
(d) the following items were considered:
    (1) Knowledge base for the establishment of standards and criteria.
    (2) Academic research roadmap for helical fusion reactor development.
    (3) Systematization of fusion engineering.
    (4) Contribution to interdisciplinary research.
    (5) Expansion and promotion of related technologies to industry”.

It was also confirmed that according to the internal discussion in 2017, the following research objects were added:

(1) Comparison with Tokamak DEMO design.
(2) Reinforcing links between the reactor design and research and development.
(3) Tritium handling technology for supporting LHDP.
(4) Focusing R&D efforts of magnets on High Temperature Superconductor (HTS) options.
(5) Further emphasis on contributing to ITER, BA, and DEMO.

From the viewpoint of superconducting magnet development, the committee highly appreciates that "close and appropriate collaboration between reactor design and R&D of elemental technologies for magnet development" which is a characteristic of R&D at NIFS, was carried out, and the targets (size, power, magnet requirements, etc.) set in the R&D process were also precise. In this context, the application of HTS conductors was considered from an early stage, and the conductor structure design and basic characteristics evaluation were carried out in an engineering and academic perspective in accordance with the targets set for the REBCO-based coated conductor, which currently has the best characteristics, and which is expected to have a ripple effect. This is because the Force-Free Helical Reactor (FFHR) concept had adopted HTS as the primary option due to their worldwide progress. Specifically, the development of an HTS/liquid hydrogen cooling system could accelerate the transition to a future Hydrogen Society. The goals set in the current reactor design (FFHR-b3: Small Helical Fusion Reactor) are also in line with the global trend of compact fusion development.

In addition, focusing on consistent "design research" and "research and development for the construction of engineering basis", the target has been appropriately prioritized and reviewed, such as at the start time of the 3rd Mid-Term Target Period, at external evaluation in FY2017, and at the time when the MEXT roadmap was shown. In particular, compiling the academic research roadmap of helical fusion reactor in a report is a wonderful goal setting for NIFS. It is also worth noting that NIFS made academic efforts to build a common engineering basis that transcends the reactor shape, including a link to the MEXT roadmap.

These findings are evaluated as excellent.

Recommendations

- Research results accumulated from the LHDP in the past must be integrated as basic physics insights which should provide the international community with guidance for the next steps in the research of fusion science. The committee recommends that NIFS seeks for measures to resolve remaining important scientific issues posed in the LHDP, in particular, clarification of preventing mechanism for high-performance plasma in light of LHD and W7-X experimental results over the last few years.

- New research goals and projects in NIFS must be defined through thorough discussion in the whole plasma and fusion science community, and NIFS should take a responsible role to realize it.

- At the end of the present LHDP in FY2022, it is more appropriate in the future that the NSRP properly self-assess its current status and designs medium-term goals based on a long-term strategy by organizing those with some logical hierarchy and classification according to scientific themes and further deepening of strategic, quantitative, and verifiable goal setting according to the following aspects.
  1) The goals of NSRP are desirable to be more science-oriented including those in choosing other option of operating as a research institute responsible for wider plasma and fusion science including tokamaks and alternatives, but by setting more specific subjects and goals, based on which various specific projects and improvements of facilities should be been planned,
  2) The verification and validation of simulation codes through the comparison with experiments are crucial for the construction of the numerical simulation reactor. In order to achieve this, it is desirable to set quantitative goals regarding what to compare and how much to improve reproducibility and predictability.
  3) It is highly appreciated to start optimization research toward a new concept of magnetic

confinement, following the proposal in the Review Comments 2019. It is also required to properly select key performance indicators (KPI) for self-evaluation of the research level of the project, and to set objectively verifiable goals.

- In future, targets of the FERP in NIFS should move to more fundamental fusion engineering applicable to various types of reactor concepts based on excellent research results in NIFS so far. In addition, more efforts should be placed on expansion and promotion of related technologies to interdisciplinary research and industrial applications.
- The scientific targets seem to have been too much focused on LHD-related science. Such focusing may have unintentionally excluded wider interests in the fusion and plasma science community, including the ITER project, plasma physics in astrophysics or particle-hadron physics, fluid dynamics, mathematical science, etc. The committee recommends NIFS to consider this point for the next step.

Perspective 2 Have sufficient results been produced as an inter-university research institute in the academic field?

Findings/Evaluation

- As an inter-university research institute, NIFS has steadily promoted more than 500 projects of the LHD Project Collaboration Research, Bilateral Collaboration Research, and General Collaboration Research. These activities are excellent. It is also excellent that NIFS has added joint research on DEMO reactor research and development in cooperation with QST toward the realization of the burning plasma era or actual fusion reactor. The total number of collaborators is more than 1,500, of which about 200 are overseas researchers. In addition, about 500 graduate students are participating in the project, and it is fulfilling its mission as an international center and educational center. More than 50 academic papers have been published as a result of joint research (about 75 in 2018), and NIFS provides support for submission fees. The number of first-author presentations at the 2020 IAEA-FEC conference (held biennially), which is considered important in the field of fusion science, is 20 within the institute and 5 by joint researchers.
- In summary, the function as an inter-university research institute for the academic community is excellent.
- Academic achievements as an inter-university research institute in the LHDP

  A large number of outstanding physics results have been obtained from the LHDP over the past several years. They cover all important aspects of plasma physics and operations relevant to fusion reactors, including isotope effect, confinement and transport, control, and plasma-wall interactions. They impact greatly the ongoing research around the world. The results were enabled by the comprehensive set of LHD diagnostics, the controllability of LHD plasmas, and the excellent research team.

Examples of results useful for magnetic confinement, in general, are the isotope effects on transport barriers, turbulence spreading which leads to reduction of divertor heat loads, isotope mixing by micro-instabilities, and the effect of Alfven eigenmodes on fast particles. Each of these results links a fundamental physics process to very practical issues for fusion.

Two results that are particularly critical for helical systems are the confinement of energetic (MeV) ions and the thermal transport which is highlighted in the comparison between LHD and W7-X, showing the tradeoff between neoclassical and turbulent transport. These two issues – energetic particle confinement and thermal transport – are key to the future of helical systems. These results have important implications for future stellarator design, and can possibly lead to further development.

- Publication status of academic journals from the LHDP

There is a number of excellent papers published in high impact factor journals, such as Physical Review Letters, Nature, Nuclear Fusion on isotope mixing effect and confinement scaling, plasma-wall interaction, plasma detachment, turbulent spreading, direct measurement of Landau damping, interchange/tearing transition. Many review papers on tokamak and helical experimental comparisons (Ida, AdvPhysX2020, Ida&Fujita, PPCF2018, Conway, Smolyakow&Ido, NF2022, Ida, RMPP2022, Ida&Rice, NF2014, Shaing, Ida&Sabbagh, NF2015) are excellent to clarify commonality and difference between two toroidal magnetic confinement geometries.

However, the number of published papers is low. The number of published papers divided by the number of the researchers in a year under evaluation is about 2, which is smaller than the expected values (> 4) as the international core research center in this field.

- Collaborative research with universities and other research institutions in the LHDP

Good opportunities to use the LHD facility are provided to Japanese scientists in universities and foreign scientists. Although for some scientists it has been difficult to visit the LHD facility due to the COVID-19 pandemic, NIFS has made good support for them to carry out the experiment remotely. Those actions are outstanding.

- Numerical Simulation Reactor Project (NSRP)

As a part of the missions prescribed in the 3rd Mid-Term Plan of the NSRP, the collaborations with domestic and foreign universities and institutions play a crucial role in maintaining the substantiality, continuity and diversity of the NIFS's total academic research projects as an inter-university research institute. The list of the projects of NSRP's collaboration research programs posted in the web information, https://www.nifs.ac.jp/collaboration/2021_general-subject.pdf (Japanese) demonstrates that a wide variety of cross-disciplinary studies have been accepted. Actually, the number of NSRP collaboration projects amounts to one third of the total number in the General Research Collaboration Research. The application system has been properly designed and categorized to manage both of the qualitative and quantitative aspects of collaborations and to keep the system working. As the main achievement of such collaborations, the following high-level achievements are worthy to be noted:

- Gyrokinetic simulation studies on turbulent transport and zonal flows.
- Hybrid(Kinetic + MHD) simulation studies on instabilities.
- Multi-hybrid (Binary Collision + Kinetic Monte-Carlo + Molecular Dynamics) simulation studies on plasma-facing material.
- MEGA code that has succeeded in reproducing the LHD experimental results demonstrating the maintenance of high beta plasma.

To enhance the collaboration with domestic and foreign universities and institutions, the NSRP has actively arranged the workshops and the plasma simulator symposium, which functioning well to present and exchange state-of-the-art results in the fusion and plasma research areas. With such great efforts, the number and the quality of these events are maintained so that the NSRP has succeeded in enhancing and promoting the research collaborations. It is desirable to maintain such activities open for researchers in all over the world.

The NSRP has accepted a wide variety of cross-disciplinary studies through the collaboration research programs. Actually, the range of the themes is wide, however, the subjects of the accepted programs seem limited within the range of the intramural researchers' expertise and interests. Furthermore, there is an obvious tendency that subjects related to the LHDP have been more likely to be selected. It was natural since the LHDP is the main goal of NIFS. As a leading institute of fusion-plasma sciences as well as an inter-university research institute, the NSRP could have played more active role in cultivating diverse research fields to promote interdisciplinary researches and to keep the NIFS's leading status in wider areas in the fusion and plasma sciences.

- Fusion Engineering Research Project (FERP)

It was confirmed that the collaborative use of the main facilities such as (a) SC magnets, (b) Liquid blanket, (c) Advanced materials, (d) Tritium, and (e) High heat-flux components, was positively promoted. Research activities using the facilities have produced many results and papers.

For helical fusion reactor design, a staged approach was employed to make technical discussion for advanced options, after the conceptual design of helical fusion reactors was summarized in 2016.

For development of the superconducting magnets, the development of conductors compatible with high magnetic field, high current, high current density, and high mechanical strength was promoted by introducing high-temperature superconductors ahead of the rest of the world in anticipation of the progress of research. In particular, research on superconductor materials such as MgB2, for future superconducting coils for fusion reactors, and evaluation of mechanical and electromagnetic properties of REBCO coated conductor were conducted in collaboration with many universities.

It was recorded that the number of collaborations increased from 2015 to 2017 (extension of the collaboration by use of the facilities) and declined in 2020 (COVID-19).

In particular, in 2017-2019, there were 70-80 collaborations and 200-350 collaboration people. Remote-experiments were also carried out to minimize the COVID-19 negative effect on the research activities in 2019-2020.

The number of scientific publications is constantly high throughout the entire period of evaluation. The absolute number and the quality (in terms of citations) are rated at a top level in comparison with other world leading fusion laboratories. The number of published papers from FERP since 2016 are 496 with 40 of top 10% papers. In addition, the number of international coauthors increased by 20% in 2019-2020 compared to that in 2017-2018, and by 70% compared to that in 2016.

Therefore, on the basis of the findings and evaluation mentioned above, NIFS made an outstanding contribution to research activities in the academic fields from the viewpoint of the role as an inter-university research institute.

Recommendations

- NIFS, as a core institution for inter-university research, needs to strengthen its functions related to fusion research at universities and to promote research using international-level experimental devices, which are difficult to be conducted at universities. In addition, it is necessary to strengthen cooperation and interactivity with budding and original research using small-scale devices that universities are good at.
- World’s high-level experimental equipment is also extremely important from the viewpoint of human resource development, as it provides an environment in which excellent young researchers can place themselves at the forefront of research.
- For more open and flexible collaboration research programs, the scope of the collaboration researches needs to be extended from the current one centering highly at the LHDP to more diversified areas covering the whole plasma-fusion sciences. There seems a big room for improvements in the application and selection categories and processes to achieve the genuine interdisciplinarity.

Perspective 3 Were sufficient results obtained from the viewpoint of the following special notes in the 3rd Medium-Term Plan?

3-1 for LHDP Deuterium experiments are carried out by upgrading facilities of plasma control, heating, diagnostics, and safety control to further improve the performance of the Large Helical Device (LHD) for systematization of physics and engineering of helical systems and comprehensive understanding of torus plasmas.

Findings/Evaluation

- Upgrading for deuterium experiments on LHD

The LHDP has been promoted by a proper machine operation on every item and the machine operation plays an essential role in achieving performance with deuterium. In fact, 99.996 % of the planned operation of the SC coils has been executed and 92.475% of the planned discharges have been completed.

The D-D plasma operation has been executed under rigorous safety management based on both the Japanese law and the agreement with Toki and Tajimi cities and Gifu prefecture. Actually, there is no radioactive accident during the LHD operation and the safety management is adequate. The handling of tritium is an important issue in deuterium experiments, and the tritium recovery rate of more than 95% has been achieved. The outstanding records of safe and effective nuclear operations of large facilities like LHD deserve special recognition from fusion researchers around the world as such a unique experience is invaluable for the development of fusion reactors and also for similar facilities in many other fields of science and engineering.

The increased heating power, a closed structure divertor, and a new vacuum pump were introduced, which were commendable for improving the LHD performance. In the negative ion source NBI (Neutral Beam Injection), an increase in the fraction of electrons in the beam current drawn from the negative ion source has been avoided by installing an electron fence made of molybdenum rods near the plasma grids. These findings are very useful for future fusion devices such as ITER. The ECH (Electron Cyclotron Heating) operation is commendable, but compared with the situation in W7-X, the ECH system for LHD has room for improvement. The ECH system in ITER is scheduled to be operational from the beginning of the experiment, and NIFS will be able to contribute to technological development. The ICRF (Ion Cyclotron Resonance Frequency) has the capability of pulse input of more than 1 MW and steady-state oscillation of more than 0.5 MW per unit, which makes it possible to perform high-power injection experiments in the world. The ICRF system operation is commendable. The introduction of a closed-divertor and a new type of optimized vacuum pump to realize a low-recycling environment is also commendable for the high performance of the plasma.

Many excellent diagnostics are developed. Especially, CXRS (Charge eXchange Recombination Spectroscopy), FIDA (Fast-Ion D Alpha), 2D-PCI (2-Dimensional Phase Contrast Imaging), HIBP (Heavy Ion Beam Probe), fast Thomson scattering system, ICE (Ion Cyclotron Emission), and the wide energy range neutron detection system are highly regarded and are expected to be internationally applied.

- Systematization of physics and engineering of helical systems and comprehensive understanding of torus plasmas

There are many results for comprehensive physics understanding in toroidal plasmas. Three highlight results, 1) Isotope mixing, 2) Turbulence spreading, 3) Direct measurement of Landau damping are published in high-impact journals. Energetic-ion-driven resistive interchange mode (EIC) has a significant impact on plasma performance and burning rate. The stabilization of EIC has been achieved by ECH due to its stabilizing effect on $m/n=1/1$ mode. The tongue deformation gives a new trigger mechanism of MHD bursts which are commonly observed such as ELMs (Edge Localized Modes) in tokamaks and solar flare in astrophysics. Lowering recycling with boron (B) powder drop was observed and the turbulence level of density was reduced after the B powder drop. The relevant achievements are excellent. The deuterium experiments led to outstanding results, including detailed and very important results on isotope-mixing and non-mixing turbulence, and the equally important result that the confinement of deuterium and hydrogen plasmas is almost identical, as expected from turbulent transport, but unexpected for neoclassical transport.

While Atomic Energy Commission (AEC) report (2005) recommended exploitation of optimization of helical magnetic configuration, termination of the present LHDP will make it difficult to convert to an advanced helical system for a further comprehensive understanding of toroidal plasmas. In this sense, configurational exploitation has been insufficient.

The committee considers that the remaining LHD experiment should be organized to focus on the research being only possible in the present LHD since the stellarator/heliotron concept offers unique and highly important advantages at the reactor stage and LHD is in a unique position right now, to significantly accelerate the understanding of reactor-relevant physics phenomena, in key areas which will not be explored in the next few years in W7-X.

Recommendations

- The knowledge of the heating and measurement devices developed for the deuterium experiments in LHD is expected to contribute sufficiently to the next fusion devices such as ITER. Furthermore, as for the systematization of physics and engineering of helical systems, further comparison with W7-X is highly recommended. There are many results for comprehensive physics understanding in toroidal plasmas, and some of them cannot be expressed by the present well-known academic frame. When an academic frame is newly developed, the knowledge becomes to be a comprehensive physics understanding.

3-2 for LHDP Achieve 120 million degrees by the end of the 3rd Mid-Term Target Period and realize ultra-high performance plasmas that can be extrapolated for use in a fusion reactor.

Findings/Evaluation

- Achievement of 120 million degrees by the end of the 3rd Mid-Term Target Period

  The realization of high-temperature plasmas with an ion temperature of 120 million degrees in the helical device by optimizing the neutral beam heating system and the generation of high-temperature plasmas with both ion and electron temperatures reaching 100 million degrees are highly regarded.

  The goal for the peak ion temperature has been already obtained ahead of the 3rd Mid-Term Target Period and the LHD team should be congratulated on this achievement. The 120 million degrees were reached in a number of discharges, albeit at low densities. T_i / T_e values close to 1 were reached with simultaneous electron and ion heating. These results shed light on confinement scalings with regard to temperature and temperature ratio and therefore add to our understanding of and ability to extrapolate to a fusion reactor.

- Realization of ultra-high performance plasmas extrapolatable for use in a fusion reactor

  The realization of ultra-high performance plasmas that can be extrapolated to fusion reactors is poor because the direction to reach more reactor-relevant conditions from either the high-density region or the high-temperature region, which are currently realized in the LHD, is not clear in the Lawson diagram. The committee observed the following points.

  a) Energy confinement: Revised energy confinement scaling (PRL2019) with strong power degradation ($\tau_E \propto P_{abs}^{-0.87}$) gives a pessimistic prospect of energy confinement at high temperatures. High Lawson parameter $n_i(0)\tau_E$ at least 100 times more than achieved in current LHD is needed to access breakeven conditions at those high-temperature plasmas. Of particular interest is the observed decrease in energy confinement at extremely high temperatures. Identifying the cause for the decrease is a significant and important challenge and a possible avenue for near-term research. The slow transition between weak temperature-degradation state ($\tau_E \propto T^{-0.5}$) and strong one ($\tau_E \propto T^{-1.5}$) is mentioned related to low nτ_E at high temperature. However, it is not clear how it relates to strong power degradation of scaling ($\tau_E \propto P_{abs}^{-0.87}$) which implies $\tau_E \propto T^{-6.7}$. Resolving those physics questions could be an important LHD research subject of the remaining year.

b) High density/temperature operation: Confinement performance of LHD and W7-X appears to be comparable at low densities of 1.5×10^{19} m^{-3}. According to Warmer's paper, neoclassical transport dominates in LHD, while turbulent transport dominates in W7-X. At the high density of 7×10^{19} m^{-3}, confinement degradation is observed in LHD compared to W7-X because $T_e = T_i \sim$ 4 keV at 4.5 MW in W-7X while T_e = 1 keV at 2 MW in LHD. This is one of the key observations for finding a path to fusion in helical devices. There are many efforts to understand the observation and the committee believes the efforts will bear fruit in near future. Improved confinement with ETB during detachment with RMP application in deuterium plasmas is practical for fusion reactors. In this plasma, a reduction of core impurity emission was also detected. An additional combination of ECH and Ne puff leads to the compatibility of good core confinement and detached divertor. This is a promising result for extrapolation to a fusion reactor. Newly-developed simulation code, KTM2 can reveal the mechanism of the X point cooling in the plasma applied to RMP.

c) Critical T_e / T_i Ratio: Identification of critical $T_e / T_i \sim 0.75$ for T_i clamp threshold in LHD is a substantial observation while it is rather pessimistic for reactor application. Since $T_e / T_i \geqq 1$ is expected in future fusion reactors under conditions where electron heating by alpha particles will be dominant, it is an important issue to elucidate the factors that cause the decrease of the central ion temperature under high electron temperature conditions.

d) Geometrical optimization: Three-dimensional helical magnetic confinement geometry has a huge opportunity for optimization other than the current LHD configuration. Therefore, the realization of ultra-high-performance plasmas that can be extrapolated for use in a fusion reactor may require major upgrades/modifications of LHD.

Recommendations

- In the remaining experimental period, it is expected that the experimental research to clarify the access method to the more reactor-relevant condition will be promoted. It is also desirable to accelerate the international collaboration with W7-X to investigate the difference in experimental results between the two devices and to establish a methodology to produce ultra-high performance plasmas that can be extrapolated to a fusion reactor in a helical device.

3-3 for LHDP Hydrogen isotope effects on the formation of internal transport barriers of ions and particle recycling characteristics in deuterium

discharges is verified through academic research based on collaboration.

Findings/Evaluation

- Verification of isotope effects on confinement and transport

  Favorable experimental results on isotope effects on confinement and transport have been obtained and documented based on collaboration, with new theoretical questions to be further investigated. New excellent results have been obtained on the isotope effects on the ion and electron transport in discharges exhibiting internal transport barriers, which are important for the extrapolation to the fusion reactor conditions. As for the formation of electron internal transport barrier (electron ITB), the threshold power normalized by density for the formation of electron ITB is lower in deuterium plasmas than in hydrogen plasmas. The threshold power for the transition to the improved confinement state of the local diffusion coefficient was found to be significantly affected by the isotope effect. As for the ion ITB formation, the reduction of ion heat transport was observed in deuterium plasmas, and the physical mechanism was clarified by linear and nonlinear transport calculations based on gyrokinetic theory. These excellent results clearly show the hydrogen isotope effect on the internal transport barrier, which is highly appreciated.

- Comparative experiments of neoclassical and turbulent transport

  Excellent results have been obtained, such as comparative experiments on neoclassical and turbulent transport in LHD and W7-X, the relation between ion ITB and electron density distribution and T_e / $T_{i,}$, achievement of divertor detachment, and observation of confinement improvement by peripheral control, and confinement improvement by impurity powder drop.

Recommendations

- Interesting phenomena related to hydrogen isotope effects have been observed, such as isotope dependence of internal transport barriers of electrons and ions, and isotope mixing. The isotope effect on the P/n_e dependence of the internal transport barrier can be considered as an outstanding achievement in understanding the physics of the internal transport barrier because of the isotope effect on the radial electric field formation or turbulent transport. Further research is recommended to clarify the underlying physics mechanism through the comparison with theory.

- The hydrogen isotope effect on the energy confinement time is about M^0-$M^{0.2}$, and the mass number dependence is weaker than that of tokamaks. In tokamaks, it is known that the improvement in energy confinement time is about 1.1-1.4 for LOC (Linear Ohmic Confinement), 1.4-1.5 for SOC (Saturated Ohmic Confinement), 1.2-1.6 for L-mode, and 1-2 times for H-mode. The differences in the isotope effects from tokamak provide LHD a unique opportunity for a systematic study to investigate the underlying physics. Elucidation of the isotope effect is one of the most important issues for understanding fusion plasmas, so further study is needed.

- Although LHD has a variety of turbulence measurement systems such as DBS (Doppler Back Scattering), BES (Beam Emission Spectroscopy), ECEI (Electron Cyclotron Emission Imaging), and HIBP measurement, they do not seem to work well organically for turbulence measurement. It seems necessary to analyze turbulence from the long to the short wavelengths simultaneously to clarify the isotope effect. It is suggested that a group-wide effort should be considered in the next cycle experiment.
- One of the important issues in the divertor and edge plasmas is to clarify the hydrogen isotope effects in the molecular activated recombination processes, which are important for the formation of detached plasmas. In LHD, maintenance of high-performance core plasma and formation of detached divertor plasma has been realized simultaneously. Therefore, it is desirable to take advantage of this experimental environment to clarify the hydrogen isotope effect of detached divertor plasma formation.

3-1 for NSRP Effectively using the supercomputer system, the Plasma Simulator, for construction of the Numerical Simulation Reactor, research for development, extension, high precision, and the integration of the simulation codes for the whole device from the core plasma to the peripheral plasma and plasma facing wall is advanced. During FY2019, the performance of the Plasma Simulator is improved more than four times compared to the current system, and various three-dimensional simulation codes for the improved system are optimized.

Findings/Evaluation

- Plasma Simulator (NIFS supercomputer system) was upgraded in July 2020 as it was delayed one year from the original schedule due to achieving the target performance, and the new system was then fully utilized in the development and operation of the various simulations, achieving its original purpose. Development, extension and integration of various simulation codes for reactor-relevant research have been achieved in most target areas. In particular, the following results are highly regarded as notable achievements.

  1) Integration of kinetic energetic particles (EP) and MHD physics using a hybrid code MEGA has been further extended to elucidate the thermal ion-wave resonant interaction and associated energy channeling as well as self-organized distribution function resulting from the resonant overlap of multiple Alfven-Eigenmodes. These studies significantly contributed to the understanding of phase space turbulence and the successful operation of helical reactor plasmas

(e.g., Todo et al. 2016, Todo et al. 2017, Wang et al. 2018). It is also highly regarded that this research has contributed to the publication of excellent international co-authored papers (e.g., Garcia-Munoz et al. 2019, Taimourzadeh et al. 2019).

2) An integrated transport analysis suite TASK3D-a has been extended and successfully used for validations against LHD experiments. In particular, isotopic dependence of transport has been thoroughly analyzed enhancing understanding of this important subject (e.g., Yamada et al. 2019). This also contributed to successful helical reactor design (e.g., Goto et al. 2017, Goto et al. 2019).
3) Regarding configuration optimization targeting next generation helical systems, turbulence-zonal flow modeling for novel nonlinear optimization methods is producing promising results based on a systematic approach (rather than on ad hoc saturation rules adopted elsewhere) effectively utilizing strengths of gyrokinetic GKV code. In particular, it is highly regarded that gyrokinetic simulations of Trapped-Electron-Mode (TEM)-driven turbulence in three-dimensional magnetic configuration of helical plasmas with hydrogen isotope ions and real-mass kinetic electrons are realized (Nakata et al. 2017). It is also highly regarded that the GKV simulations well contributed to high-T_i and high-T_e isotope plasmas in LHD (e.g., Takahashi et al. 2018, Nakata et al. 2019). It is also commendable that an optimization scheme and codes for coils and magnetic configurations are newly developed for exploration of a novel concept of magnetic confinement.
4) It is notable that EMC3-EIRENE modelling contributes to the understanding of edge impurity transport in the stochastic layer of LHD (e.g., Dai et al. 2016, Kawamura et al. 2018). Since the fluctuations and turbulent transport in the edge (SOL/divertor) plasma is one of the important topics for the fusion research, a more organized research program on the edge transport may need to be promoted.

Recommendations

- The committee highly appreciates the significant contributions of the NSRP to the LHDP and fusion science by conducting a number of advanced simulation studies as described above. However, the committee worries that the top 10% paper rate of the NSRP is 6.7%, which is below the international average. Also, the average international co-authorship rate is 39.1%, which is not high enough for an international research institute. The committee hopes that the NSRP will extend the study by advancing the cooperation with wider disciplines and more activating international joint research.

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3-2 for NSRP Modeling of turbulent transport in core plasma and the application of the model into the integrated transport code are completed by the end of FY2019, and the incorporation of multiple ion species effects into various transport codes is done by the end of the 3rd Mid-Term Target

Period. Furthermore, by the end of the 3rd Mid-Term Target Period, molecular dynamics simulation techniques are developed by improving programs and building new models necessary for evaluating the physical properties of plasma facing materials such as tungsten.

Findings/Evaluation

- Turbulent transport of particles, momentum, and heat in the high temperature core plasma influences confinement performance of magnetic fusion devices, and plays leading roles in formation of zonal flows, electric field structures, and density and temperature profiles. Towards performance prediction of large-scale fusion experiments, such as ITER, elaborate efforts have been devoted to numerical simulation studies on the plasma turbulent transport and their verification and validation activities worldwide. The NSRP also follows the research trend, and has made several important achievements in studies of turbulent transport in the LHD plasma. It is noteworthy that quantitative evaluation of transport for non-axisymmetric (helical) devices with three-dimensional field configuration, such as LHD, is accompanied with qualitatively different difficulties compared with those for axisymmetric (tokamak) systems. This is because not only the turbulent transport but also the neoclassical transport should influence the plasma confinement, where the three-dimensional field configuration complicates the numerical modeling. In spite of these difficulties, the NSRP successfully promoted the state-of-the-art in the transport research for helical systems, and produced the internationally visible research outcomes (e.g., Nakata et al., PRL 2017, Ida et al., PRL 2020, and Warmer et al., PRL2021).

- More specifically, there have been sufficient results obtained in the areas of turbulent transport modeling in core plasma, its application into the integrated transport codes and the incorporation of multiple ion species effects into various codes. The following high impact results are noteworthy.
  1) Well-coordinated joint research between the NSRP and the LHDP on the isotopic dependence of turbulent transport led to internationally visible research outcomes which will contribute to successful design of future helical reactors. A possible mechanism of isotope effects in turbulent transport leading to the confinement improvement was predicted in prior to the LHD deuterium experiments. In this campaign, high resolution capabilities of phase-space dynamics in GKV code and of reliable fluctuation and profile measurements in LHD were essential in identifying the crucial role played by zonal flows.
  2) Turbulent transport modeling has also made a progress by means of a statistical approach including the zonal flow response, which leads to a new research activity to create a novel confinement concept through optimization of turbulent transport and zonal flows. Based on gyrokinetic simulation GKV, two types reduced transport models were proposed (that is, the heat diffusivity model and the quasi-linear flux model), which may contribute to reduction of the computational costs. The quasi-linear model combined with the gyrokinetic simulations and

the zonal flow response has been incorporated into the integrated code TASK3D, and is utilized for the validation research against the LHD experiment, yielding successful and highly visible results as stated in sec. 3-1 for NSRP.

3) Intricate interplay between turbulence and neoclassical transport has been identified. An impressive example is simulations of the impurity hole in LHD using GKV and FORTEC-3D codes, which provides an insight into the formation mechanism. In addition, extension of gyrokinetic simulations using global codes is in good progress with promising initial results.
4) The major achievements listed above rely on multiple ion species extension of the simulation codes that includes their mutual interactions while maintaining conservation laws. Incorporation of multiple ion species effects is completed into the drift kinetic code FORTEC-3D, GNET, the gyrokinetic code GKV, and the integrated transport code TASK3D. As a result, a quantitative balance was discovered between turbulent and neoclassical heat fluxes. This provides a large contribution to resolution of impurity hole effect as discussed above.
5) Several research progresses have also been made in relation to simulation studies of plasma facing material and plasma-neutral transport in the peripheral region. A multi-hybrid simulation technique was developed on the basis of binary collisions, kinetic Monte-Carlo, and molecular dynamics methods. As a result, formation process of tungsten "fuzz" nano structures caused by helium plasma irradiation was realized by simulation. Moreover, a recycling model was constructed for hydrogen plasma-wall-interaction on tungsten wall on the basis of molecular dynamics. As a result, a reaction process of emission of molecular hydrogen on the tungsten surface was discovered. In addition, a coordinated collaboration of a plasma-neutral transport code, EMC3-Eirene code, and the LHD diagnostics has demonstrated reproduction of radiation power profiles of H and H_2 in LHD.

Recommendations

- These traditional strengths of NIFS/NSRP in the field of turbulent and neoclassical transport and confinement based on theory and simulation should be maintained and effectively utilized for the future. Successful balance and synergistic cooperation between flux tube codes (GKV) with high resolution of phase space dynamics and global codes (such as GT5D and FORTEC-3D) addressing self-organization of mesoscopic structures (avalanches, staircases, and so on) as well as the edge turbulent transport should be one of the high priority items in reorganizing the future research efforts. A continuous effort is expected in the reduced transport modeling for better agreement with the LHD experiments and applications to other devices in the future research in the post LHD era.

3-3 for NSRP As supporting research to achieve the above goals, the code accuracy by comparison with the experimental results on the three-dimensional equilibrium, transport, instability and nonlinear evolution of

magnetically confined plasmas, including LHD plasmas, is improved while conducting simulation research on related basic physics.

Findings/Evaluation

- In order to employ the developed codes for guiding the world fusion program not only in current and near future experiment including ITER but also future reactors, it is especially important to verify and validate the code against current experimental results and to feed them back. The simulation research activities, leading to fruitful collaborations between the NSRP and the LHDP, are highly regarded, which has identified and interpreted key physics processes regarding equilibrium, MHD, neoclassical and turbulent transport etc. by comparing experimental results obtained in LHD experiments, etc., with developed codes and improved the degree of completion.
- The followings are well-visible results, which are highly regarded.
  1) Studies on EP driven AE mode and EGAM in LHD and JT-60 using MEGA and new energy transfer channels leading to bulk ion heating are visible results for the world fusion community. The finding for the new damping mechanism of MHD modes due to trapped thermal ions results from the feedback from the characteristic LHD configuration and related experiments. The kinetic or hybrid plasma simulation codes developed for transport studies, i.e. the isotope effect in LHD due to the zonal flow enhancement in deuterium plasmas and different neo-classical and turbulent transport characteristics in LHD and W7-X using GKV, have been improved through validation activities for the LHD experiments and provided key contributions for the LHDP in the 3rd Mid-Term Target Period, and in turn benefit the transport analyses of the LHD experiments as shown in the two recent papers published on Physical Review Letters. The latter results for the comparison in different machines provide an important database in designing the next generation helical system. There still exist unknown factors which are not simply explained in the present codes, e.g. the impurity transport observed in LHD has not be explained using the GKV, indicating that some missing physics still exists. However, identifying the problem is a valuable outcome in refining the code and then physics models.
  2) It is also highly regarded that some reduced models have been explored based on the simulation results, e.g. those of turbulent transport and zonal flows based on quasi-linear ansatz, indicating that simulation has progressed to serve as an experiment. On the other hand, the non-local and/or global extension of such models, which have extensively discussed especially in tokamaks, are fascinating problems. It is commendable that the NSRP has begun to focus on global simulation aiming at more accurate evaluation and prediction of experiments, e.g. XGC-S, extended GT5D with the general 3D equilibrium based on global gyro-kinetic modeling, which are not easy due to the complication of the 3D system and also the requirement of larger computer resources, but highly expected in the NSRP in the future.

- In addition to simulations centered on helical systems, basic physics studies are also promoted by simulations of the magnetic reconnection, Hall MHD turbulence, modeling of detached plasma, the merging of spherical torus, magnetic reconnections based on multi-scale kinetic model, turbulence simulations of high Reynolds number based on large eddy model, etc., which are evaluated as excellent results.

Recommendations

- It is recommended that the NIFS should play more active role in cultivating diverse research fields to promote interdisciplinary researches and to keep the NIFS's leading status in wider areas in the fusion and plasma sciences. From this viewpoint, NIFS should conduct simulation research on related basic physics leading to the academic development of fusion science and the expansion to other academic fields. On the other hand, it is not easy to see a unified strategy how to expand plasma and fusion science to broader academic science. It is a time to consider how to proceed them in the balance with those of more fusion oriented world-wide urgent problems including ITER toward the next Mid-Term Target Period.

3-1 for FERP Aiming for the early realization of fusion reactors, the conceptual design of helical fusion reactors is summarized, and the numerical targets of each development issue is concretely defined in 2016.

Findings/Evaluation

- Fusion engineering activities overall

  By promoting R&D of elemental technologies in fusion engineering in close relation to helical fusion reactor design, it was possible to seek the consistency of each technology and clarify the critical path of the development allowing to set priority in R&D issues and to clarify the significance of technological development including innovation. Most of the results obtained contribute not only to helical fusion reactors but also to fusion engineering in general by widespread academic dissemination. Furthermore, it is highly expected that the reactor design technology developed through the past research will not be limited to helical reactors but will be developed as shared knowledge in the form of open innovation.

  In 2016 the conceptual design and the R&D activities were summarized in detail in a ~450 pages report [1] (in Japanese) with numerical targets of each development issues included in the appendix. Smaller size for the technology demonstration should be cost effective to solve the key issues toward a fusion reactor. The summarized report clearly clarifies the roadmap, design policy, technology gap, R&D and simulations for the Helical Fusion reactor. It is worth noting that the conceptual design of the helical fusion reactor was summarized, and the numerical targets of each development issue were embodied. In addition, due to the progress of the design study, the design specialized for solving each prioritized issue has been promoted, and as a result, it has been linked to the step-by-step development toward the DEMO reactor. These findings are evaluated as excellent.

Various technologies have been considered in the FFHR design activity. Two design policies (1. Solid development strategy based on the achievements of the LHD experiments (ex. FFHR-d1[2]), 2. Pursue the possibility of early demonstration of electricity generation by configuration optimization and the use of advanced technology (ex. FFHR-c1[3], FFHR-b3)) have been proposed. Along with these design policies, several options for LHD-type helical fusion reactors were designed with suitable numerical target values. Features of helical reactor design have become clear by comparing to tokamak reactor concepts. In addition, structural design standards and criteria for helical reactors were proposed. These FFHR design activities have made significant progress in helical reactor designs, which will contribute to not only helical system engineering but also other fusion reactor concepts. For these reasons, helical reactor designs of FFHR projects with clear numerical targets are evaluated as outstanding.

[1] ”Full Report on the NIFS Fusion Engineering Research Project for the Mid-Term of FY 2010-2015”, NIFS-MEMO-79.

[2] T. Goto et al., Nucl. Fusion Res. 57 (2017) 066011.

[3] T. Goto et al., Nucl. Fusion Res. 59 (2019) 076030.

- Individual technological development

The comparison between helical and tokamak reactors reveals that a high *R*/*a* (aspect ratio) is preferred in helical reactors to obtain blanket space compared to low *R*/*a* in tokamaks which is beneficial for confinement and current drive. Whereas the size of central solenoid coil is one ingredient limiting the minimum size of tokamak reactors, high current densities in the helical coils and advanced shielding are necessary for compact size helical reactors.

Integrated physics analyses have been conducted using numerical tools developed for the experimental data analysis in the LHDP. They reveal that an improvement of the plasma performance can be achieved by a slight modification of the helical coil winding.

For the efficient use of the high field capabilities of HTCs (High T_c superConductors), topology optimization was applied to the structural design of the coil support. In the case of the reactor variant FFHR-c1 (operating with a maximum field of 20 T) a 25% weight reduction can be achieved, resulting in the reduction of several thousand tons [4].

For the development of superconducting conductor for helical coil winding, in addition to the conventional low-temperature metallic superconducting conductors such as Nb_3Sn and Nb_3Al, the adoption of copper oxide high-temperature superconducting (HTS) conductor (REBCO-based coated conductor) [5] has been actively promoted. R&D has been properly set up and planned for high thermal stability and high current density (from the initial 25A/mm^2 to 45A/mm^2 and then to 80A/mm^2 in stages), taking advantage of the excellent properties of HTS conductors. These are precise indications of the necessity and importance of developing HTS magnet technology. Additionally, the HTS has potential for segmentation of coils and for He-free cooling systems. It is appropriate to attempt the preparation of three conductor options (STARS, FAIR, and WISE conductors) as high-current superconducting conductors using REBCO coated conductors, each one providing different characteristics. STARS conductor is a high-strength conductor that enables segmentation, which is a solution to the problem of helical coil manufacturing and maintenance, segmentation. FAIR conductor is as a conductor that can be easily wound and is expected to be used for pulsed coils, and WISE conductor was proposed as a conductor for non-insulated coils based on a new concept. Needless to say, even if a conductor is developed, there is a large technological gap before the conductor can be used for coil winding. So further progress in research through academic and engineering approaches is expected. This will provide useful knowledge for the future development of high-current, high-capacity high-temperature superconducting magnets.

For in-vessel components, advanced liquid blanket system in FFHR design is being studied in collaboration with many universities, especially through the magnetic field (3T) environments tests of liquid blanket collaboration platform called Oroshhi-2 [6], which uses LiPb and FLiNaK (120L each). For the divertor, several principles were investigated including the advanced solutions using either liquid tin or small pebbles for power and tritium exhaust. The molten tin shower divertor has also evolved to fusible metal pebble divertor and expanded to the possibility of the ceramic pebble divertor in cooperation with the liquid metal blanket system. In conjunction with these studies, the concept of a cartridge-type blanket is reflected in the design of FFHR along with maintenance scenarios.

In the power generation systems, the application of a supercritical CO_2 gas turbine system has been investigated. The cycle thermal efficiency is evaluated 42%, which greatly exceeds the values of water/steam power generation systems and helium gas turbine power generation systems.

These research results significantly contribute to the progress of not only helical reactor development but also the other fusion reactor concepts. Therefore, these activities are evaluated as excellent.

[4] H. Tamura et al., J. Phys.: Conf. Ser. 1559 (2020) 012108.

[5] N. Yanagi et al., Nucl. Fusion 55 (2015) 053021.

[6] A. Sagara et al., Fusion Science and Technology 68 (2015) 303-307.

- Strengthening of collaboration between reactor design and engineering R&D activity

It is excellent that the same researchers have been engaged in both the discussions to determine the reactor design parameters and the necessary engineering R&D, and a system has been established and implemented that allows close coordination between reactor design activities and R&D. As a measure to share information among researchers, which is important in this process, all the R&D issues being conducted in the FERP were clearly described, and the overall picture of each issue and the relationship between individual issues were visualized. Two tools, the "Design Issues Panel" and the "R&D Status Bar," were prepared as specific methods for visualizing work [7]. This new visualization method is suitable for the unique situation of fusion reactor development, which requires close feedback between reactor design activities and R&D. Furthermore, it is useful for understanding the relationship between projects as academic research and a wide range of R&D from a bird's eye view, and it contributes to the acceleration of fusion R&D while appropriately complementing the previous visualization methods such as the Action Plan. The systematization chart and the 13 fields and 58 themes of R&D issues are well organized, and if appropriately updated in the future, they are expected to be useful for the development of fusion engineering.

These efforts are highly evaluated as excellent.

[7] T. Goto et al., J. Plasma Fusion Res. Vol.97, No.4 (2021)232-237 (in Japanese).

Recommendations

- The visualization tool developed in this project should be utilized effectively to develop a targeted academic roadmap and to establish a systematization of fusion engineering from a broader perspective. It seems that the academic roadmap has not been completed yet, but it would be desirable to present at least an image of it as soon as possible.

3-2 for FERP By promoting refinement of reactor design, and the interrelated enhancement of performance and reliability of core equipment, and by progressing development research for establishment of standards and criteria, the engineering design of a full-scale prototype of the large high-field superconducting magnet and the advanced blanket system are summarized, and the academic research roadmap for helical fusion reactor development is summarized in the report.

Findings/Evaluation

- The refinement of reactor design was conducted, and efforts were made toward the design of a full-scale prototype of the large high-field superconducting magnet and the advanced blanket system, including the cryogenic system design and the in-vessel component design.

- Superconducting magnet development

  For superconducting magnet and cryogenic system design, three options were investigated for the coils and the cooling systems such as (1) cable-in-conduit LTS cooled with forced convection supercritical helium, (2) LTS indirectly cooled with liquid helium, (3) HTS directly cooled with helium gas (potentially liquid hydrogen and neon). Finally, the HTS option was selected, and three types of conductors have been developed (STARS Conductor, FAIR Conductor, WISE Conductor). These R&Ds greatly promote the HTS development. As for the engineering design for a full-scale prototype of the large high-field superconducting magnet, the project is planning to test the characteristics of several-meter class conductor samples using a large-diameter high-field conductor test rig. Based on this, a feasible plan to fabricate a medium-scale "R&D coil" with a 10m class practical conductor and to conduct a comprehensive demonstration test has been established. Researches on liquid hydrogen cooling and magnetic refrigeration have been conducted for the cooling technology. These are extremely useful to establish cooling systems and technologies for high-temperature superconducting magnets, and good progress is expected in the future. The review panel members evaluate the above accomplishments as outstanding.

- Liquid blanket and divertor development

  Experimental studies on liquid blanket are proceeding into the new stage of integrated tests of liquid blanket technologies in a circulation system simulating blanket conditions have been started in Oroshhi-2 in collaboration with domestic universities. As for the engineering design of a prototype of the advanced blanket system, the definition of "full-scale prototype of the blanket system" is still unclear, however, several fundamental R&D activities have been progressed towards advanced blankets and divertors.

  Particularly:

  1) Low-activation high-purity vanadium alloys with significantly reduced impurity levels (C, N, O) were developed leading to a strongly improved machinability. They provide an advanced option for blanket structural materials, by improving the production process.

  2) The FLiNaK loop with 3T SC magnet provided the very necessary first-hand experimental data which will accelerate the speed and improve the reliability of the design development of liquid blanket.

  3) The Advanced Multi-Step Brazing (AMSB) divertor component sample and the HHF (High Heat Flux) test result provide a new direction for the future reactor divertor component design by improving the heat flux removal capability and the thermo-hydraulic safety as a consequence.

  4) The international collaboration for establishing standards for small specimen test technology (SSTT) has been joined and it could be shown that very thin specimens (ferritic steel, F82H) could reveal similar creep rupture time as the standard samples.

  5) In order to improve the material properties of W and Cu under higher thermal and neutron

load in the divertor, dispersion strengthening by oxide particles has been successfully applied and new materials such as TiO_2 DS W and Y_2O_3 DS Cu were developed.

These researches greatly contribute to the engineering design of advanced blankets and in-vessel components. The review panel members evaluate the above accomplishments as excellent.

- Academic research roadmap

  The prospect for establishing the academic research roadmap for the helical reactor has been summarized, reinforcing the interaction between reactor design and R&D as an outcome of the reactor design studies. This is excellent, as it sets the goals of academic research to support the reactor design options and the development roadmap, and establishes a step-by-step promotion strategy considering TRL (Technology Readiness Level), development lead time, etc.

Recommendations

- The committee recommends that the NIFS should promote fundamental research for advanced blanket design and adopt these results to DEMO TBM (Test Blanket Module). NIFS should also play a key role in design and R&D for DEMO TBM using advanced blanket concepts.

- The committee recommends that the NIFS should promote its R&D of HTS design and fabrication technologies, not only for magnetic confinement fusion reactors, but also the other applications to expand their research toward fields outside of fusion reactor development, supported by academic studies and discussions at a higher level.

- The NIFS needs to clarify what the Academic Research Roadmap will be used for in the future and organize it according to the purpose of use. For example, if the roadmap is to be used as a roadmap for engineering design for the early realization of a fusion reactor, it is necessary to clearly define the organization in charge of research and development, considering the human resources of the NIFS and collaborators in universities, and the expected budget scale.

- The committee recommends that the heat removal capability of the new pebble divertor should be studied and documented.

- In the future, there will be divisions between fields that are pursued as academics and fields that are developed for realization. In each of these fields, it is necessary to enhance the valuable human resources which have been accumulated in the NIFS as well as universities.

3-3 for FERP The functions of domestic and international collaborations are strengthened by expanding performance and establishing collaboration centers for largescale facilities such as "heat/mass flow

loop" and "the large-diameter high magnetic field conductor test facility" that were launched in the second phase. The systematization of fusion engineering and its contribution to interdisciplinary research by accumulating knowledge for the establishment of standards and criteria are promoted, and the expansion and promotion of related technologies to industry are planned.

Findings/Evaluation

- The functions of domestic and international collaborations have been strengthened by expanding performance and establishing collaboration centers for large-scale facilities, such as the "Heat/Mass Flow Loop" and the "Large Diameter High Magnetic Field Conductor Test Facility". As for domestic joint research, the development of in-vessel components related to engineering projects using these facilities has been adopted in the largest number. Specifically, in Japan, the JT-60SA group of the QST Quantum Research Institute and internationally, the SPARC/ARC development groups of ITER and MIT-PSFC have been using the large-diameter high magnetic field conductor test facility to evaluate superconducting high current conductors under high magnetic fields [8]. As for the high-temperature superconducting (REBCO) conductor, MIT and CFS (Commonwealth Fusion Systems) have jointly fabricated a REBCO pancake coil for SPARC-TF and conducted a cooling and energizing test (operating temperature: 20 K, energizing current: 40 kA, maximum magnetic field: 20 T) in the recent autumn. This is the world's first successful demonstration of a large-diameter, high-field, high-current REBCO coil. The REBCO-TSTC (Twisted Stacked-Tape Cable) conductor used in this coil was tested using the NIFS the large-diameter high magnetic field conductor test facility. Besides the superconducting properties, the current distribution in the stacked conductors during excitation and demagnetization has been evaluated, and these results will provide very important data and information for high current conductors of this type.

  [8] T. Obana et al., CRYOGENICS 73 (2016) 25.

- As for the accumulation of knowledge for the establishment of standards and criteria, there are many issues that need to be addressed, such as the establishment and maintenance of test methods, verification of validity, and implementation of tests due to the complex reactor structure of the FFHR. In response to these issues, NIFS has been examining standards for fusion reactor structural design based on the discussions at ASME/JSME and has been leading the standardization activities of the IEC/TC90 Superconductivity Committee on superconducting device cooling systems and has been steadily developing standards for micro-specimen test methods for reduced activation ferritic steel.

- Regarding the systematization of fusion engineering, the link between reactor design issues and research and development issues has been visualized. The key words that link the issues to be solved for the realization of a fusion reactor and the research themes which are necessary for the solution have been clarified. Reinforcing the collaboration between reactor design and R&D in the FERP is a very unique feature in fusion related laboratories worldwide.

- Expansion and contribution to interdisciplinary research and industry activities based on accumulated knowledge in NIFS are also in a good shape. Specifically, to optimize the neutron field in the Boron Neutron Capture Therapy (BNCT), a single crystal diamond detector for thermal-epithermal neutrons in fast neutron and gamma-ray field has been developed, helping to understand the damaging rate and the damage response of cancer cells. BNCT targets are exposed to similar heat flows as divertor targets. Therefore, the high heat load test facility (ACT2) could be used to characterize their thermal performance.

- In addition, the cryogenic technology has been applied to Japanese large-scale cryogenic gravitational wave telescope, KAGRA (KAmioka GRAvitational wave detector). Here the bonding of between Sapphire fibers and the mirror at liquid nitrogen temperatures has been characterized and the overall cooling process has been developed.

- Even more, the application of Transmission Electron Microscopy (TEM) to automobile industry for the examination of shallow surface layers has been performed.

- It is concluded that the evaluation from the following perspectives is excellent: strengthening the functions of joint research with domestic and overseas institutions by expanding and establishing large experimental facilities; contributing to the systematization of fusion engineering and interdisciplinary research by accumulating knowledge for the establishment of standards and criteria; and developing and promoting related technologies to the industrial world.

Recommendations

- Development and promotion to industry is very important in terms of manufacturing, and joint research with industry will pave the way for this. Although more than a dozen joint research projects between NIFS and industry are conducted annually, the number of projects and the contract amount are both very low compared to joint research conducted by universities with industry. The committee recommends that NIFS should strengthen its relationship to the industrial sectors.

- While the contribution to interdisciplinary research is important, NIFS should clarify its significance in the objective of early realization of fusion reactors and decide how it should be added to the goals for the next period.

Perspective 4 Was contribution made to the enhancement of the functions of the universities and the development of the community as a domestic and international core research center in this field?

Findings/Evaluation

- Frameworks of collaboration research

The commendable contributions of NIFS are recognized as a domestic and international core institute in fusion science. The contributions to the plasma and fusion science community are obvious through three existing frameworks for collaboration researches, i.e., LHD Project Collaboration Research, Bilateral Collaboration Research, and General Collaboration Research. It should be emphasized, in addition to these three frameworks, that the DEMO R&D Collaboration Research has been newly established since 2019. The establishment of this new framework is highly regarded since it is regarded as that NIFS starts to bear the substantial responsibility as the core institute in the new phase of the fusion science, that is, in the era of burning plasmas research to realize a fusion reactor.

The contributions of NIFS are evidenced by the following numbers of collaboration works.

i) The total number of the proposed collaboration projects is more than 500, and the number of participating researchers is more than 1,400, while the number of members in the plasma and fusion science community is roughly 1,500. This means that most of the community members are involved in the NIFS collaboration.

ii) In the LHD Project Collaboration Research, approximately 25 projects are carried out every year. In the new DEMO collaboration research, 6-7 research projects are selected every year. The budgetary dimension allocated to each project in both frameworks is comparable to that of the Grant-in-Aid for Scientific Research (B). Thus, it is no doubt that the frameworks of collaboration research indeed support the university research activities substantially.

iii) In bilateral collaboration research, approximately 100 projects are carried out every year through hub institutes (Tsukuba, Kyoto, Osaka, Toyama, Kyushu University), which own relatively large instrumental devices associated with the LHDP. The bilateral research activities also support the university activities in their own specific aspects.

iv) In addition, NIFS formed a committee that lend rather expensive instruments, such as fast cameras, to university laboratories. The rental system carries more than 50 leases every year, thus, provides contributing to enhancing the university function.

It is good to see that the number of overseas experiment proposers and experiment proposals to the LHDP has increased in the 22nd and 23rd cycles. On the other hand, the number of domestic proposers and experiment proposals has not been increased. Therefore, efforts should be made to improve the absolute number of proposals for future collaborations.

Evidence that NIFS is a well-recognized core research center of international repute for plasma science can be seen in achievements by researchers engaged in the NSRP, as follows.

1) Contribution through NSRP collaboration program: Consecutive annual increment of number of NSRP collaboration subjects proposed by non-NIFS members and of collaborators of non-NIFS members is highly estimated as a good reason of NIFS

contribution to development of the community through collaboration and research exchange. Meanwhile, the number of presentations and participants of Plasma Simulator Symposium is almost the same for years. This fact is not reflected by the consecutive annual increment. This discrepancy should be analyzed with a special emphasis of their circumstances and background.

2) Contribution through collaboration with universities and institutes: the NRSP made a large contribution to the enhancement of the functions of the universities and the development of the community through research collaboration as the subjects of the research collaboration cover a broad range of the field. A sample of the wide range of topics includes electromagnetic gyrokinetic simulation of turbulent transport in helical systems, tungsten transport and redeposition in LHD, simulations relevant to cosmology and relativistic jets near black holes, and dynamics on a cerebral cortex. Consecutive annual increment of numbers of workshops until 2019 is highly estimated. It should also be remarked that the major simulation codes (MEGA and GKV) are provided for research collaborations, and contributed to analysis of Heliotron-J experiments in Kyoto University. GKV code has also been released to public as an open-source code, and contributes to extension of the research community through the annual user guidance.
3) Contribution of personnel development through the JIFT program: Another metric is the participation of NIFS in the US-Japan Joint Institute for Fusion Theory (JIFT) program which has fostered an array of visits of NIFS scientists to the US and US scientists to NIFS. Director General Yoshida’s reorganization plan will almost certainly engender greater interaction with more basic science.

Also about 150 collaborating activities related to the FERP are carried out per year. Meanwhile, about 20-30 collaborations with QST and industries are mentioned. The collaborative activities have covered research facilities located at NIFS and collaborative universities and institutes, including research areas in SC Magnets, Liquid Blanket, High Heat Flux Components, Tritium and Advanced Materials. A clear statistic trend is for the General Research Collaborations, the research in SC magnets and in-vessel components are dominant, while PWI study is dominant for Bilateral Research programs.

- Trials to build new research environment

It should be emphasized that new systems and concepts have been developed in the implementation of LHD experiments; a remote access system, a unified data collection system (for domestic fusion experiments, mainly related to bilateral collaboration research, and possibly needed to extend other possible laboratories), and the open-access of LHD data for worldwide researchers. These systems work to maintain the collaboration activities as usual despite the COVID-19 pandemic, which prevents researchers from traveling. Also, these trials are highly regarded as the international core institute along with the present international trend, called open science. These trials, in fact, results in increasing the number of overseas experimental proposals; approximately 200 researchers have visited NIFS for collaborations amongst totally 1,500 researchers in the 22nd and 23rd cycles. Moreover, approximately 500 students have visited NIFS, which indicates that NIFS works as a core in young scientist education.

- Publications

  The total number of published papers should be sufficient with a good number of publications in journals of high impact factor. However, the average number of publications per researcher is about 2, and the published paper of high impact factor could be produced by the limited number of researchers. Thus, it should be strongly recommended that individual researchers in NIFS should make effort to produce more publications with trials to aim at high impact factor journals and the headquarter of NIFS should make efforts to create a better environment for researchers to produce more published papers.

  On the other hand, a good number of joint publications between NIFS researchers and external collaborators have been produced in collaboration. The increase in the number of IAEA-FEC publications, in which the co-investigators are the first authors, indicates that NIFS is contributing as a national center of excellence in this field. As for the number of LHD-related papers published, it is preferable to indicate the number of papers in which the first author is outside the institute.

Recommendations

- Regarding this perspective, the committee would like to remind NIFS of three missions as the core institute in fusion science as follows.

  1) Research that cannot be realized in university laboratories.
  2) Implementation of large-scale projects involving universities for the plasma and fusion science community.
  3) Support of activities in universities and contribution to strengthen the functions of universities in research and education.

- It is noted that General Collaboration Research plays an important role in all NIFS collaboration programs (>70%). The committee suggests that NIFS considers a more detailed category/definition for the collaborations, to promote research of the plasma and fusion science community and to attract more attention from the other research community.
- The committee notes that the termination of the present budgetary support to the LHDP would lead to the termination of the LHD Project Collaboration Research, which causes significant damage to the plasma and fusion science community. It is strongly recommended, thus, that NIFS should make efforts to find an alternative to the present framework to support activities in universities.

- Facing budgetary difficulties, it is needed to pursue the external funds such as JSPS Grant-in-Aid Scientific Research much more than before. However, the resulting number of adaptations has been limited and rather small. The committee recommends that NIFS should make a systematic analysis of the reason of this situation and take measures. The planning-out action for the strategy of raising funds up to a sufficient amount for excellent research programs is one of the important issues of NIFS.
- It is time to enter a new phase of nuclear fusion research to realize burning plasma and reify DEMO project, therefore, the committee recommends that NIFS should be a hub to connect the universities in the coming nuclear fusion research and promote related activities in universities.
- The committee also recommends that NIFS makes more effort to enhance flexibility for collaborative use of the major facilities.

Perspective 5 Was internationalization promoted through exchanges of researchers and joint research with overseas research bases, based on international exchange agreements?

Findings/Evaluation

- Scientific achievements under agreements

It is commendable that NIFS has proceeded with the LHD experiments under the agreements with 33 institutes in 15 countries, and under the concept of open science. The number of the agreements should be sufficient compared to the standard. The activities result in a tremendous increase in the number of overseas proposals. Moreover, in spite of the COVID-19 pandemic, international collaboration in the LHDP has greatly expanded in the last 1 – 2 years. Experimental proposals now account for 24% of all proposals, more than double (2.6 times) that of recent years. Collaborations have extended to China, the United States, South Korea, and Europe. This is an excellent trend, although the absolute number itself is not so large. The trend results in substantial achievements such as in impurity powder dropping experiments, comparison between LHD and W7-X (Warmer, PRL2021), energetic-ion-driven resistive interchange mode (Valera, NF2020), measurement of ion cyclotron emission (Reman, NF2021).

International research collaborations are actively promoted under the NSRP, such as research exchanges and workshops through the JIFT program, research collaborations through the W7-X experiments at the Max-Planck Institute for Plasma Physics, collaborations with China and Korea through the A3 foresight program and those with Princeton Plasma Physics Laboratory, or Wisconsin university. The NSRP has performed varieties of activities and collaborations, which makes NIFS internationally visible as a leading institute of fusion-plasma science in the world. According to the evaluation materials on activities associated with these exchange programs, number of visitors in each year is 122 (in 2016), 148 (2017), 108 (2018) and 115 (2019). The number of oversea trips from Japan is slightly larger; 159 (2016), 132 (2017), 156 (2018) and 147 (2019). These numbers are not very small but some breakthroughs can be achieved via long term visits. Especially, the number of visitors will be increased in future if NSRP/NIFS broadens the scope of research beyond LHD-related sciences and attract scientists working on wider subjects of plasma physics. The following programs and associated results are highly regarded.

A large number of topics is tackled ranging from magnet research (US: HTS; ITER/BA:SC), cryogenics (ITER/BA), negative ion hydrogen sources (DEU,Germany), materials research (US, China, IAEA), to plasma wall interaction (China, EU, DEU, IAEA, IEA) and the fusion neutron source (ITER/BA). Specifically, there is a strong collaborative effort with the Chinese fusion program. Various unique activities were performed, including collaboration with EAST under the JSPS-CAS Bilateral Joint Research Projects, Post-CUP (Japan-China Core University Program) on tritium research, personal exchanges on reactor design and magnet engineering in the frame of a joint working group (JWG) and the biannual meeting "Japan-China Symposium on Materials for Advanced Energy Systems and Fission & Fusion Engineering (JCS- series)" is successfully organized since 1993.

- Technological achievements in international collaborations

It is commendable that NIFS has made the following achievement in technological aspects through international collaborations.

As for the LHDP, a fast Thomson scattering system has been developed under a collaboration with the University of Wisconsin, while the collaboration activities have been carried out productively in neutron diagnostics with the Max-Planck Institute and NFR, Korea, and in plasma heating system with Pohang and Warwick University. It should be also stated that TESPEL is used in TJ-II and W7-X and that NIFS original EUV (Extreme UltraViolet) spectrometers are used in HL-2A and EAST, China. Recently, the measurement of the ratio of deuterium to hydrogen with CXRS is applied in W7-X. Besides, a quasi-axisymmetric helical device named CFQS is being constructed in collaboration with SWJTU in China, which contributes to the unified understanding of toroidal plasmas. The project itself can be commendable, however, it may not be timely in the present diplomatic situation and such projects may be carried out under the leadership of NIFS.

The NSRP activities have been quite visible in the research area of turbulent transport, gyrokinetics (both in fundamental theory and simulations), as well as energetic particle physics and their validations against LHD experiment.

Based on the above MOUs, many important international collaborations on theory and simulation have been performed. It is remarked that researchers in early carriers are largely benefitted from the JIFT activities, which have been very successful and researchers in both countries have received large benefits from this activity. The collaboration on optical vortex and on non-axisymmetric extension of XGC-1 code is a typical recent example. This is important not only in scientific outcomes but also in constructing tight connections and network for collaborations. As a leading institute for plasma physics in Japan, NSRP/NIFS has been playing a role of gateway for graduate students and young researchers in Japan towards the world. A good example is the collaboration of Yanagihara (Nagoya) and Dodin (PPPL).

Amount of overall activities has been sufficiently large. In the future, it is important for NIFS to continue to hold the frameworks for international collaborations such as the JIFT, Japan-Europe, or Asian networks and support young people belonging to universities by giving an opportunity to collaborate with foreign researchers. Through such international activities, NSRP/NIFS can continue to be a leading institute of fusion-plasma science, and a gateway connecting Japan and foreign countries for all the plasma scientists both in Japan and in the world.

The technologies developed in NIFS are highly regarded internationally. Furthermore, NIFS collaborates in dispersion interferometer in the diagnostics as well as in neutral beam injection with a negative ion source, a cooling system using cryostat pump, as for the ITER project. These collaborations are also highly regarded in terms of international contribution in the age of burning plasmas.

- Education

In the aspect of education, winter schools have been held under collaboration with Chiang Mai University and the atomic energy institute in Thailand, while a summer school was held with Saint Petersburg technological institute.

Recommendations

- The number of international agreements is sufficient. Thus, the committee recommends that NIFS should assess their effectiveness and should better activate the substantial number of exchanges of researchers and collaboration research based on the present agreements, rather than increase the number of agreements. For this purpose, it is important to construct a better environment and system for collaboration.

- For the coming age of burning plasmas and DEMO, the DEMO R&D Collaborative Research, participation in the ITER and BA activities, and participation in the joint team of DEMO reactor design should be further strengthened.

- In the future, the NSRP is further and strongly expected that, in addition to succeeding the expertise from the previous researches on numerical simulations and fundamental theories of fusion science, the NSRP broadens the scope of forefront research with gaining respect from abroad and attracting collaborators by utilizing various international MOUs or frameworks such as NINS interdisciplinary projects or IRCC-AFP (International Research Collaboration Center - Astro-Fusion Plasma), in collaborations with astrophysicists, particle-nuclear physicists or mathematical scientists.

- The LHDP as the leading program has been a natural “attractor” of international collaborations. In the post-LHD era, international collaboration should play even more important roles of the NSRP and NIFS with new organization based on scientific themes, and especially the JIFT program to organize workshops/conferences and inviting or sending researchers. Exchange programs such as JIFT US-JPN WS or Asian TTF are so important and desirable to be further extended. Creating a winter school/workshop on interdisciplinary subjects like Festival de Théorie in France or Activities at Kavli Institute at UCSB will be one possibility of future NIFS international activities.
- The remote collaboration capabilities cultivated during the COVID-19 pandemic should be effectively incorporated into future collaborative work.

Perspective 6 Was human resource development tackled together with universities and other organizations to achieve results?

Findings/Evaluation

- The committee favorably notes the fact that NIFS is actively engaged in human resource development in cooperation with domestic and international universities.
- Education programs and activities

  NIFS has instituted an excellent educational system and carried out programs that contribute toward developing human resources in the plasma and fusion science community. It has its own graduate university, SOKENDAI (Graduate University for Advanced Studies), for the specialized study of fusion science. It is a remarkable achievement that the average number of published papers per SOKENDAI student was above 4. The high and persistent level of NIFS’s dedication to the education of students in collaboration with university has to be seen as an excellent achievement.

  Moreover, NIFS has concluded agreements with partner graduate schools, Nagoya University, Kyushu University, and the University of Tokyo, and the opportunity to study in or with NIFS is opened to the graduate students in these universities. Other than postgraduate education, NIFS has special joint-use programs for students, e.g., short-term training and internship. NIFS has carried also Center of Excellence program and held international summer school.

Such enriched institutions result in the recent increase of the postgraduate students at NIFS. In 2021, about 70 postgraduate students are studying in NIFS. In 2017 – 2019 NIFS took care of more than 15 graduate students per year, only in 2020 and 2021 the number was reduced to about 2/3 most probably due to the pandemic. On the other hand, the number of master and bachelor students receiving training by NIFS almost tripled in 2020 and 2022 compared to earlier years benefitting from the increased use of remote participation possibilities.

Among the projects carried out in NIFS, there is no doubt that the LHDP has made excellent contributions to human resource development in the plasma and fusion science community. Meanwhile, looking at the recent trend of the student population in the LHDP, there is a tendency to stagnate; the number of students joining the LHDP is about 20 and nearly constant during these several years. This might be correlated with the recent trend of fusion research activities in the universities.

The NSRP has played an active role in enlightening the high school students in the Super Science High schools (SSH) program by introducing particularly three subjects of "Numerical Simulation," "Programming and Visualization," and "Virtual Reality".

In every summer and winter, SOEKNDAI/NIFS also provides and sponsors opportunities for domestic and international students and young scientists to study the leading-edge fusion sciences. In particular, the winter schools succeed in collecting a constant number of Asian participants each year.

- Research fellowship program

Two special research fellowship programs (NIFS special research fellowships and SOKENDAI special research fellowship) have been established in NIFS. The NIFS special research fellowship program was established to develop human resources who can play a leadership role in ITER and DEMO development. The NIFS Postdoctoral Fellowship Program was established to foster human resources who can play a leadership role in ITER and DEMO development and provides financial support for about two students every year for three years of doctoral course and two years of postdoctoral course. These two programs are based on the recommendation by the Fusion Science and Technology Committee in MEXT. The SOKENDAI special researcher program provides financial support to one SOKENDAI student every year for three years of doctoral course and two years of postdoctoral period. This special research program is expected to make a significant contribution to the development of the next generation of researchers in fusion-related fields and is highly regarded.

- Building up career

It is outstanding that the COE researchers have been employed at universities in Japan and abroad. This clearly shows that NIFS plays an important role in the career paths of young researcher in the plasma and fusion science community.

It is also outstanding that many students have participated in international projects, such as the Japan-U.S. Science and Technology Cooperation Program, that provide the platform for cultivating internationality, which is one of the most important characteristics of the plasma and fusion science community.

Recommendations

- The committee recommends that NIFS should evolve the human resource development responding the demands of the future fusion science activities.
- It is desirable to contribute to human resource development that is not only international but also interdisciplinary across various academic fields surrounding fusion science and technologies. In terms of human resource development, it is recommended to establish management system which takes into consideration the carrier path of young researchers in NIFS, not only students and post-doctoral fellows but also assistant professors and associate professors.
- Fusion research is a comprehensive research enterprise that crosses various fields of science and engineering such as chemistry, materials science, mechanics, electricity, and nuclear science. Therefore, it is very difficult for a single university to provide graduate education that covers the various basic knowledge required for fusion science and engineering research. Therefore, it is desirable for universities and fusion research institutes to collaborate to prepare lectures on the fundamentals of fusion science and engineering as video content and online textbooks on an e-learning system, so that students at each university can take the lectures anytime and anywhere they want.
- In order to foster young researchers with an international mindset, NIFS should actively send graduate students to overseas research institutes for a long period of time by utilizing the science and technology cooperation programs of such as Japan- U.S., and/or Japan-EU.
- The activities of postdocs and the overall postdoc system at NIFS do not reach the commendable level. The number of JSPS research fellows (the PD levels) has been zero in the last few years. These facts show that NIFS has failed to provide attractive career paths to the young scientists compared with well-known scientific institutes overseas. To maintain the high-level standards and the vitality of the institute in the plasma-fusion research field, it is essential to keep the constant entry of new talented researchers into the community. Using the characteristic feature of interdisciplinarity, the NSRP is expected to play a leading role for building and managing an open and flexible postdoc program, which may also contribute to drive research exchanges among NIFS and domestic as well as international institutions.

- The committee suggests the assessment of effort management for education in NIFS, and effectiveness of SOKENDAI and cooperative laboratories in collaborative graduate schools on another occasion.

Annex

1. List of Members of External Peer Review Committee ····················· 1

2. Backgrounds ·· 5

Annex 1: List of Members of External Peer Review Committee

[External Peer Review Committee members]

●	Dr. Ueda Yoshio	Professor, Graduate School of Engineering, Osaka University
●	Dr. Ohno Noriyasu	Professor, Graduate School of Engineering, Nagoya University
	Dr. Ozawa Tohru	Professor, Faculty of Science and Engineering, School of Advanced Science and Engineering, Waseda University
	Dr. Kaneko Toshiro	Professor, Graduate School of Engineering, Tohoku University
●	Dr. Kishimoto Yasuaki	Professor, Graduate School of Energy Science, Kyoto University
	Dr. Kurihara Kenichi	Managing Director, Fusion Energy Directorate, National Institutes for Quantum Science and Technology (QST)
	Dr. Fujisawa Akihide	Professor, Research Institute for Applied Mechanics, Kyushu University
	Dr. Matsuoka Ayako	Professor, Graduate School of Science, Kyoto University
◎	Dr. Yamada Hiroshi	Professor, Graduate School of Frontier Sciences, The University of Tokyo
○	Dr. Yoneda Hitoki	Professor, Institute for Laser Science, University of Electro-Communications
	Dr. Watanabe Tomohiko	Professor, Graduate School of Science, Nagoya University
	Dr. Stewart Prager	Professor, Astrophysical Sciences, Princeton University, USA
	Dr. Philip J Morrison	Professor, Department of Physics, The University of Texas at Austin, USA
	Dr. Yuntao Song	Director-General, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

[Specialist Committee members]

Dr. Kikuchi Mitsuru	Representative director & CEO, Division of Plasma Physics, Association of Asia-Pacific Physical Societies
Dr. Hanada Kazuaki	Professor, Research Institute for Applied Mechanics, Kyushu University
Dr. Nagasaki Kazunobu	Professor, Institute of Advanced Energy, Kyoto University
Dr. Kusano Kanya	Director & Professor, Institute for Space–Earth Environmental Research, Nagoya University
Dr. Iso Satoshi	Professor, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK)
Dr. Kimura Yoshifumi	Professor, Graduate School of Mathematics, Nagoya University
Dr. Yokomine Takehiko	Professor, Graduate School of Engineering, Kyoto University
Dr. Kasada Ryuta	Professor, Institute for Materials Research, Tohoku University
Dr. Hayashi Takumi	Director, Department of Blanket Systems Research, Rokkasho Fusion Institute, National Institutes for Quantum Science and Technology (QST)
Dr. Ishiyama Atsushi	Professor, Faculty of Science and Engineering, School of Advanced Science and Engineering, Waseda University
Dr. Hantao Ji	Professor, Astrophysical Sciences, Princeton University, USA
Dr. Thomas Sunn Pedersen	Head of Stellarator Edge and Divertor Physics, Max-Planck-Institute for Plasma Physics, Greifswald, Germany
Dr. Taik Soo Hahm	Professor, Seoul National University College of Engineering, Korea
Dr. Rudolf Neu	Professor, Max-Planck-Institute for Plasma Physics, Garching, Germany

◎: Chairperson, ○: Vice Chairperson, ●: Expert Subcommittee's Chairperson

Expert Subcommittee on the Large Helical Device Project

[External Peer Review Committee members]

●	Dr. Ohno Noriyasu	Professor, Graduate School of Engineering, Nagoya University
	Dr. Fujisawa Akihide	Professor, Research Institute for Applied Mechanics, Kyushu University
	Dr. Matsuoka Ayako	Professor, Graduate School of Science, Kyoto University
	Dr. Stewart Prager	Professor, Astrophysical Sciences, Princeton University, USA

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Dr. Nagasaki Kazunobu	Professor, Institute of Advanced Energy, Kyoto University
Dr. Hantao Ji	Professor, Astrophysical Sciences, Princeton University, USA
Dr. Thomas Sunn Pedersen	Head of Stellarator Edge and Divertor Physics, Max-Planck-Institute for Plasma Physics, Greifswald, Germany

●: Expert Subcommittee’s Chairperson

Expert Subcommittee on the Numerical Simulation Reactor Research Project

[External Peer Review Committee members]

●	Dr. Kishimoto Yasuaki	Professor, Graduate School of Energy Science, Kyoto University
	Dr. Ozawa Tohru	Professor, Faculty of Science and Engineering, School of Advanced Science and Engineering, Waseda University
	Dr. Watanabe Tomohiko	Professor, Graduate School of Science, Nagoya University
	Dr. Philip J Morrison	Professor, Department of Physics, The University of Texas at Austin, USA

[Specialist Committee members]

Dr. Kusano Kanya	Director & Professor, Institute for Space–Earth Environmental Research, Nagoya University
Dr. Iso Satoshi	Professor, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK)
Dr. Kimura Yoshifumi	Professor, Graduate School of Mathematics, Nagoya University
Dr. Taik Soo Hahm	Professor, Seoul National University College of Engineering, Korea

●: Expert Subcommittee’s Chairperson

Expert Subcommittee on the Fusion Engineering Research Project

[External Peer Review Committee members]

●	Dr. Ueda Yoshio	Professor, Graduate School of Engineering, Osaka University
	Dr. Kaneko Toshiro	Professor, Graduate School of Engineering, Tohoku University
	Dr. Kurihara Kenichi	Managing Director, Fusion Energy Directorate, National Institutes for Quantum Science and Technology (QST)
	Dr. Yuntao Song	Director-General, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

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Dr. Yokomine Takehiko	Professor, Graduate School of Engineering, Kyoto University
Dr. Kasada Ryuta	Professor, Institute for Materials Research, Tohoku University
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Dr. Ishiyama Atsushi	Professor, Faculty of Science and Engineering, School of Advanced Science and Engineering, Waseda University
Dr. Rudolf Neu	Professor, Max-Planck-Institute for Plasma Physics, Garching, Germany

●: Expert Subcommittee’s Chairperson

Annex 2: Backgrounds

The National Institute for Fusion Science (below as NIFS) was established in 1989 as an inter-university research institute to advance fusion research in universities in Japan.

Since 2004, NIFS has been a research institute under the Inter-University Research Institute Corporation National Institutes of Natural Sciences (below as NINS) for enhancing further the domestic research collaboration. Upon becoming an inter-university research corporation, a system for mid-term goals and mid-term planning spanning six years was introduced, and a system of annual evaluations regarding the progress, too, was introduced. This annual evaluation focuses primarily upon administrative management. However, at NIFS it has been determined that receiving external evaluations of research results is important. Under the NIFS Advisory Committee, each year an External Peer Review Committee is organized, and the members evaluate the research. The topics of evaluation are determined by the Advisory Committee. The evaluation is undertaken by the members of the External Peer Review Committee, which is composed of experts who are external members of the Advisory Committee and external experts who are appropriate for evaluating the topics. The External Evaluation Committee submits its evaluation results to the Advisory Committee. Then, NIFS, together with making the results public by uploading that information to the NIFS homepage, utilizes this information to improve research activities in the following years.

The topics for evaluation for the External Peer Review Committee are discussed and decided upon by the Advisory Committee, and those topics for evaluation differ each year. Most recently, in 2017 the Fusion Engineering Research Project, in 2018 the LHD Project, in 2019 the Numerical Simulation Reactor Research Project, and in 2020 the “Division of Health and Safety Promotion”, the “Division of Information and Communication Systems”, and the “Division of External Affairs” were topics evaluated by external reviewers. This year, 2021 at the end of 3rd Mid-Term Plan Period (2016-2021), all three projects in NIFS, i.e. the “LHD Project”, the “Numerical Simulation Reactor Research Project”, and the “Fusion Engineering Research Project” were selected and reviewed by the external examiners.

As external members of the External Peer Review Committee this year there are eleven external members from the Advisory Committee and three members from abroad. Further, fourteen (including four members from abroad) experts are invited from outside NIFS. Thus is the External Peer Review Committee composed, and thereby the evaluation was undertaken.

The first meeting of the External Peer Review Committee including the Experts’ Subcommittee was convened on October 12, 2021. The Committee discussed the process for moving forward with this fiscal year’s external peer review, and decided upon the perspective of the evaluation. The second meeting of Experts’ Subcommittee on the “Numerical Simulation Reactor Research Project” was held on November 22, 2021. The second meeting of Experts’ Subcommittee on the “LHD Project” was held on November 26, 2021. The second meeting of Experts’ Subcommittee on the “Fusion Engineering Research Project” was held on December 6, 2021. At the second meeting of

Experts' Subcommittee, NIFS provided a detailed explanation that utilized documents from the material of viewgraphs and reports based on the perspectives. A question-and-answer session also was arranged. Extra-meetings primarily for international members were organized for "Fusion Engineering Research Project" and "LHD Project" on December 8, 2021, and "Numerical Simulation Reactor Research Project" on December 9, 2021 with participation of major members in Japan. Subsequently, the second meeting of the External Peer Review Committee and the third meeting of the Experts' Subcommittee was held on February 4, 2022. The Committee discussed the coordination of the evaluation work and confirmed the configuration of the external peer review report based on the drafts from three sub-committees. Then, the committee elaborated the report through communications by electronic mail. Upon confirmation and examination by the External Peer Review Committee and the Experts' Subcommittee, the external review report was finalized on February 28, 2022.

In the external evaluation regarding NIFS's "LHD Project", the "Numerical Simulation Reactor Research Project", and the "Fusion Engineering Research Project" which were implemented this fiscal year, the perspectives for the evaluation were determined as follows.

Evaluation items in FY2021 External Peer Review

In the external evaluation of the "Large Helical Device Project, the Numerical Simulation Reactor Research Project and the Fusion Engineering Research Project" to be carried out in FY2021, the perspective of the evaluation are set as follows for the 3rd Medium-Term Plan.

Each item of the perspective is based on the evaluation of the validity and achievement of research and other activities carried out by the National Institute for Fusion Science as an inter-university research institute, and recommendations on future directions based on them.

In addition, it should be noted that the evaluation is conducted in the light of the statements : "As a core research base for nuclear fusion science research in Japan, it will aim to systematize academically and develop nuclear fusion science, related science and engineering, in cooperation with universities and research institutes" ; and "Toward the realization of controlled thermonuclear fusion with excellent environmental safety, the relevant research in Japan as a whole, from joint research using large-scale experimental equipment and computers to support of the burning fusion experiments through international collaboration, will be promoted", in the section of goals related to research levels and research results in the 3rd Medium-Term Goal.

1. **Were the goals set appropriate from the perspective of the National Institute for Fusion Science, and have they been appropriately updated in light of research results and research trends, and have the corresponding measures been taken accordingly?**

2. Have sufficient results been produced as an inter-university research institute in the academic field?

3. Were sufficient results obtained from the viewpoint of the following special notes in the Third Medium-Term Plan?

(Large Helical Device Project)

3-1 Deuterium experiments are carried out by upgrading plasma control, heating, diagnostics, and safety control facilities to further improve the performance of the Large Helical Device (LHD) for systematization of physics and engineering of helical systems and comprehensive understanding of torus plasmas.

3-2 Achievement of an ion temperature of 120 million degrees by the end of the third mid-term target period and realize ultra-high performance plasmas that can be extrapolated for use in a fusion reactor.

3-3 Hydrogen isotope effects on the formation of internal transport barriers of ions and particle recycling characteristics in deuterium discharges verified through academic research based on collaboration.

(Numerical Simulation Reactor Research Project)

3-1 Effectively using the supercomputer system, the Plasma Simulator, for construction of the Numerical Simulation Reactor, research for development, extension, high precision, and the integration of the simulation codes for the whole device from the core plasma to the peripheral plasma and plasma facing wall is advanced. During FY2019, the performance of the Plasma Simulator is improved more than four times compared to the current system, and various three-dimensional simulation codes for the improved system is optimized.

3-2 Modeling of turbulent transport in core plasma and the application of the model into the integrated transport code are completed by the end of FY2019, and the incorporation of multiple ion species effects into various transport codes is done by the end of the third mid-term target period.

Furthermore, by the end of the third mid-term target period, molecular dynamics simulation techniques are developed by improving programs and building new models necessary for evaluating the physical properties of plasma facing materials such as tungsten.

3-3 As supporting research to achieve the above goals, the code accuracy by comparison with the experimental results on the three-dimensional equilibrium, transport, instability and nonlinear evolution of magnetically confined plasmas, including LHD plasmas is improved, while conducting simulation research on related basic physics.

(Fusion Engineering Research Project)

3-1 Aiming for the early realization of fusion reactors, the conceptual design of helical fusion reactors is summarized, and the numerical targets of each development issue is concretely defined in 2016.

3-2 By promoting refinement of reactor design, and the interrelated enhancement of performance and reliability of core equipment, and by progressing development research for establishment of standards and criteria, the engineering design of a full-scale prototype of the large high-field superconducting magnet and the advanced blanket system are summarized, and the academic research roadmap for helical fusion reactor development is summarized in the report.

3-3 The functions of domestic and international collaborations are strengthened by expanding performance and establishing collaboration centers for large-scale facilities such as "heat/mass flow loop" and "the large-diameter high magnetic field conductor test facility" that were launched in the second phase. The systematization of fusion engineering and its contribution to interdisciplinary research by accumulating knowledge for the establishment of standards and criteria are promoted, and the expansion and promotion of related technologies to industry are planned.

4. Was contribution made to the enhancement of the functions of the universities and the development of the community as a domestic and international core research center in this field?

5. Was internationalization promoted through exchanges of researchers and joint research with overseas research bases, based on international exchange agreements?

6. Was human resource development tackled together with universities and other organizations to achieve results?

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