National Institute for Fusion Science

Special Review Meeting
by Advisors and Foreign Researchers
in FY 2008

Review Report

March, 2009

Contents

1. Agenda for the Meeting

NIFS Special Review Meeting by Advisors and Foreign Researchers in FY 2008

December 13, 2008 (Sat.)

Special Conference Room 3F, HIDA Earth Wisdom Center, Takayama, Gifu, Japan

Reviewers:

● Advisors

Prof. Hiroshi Takuma	Advisor (Emeritus Professor, the University of Electro-Communications)
Prof. Kyoji Nishikawa	Advisor (Emeritus Professor, Hiroshima University)
Prof. Michael Tendler	Advisor (Professor, Royal Institute of Technology, Sweden)
Prof. Satoshi Itoh	Advisor (Emeritus Professor, Kyushu University)

● Foreign Researchers

Dr. Carlos Alejaldre	Deputy Director-General for Safety and Security, ITER, France
Dr. Gyung-Su Lee	President, National Fusion Research Institute, Republic of Korea
Prof. James W. Van Dam	Director, Institute for Fusion Studies in the University of Texas at Austin, USA
Prof. Robert Wolf	Professor, Max-Planck-Institute for Plasma Physics, Germany
Prof. Thomas Klinger	Professor, Scientific Director of Max-Planck-Institute for Plasma Physics, Germany

NIFS members:

Prof. Osamu Motojima, Prof. Shigeru Sudo, Prof. Akio Komori, Prof. Hiroshi Yamada, Prof. Shinsaku Imagawa, Prof. Noriyoshi Nakajima, Prof. Shoichi Okamura, Prof. Motoyasu Sato, Prof. Akio Sagara, Assoc. Prof. Satoru Sakakibara, Assoc. Prof. Ryuichi Sakamoto, Assoc. Prof. Masayuki Yokoyama, Assoc. Prof. Tomohiko Watanabe, Assoc. Prof. Takuya Nagasaka, Mr. Yasuo Kainai

Program:

8:30	Opening
8:30 -	Opening Address (5 min) Director-General, Osamu Motojima
8:35 -	Introduction of NIFS Activities (20 min) Deputy Director-General, Shigeru Sudo
8:55 -	Current status and research subjects, future plans of NIFS (160 min) [40 min / item (Report 25 min + Q&A 15 min)] 8:55 - 9:35 Large Helical Device (LHD) Project Executive Director, Akio Komori 9:35 - 10:15 Simulation Science Project Director, Noriyoshi Nakajima ---- Coffee Break (15 min) ---- 10:30 - 11:10 Coordination Research Director, Motoyasu Sato 11:10 - 11:50 Fusion Engineering Research Director, Akio Sagara

---- Lunch Break (60 min) ----

12:50 -	Recent results and topics (240 min) [60 min / item (Report 40 min + Q&A 20 min)] 12:50 - 13:50 High Beta and Related 3-D MHD Characteristics Assoc. Prof. Satoru Sakakibara 13:50 - 14:50 High Density Operation and Its Prospect for Helical Reactor Assoc. Prof. Ryuichi Sakamoto ---- Coffee Break (15 min) ---- 15:05 - 16:05 Turbulent Transport and Zonal Flows Assoc. Prof. Tomohiko Watanabe 16:05 - 17:05 Development of long-life liquid blanket Assoc. Prof. Takuya Nagasaka
17:05 -	General comments from reviewers (40 min)
17:45 -	Closing Address (5 min) Director-General, Osamu Motojima
17:50	Closing

2. Reviews on NIFS Research Activities

Reviewer: A

1. Project Activities
(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

The achievements of LHD Project since its start-up in 1998 are very impressive and cover all the main issues needed to be solved for the successful development of fusion energy, giving tremendous hope for helical systems as fusion energy producers, as most if not all the parameters needed for efficient fusion production in terms of density or pressure have been achieved. The challenge now is to do them simultaneously.

Furthermore the more extreme operational regimes investigated show no sign of having reached any fundamental physical limit other than the technical limitation associated to heating sources or particle/energy exhaust and in both cases, upgrades are foreseen.

In my opinion, LHD has proven for the first time in the History of Fusion Research that helical systems are serious candidates for future generations of fusion power, having properties quite similar to advanced Tokamaks but without the difficulties associated to a strong toroidal current: instabilities, disruptions, density limits…..

Technically, to prove the capability of stable plasma production for over one hour is an achievement that could be extended to more demanding regimes.

b) Specific Researches (on topics)

The development of the disruption-free, high density regime is in my opinion one of the more hopefuls regimes developed by the fusion community in the last years.

The extension of <ß> to reactor relevant values of 5% is again a breakthrough that should be highlighted, particularly because it looks like the actual limit of the configuration has not been reached and the absence of hard limits is very encouraging.

c) Future Plan

Given the results obtained, the plans to upgrade the heating capability of the machine, the introduction of a closed helical divertor and working with deuterium are absolute needs and I would recommend that all efforts are made to find the needed resources to take the machine to its physical limits.

(2) Simulation Science Project

a) General View and Achievements

A very ambitious project was presented on plasma simulation that covered specific LHD confinement simulation as well as laser fusion simulation with very encouraging results already. The fact that this group works closely with the experiments is in my opinion something that should be supported. It was very good to see that young generations are participated actively in this field.

b) Specific Researches (on topics)

To include in the simulation data coming from other machines with quite detailed diagnostics for radial electric fields like TJ-II could be a good addition to the very excellent work presented.

The work on materials is particularly important for the future of fusion machines.

I would recommend that comparison with Tokamaks is taken into account.

c) Future Plan

The plan presented is very ambitious but realistic at the same time. Adequate computing resources should be obtained at the highest level for this task to be successful.

(3) Coordination Research

a) General View and Achievements

I would like to praise the effort done in this field. It is very normal in other large experiments to be disconnected from other communities, but it was a pleasure to see the on going interactions with industry, other scientific institutions and the fusion laser community as well as outreaching programs.

I would strongly encourage to emphasize the work on "tritium for Fusion", since as we approach the operation of ITER, more and more issues have to be resolved and through this collaborative effort a great contribution could be expected. This is a key-issue to be solved for the successful implementation of fusion energy.

The effort made on "Kids Fusion Science Museum" is to be highly praised.

b) Future Plan

Special care has been taken to present future plans taking into account the planning of the ITER project and that is in my opinion the key to success since ITER will clearly have a strong influence in all fusion world programs.

I would recommend a closed interaction with JAEA

(4) Fusion Engineering Research

a) General View and Achievements

The subjects of the research presented were very well chosen and the results obtained world-relevant. Many international collaborations are maintained, giving good confidence in the impact of the research.

To include objective indicators like publications is also very useful for reviewers.

b) Specific Researches (on topics)

Long life liquid Flibe and Li blanket studies were impressive. The main difficulty will be the possibilities to test in real environment these designs as the possibilities to do it in ITER are limited.

Neutronics studies are very much needed and welcome in view of the approaching ITER operation.

c) Future Plan

For its importance, enough resources should be found for the future plan presented.

2. Others

I would like to take this opportunity to congratulate the whole NIFS for the achievements of the last years. They covered not only experimental results in LHD that are world record relevant but for all the accompanying program that surrounds LHD in science, collaborations with so many institutions in Japan and worldwide, technology program as well as a very important, even if modest, public relations program.

It is very encouraging to see a new generation of young scientists and engineers already producing world-class results and I would recommend that for the next review, special thought be given as to how to maintain such high standards and world leadership for the long term.

The whole team should be proud of the achievements obtained under the leadership of Prof. Motojima and I would like formally to give him my congratulations with the request that it be given to the whole team.

Reviewer: B

1. Project Activities
(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

The fusion energy research has been mainly studied by the tokamak type devices.
Even if TRIAM-1M has already demonstrated steady-state operation using LHCD. However, the tokamak type is difficult to achieve the high efficient continuous operation. On this point of view the helical devices are extremely favorable. But before LHD experiments, the research for the helical fusion “reactor” has almost not studied. For last six years the LHD experimental research has been carried out energetically, and the high temperature and high density plasmas are established. Especially the achievement of the high β of 5% seems to be amazing result.
The results which are higher than initial expected parameter are should be evaluated as the valuable results.

b) Specific Researches (on topics)

1. High ion temperature : 5.2 keV at $n_{e} = 1.6 \times 10^{19}\ m^{-3}$
2. Maximum β =5.1%, 4.5% for the steady state (>100 τ_{e})
3. Maximum density : $1.2 \times 10^{21}\ m^{-3}$
4. Prove of IBD

Furthermore many interesting results are shown.

c) Future Plan

The power up of the heating, the closed helical diverter and D-D experiment are prepared. Then the higher beautiful results should be expected. The setting of the helical diverter is well considered not to effect on the experimental schedule.

The design of the helical reactor is seemed to proceed referring of the experimental results from LHD. Reasonable design should be expected.

(2) Simulation Science Project

a) General View and Achievements

It is appreciated that the simulation study has proceeded energetically.
In the high temperature plasma miscellaneous phenomena coexist and interact each. So even if the simulated result resembles the experimental result, its phenomena may be not same as one in accurate plasma. We should keep mind on this point.

The simulation group and the diagnostic group should contact sharply each other.

b) Specific Researches (on topics)

c) Future Plan

The simulation group is recommended to put emphases on the simulation of the helical reactor.

(3) Coordination Research

a) General View and Achievements

The many jobs are explained, but it is difficult to understand the final object of each jobs. It is not shown what “Boomerang” effect is obtained. So it is difficult to evaluate at present time.

b) Future Plan

It should be necessary to select the important tasks, for example, a helical diverter, prepare of D-D experiments.
The final objects should be also shown.

(4) Fusion Engineering Research

a) General View and Achievements

Blanket, neutron, magnet et cetera are explained, but the parameters of the expected reactor (size, magnetic strength, dimensions of plasma) are not shown. If the scale of a reactor which must be developed is shown, the attained grade is easier to understand.

b) Specific Researches (on topics)

I am strongly interested in the developed results of superconductors. The results are evaluated high.

c) Future Plan

The plan of the helical reactor is expected. The comparison between helical and tokamak reactors should be carried out with considering strong and weak points. The scales of helical and tokamak reactors should be also shown.

Considering the energy problems, the scale and budget are not so large problem but the realization is most important.

2. Others

During these several years the organization has been improved and a lot of extreme results are reported. Especially many excellent results of LHD experiments are should be evaluated extremely high.

I would like to say congratulation to Prof. Motojima, Director-General, and staff of NIFS.

Reviewer: C

1. Project Activities

(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

Based on the pure academic debate between plasma nuclear fusion researchers in Japan, the Large Helical Device project was adopted in 1986 as the next-generation large-scale research plan, which university officials should work on with all their strength. Upon the adoption of the project, while keeping in mind that the external conductor type helical magnetic field confinement system has the capacity of a steady-state operation with lower re-circulating power and the capacity of a long-time sustainment of high-temperature high-beta plasmas, it was desired that LHD, for the time being, would contribute to a comprehensive understanding of plasma physics by the torus magnetic field confinement system including the internal current type tokamak devices. As specific research plans, following subjects were addressed: 1) the optimization of the high $n\tau T$ plasma confinement by various magnetic configurations; 2) elucidations of a) physics like the pressure-driven instability in the high-beta region as well as b) its impact on the confinement; 3) the control of impurities due to a long-time operation and the provision of basic resources concerning issues like a fuel supply and discharge; 4) research in the high-energy particle confinement characteristics under the helical ripple magnetic field; 5) nuclear reaction simulation research; and so on.

It is highly commendable that the LHD project, following the above research goals, has been consistently carried out for the past 10 years ever since its first shot in March 1998, that it has produced the results almost as they were primarily expected, and that it has made a unique and valuable contribution to the global core plasma magnetic field confinement research. Especially, it has largely contributed to the comprehensive understanding of a torus magnetic field confinement system that has a prospect over the nuclear fusion reactor core such as the actualization of the long-time sustainment of the high-beta plasmas to provide the important basic resources in terms of their MHD characteristics, transport, or peripheral control and also the discovery of ITB that maintains the central peak high-density by means of the pellet injection.

b) Specific Researches (on topics)

・ Optimizing the confinement

By changing the position of magnetic axes and the aspect ratio, the confinement of high-beta plasmas was optimized in terms of the MHD characteristics, heating efficiency, and transport. The maximum $\langle\beta\rangle=5.1\%$ was achieved. Also, the steady-state operation that is 85 times as long as the energy confinement time was actualized at $\langle\beta\rangle=4.8\%$. Furthermore, while methodically examining the impact on MHD equilibrium, stability, and transport due to the pressure-driven instability and the peripheral magnetic surface collapse, heating by the vertical neutral beam injection was actualized to study their confinement characteristics. Reviewed from the standpoint of torus magnetic field confinement plasma physics and also from the point of views that overlooks a reactor, these results made highly excellent contributions.

・ Internal Diffusion Barrier (IDB)

While generation and maintenance of the central peak high-density, high-pressure configuration were already found out in the conventional local island diverter configuration at the time of a consecutive pellet injection to the central part, it was newly discovered that they could also be actualized in the ordinary helical diverter configuration by means of an outward shift of magnetic axes and so on; thus, their operation region (magnetic axis / β) was identified. I believe that it is such an important progress from the standpoint that surveys the reactor core plasma generation and sustainment in the helical system. According to the experiment result, the electron temperature gradient stays gentle even where the electron density gradient is steep. It is further expected that from now on, a detail study should be carried out in cooperation with the Theory and Simulation groups to elucidate the physical mechanism of diffusion coefficients considering the IDB formation as well as to identify and control instabilities like CDC.

・ Edge Plasma Control

Control of a peripheral magnetic surface disorder as a result of the beta value increase is a challenge that cannot be ignored when one attempts to bring the helical type plasma sustainment into a steady-state operation. The fact that the confinement deterioration was not observed in the region <β> – 4.8% is an achievement to be noted.

Also, varieties of researches are carried out such as the generation of impurity halls under the high ion temperature, the impurity shielding by means of a collision friction at a high density, various analyses concerning the effect of the ergodic layer, designs of the closed helical diverter configuration, and so on. Further progress will be much expected to those respectively as research that may provide more insights on the peripheral control of particle / heat flux.

c) Future Plan

The most desirable future plan is the start of the deuterium experiment. Well, it can be understood that it involves a quite difficult issue to obtain the public permission; however, taking into consideration that the original plan has been carried out up until now, I cannot stop hoping that the research in the confinement characteristics by using deuterium, especially research in the isotope effect to the confinement scaling law of the ions and impurity particles shall be started. Then, I anticipate further that, those researches would eventually develop into a nuclear reaction simulation research by the ICRF minority heating due to the mixing of a small amount of He^3.

Yet, I say that any major reconstructions or a new construction of another large helical device is still too early to carry out at this point. For the time being, it will be best to aim at a further progress in research by utilizing the present LHD (necessary upgrades or reconstruction like the heating power reinforcement and the diverter configuration remodeling should be taken care of). Then, the next term research plan should be carefully thought over, studying the ITER and ICF related achievements, from the standpoint of the nuclear fusion research in general.

(2) Simulation Science Project

a) General View and Achievements

First of all, I would like to highly commend the simulation research group for the fact that it has developed into a big research group. Then, I want to congratulate the group on the achievement that the group succeeded in carrying out 3 projects simultaneously: 1) LHD and Magnetic Confinement Simulation Project; 2) Laser Fusion Simulation Project; and 3) Plasma Complexity Simulation Project.

Among those three, 1) LHD and Magnetic Confinement Simulation Project is the central project.

In this project, 3 sub groups – the two-fluid model research group, the kinetic model research group in the core plasma, the kinetic model research group in the core plasma, and the peripheral plasma research group – have made sure and steady research achievements by developing the two-fluid model, the gyro kinetic model, and the boundary modeling, respectively. Furthermore, it seems reasonable that NIFS attempts to develop a multi-hierarchy simulation model by integrating the research results of these 3 sub groups and, thus, to promote the Numerical Test Reactor Project. At the same time, it will be much expected that this research project will play a leading role in the simulation research related to the multi-hierarchy phenomena in various fields.

b) Specific Researches (on topics)

I think that the achievements made in the research in the ITG turbulence and zonal flows in the helical system by using the gyro kinetic Vlasov model will deserve a special attention. Many researches on the ITG turbulence and its stabilization by the zonal flow have already been carried out in axisymmetric tokamak system. In the non-axisymmetric helical system, too, the zonal flow and its turbulence suppression effect are likewise confirmed experimentally with the NIFS compact helical device (CHS). Yet, I suppose that it is the first time when the detail analysis by means of simulation research in the helical system was performed. The analysis was performed while taking into consideration the radial electric field effect due to non-axisymmetricity, and it revealed that the turbulence diffusion suppression due to zonal flows would work strongly in the magnetic field configuration that minimizes the neo-classical ripple diffusion and that the turbulence diffusion be thus suppressed. Some parts are still left uncertain about how the radial electric field was adopted; yet, analyses that self-consistently adopt the electric fields generated due to the ambipolarity of the particle diffusion flux will be further expected.

c) Future Plan

Modeling and the simulation numerical method are the keys in the simulation research. These are not limited within specific subjects (helical plasmas), but they can also be applied to many different complexity analyses. In fact, researches on self-organization in the open system, that were major subject in the previous Theory and Computer Simulation Center were developed into the application to many other fields of research.
One can conclude that the researchers have developed a new paradigm of the method to research the systems with complexity in nature.
The comprehensive research in the multi-hierarchy phenomena has become a subject that cannot be avoided in such areas like research in the global scale weather phenomena as well as the atmosphere and ocean current, research in the earth inner structure and diastrophism, or in the areas of bioscience and space science.
I would truly hope that through active collaborative researches with related research organizations including other NINS institutes, the Department of Simulation Science should play a central role to lead the way for new simulation research that includes various fields of researches addressed above.

(3) Coordination Research

a) General View and Achievements

It should be specifically noted that the Coordination Research Center has been carrying out various activities like the international collaboration, ITER related research collaboration, laser related research collaboration, atomic/ molecular/edge plasma data collection and analysis, industrial collaboration, and the NIFS Science Museum for Kids with only a limited number of personnel.
From the aspect of nuclear fusion science, activities were more or less focused on spin-off related actions in the past; therefore, it is quite desirable that they are now being shifted toward actions aiming at a nuclear fusion reactor.

b) Future Plan

It will be much expected that more emphasis will be placed upon collaborative researches in tokamaks (ITER, torus tokamak), which is believed to actualize a nuclear fusion reactor in the shortest span at this point along with a helical series, as well as ICF (FIREX).
Among these above, there may be issues related to the NIFS future plan.
Thus, it will be advisable that academic debates on the future plan should be called forth then organized among nuclear fusion related researchers in Japan by utilizing the national inter-university system.

(4) Fusion Engineering Research

a) General View and Achievements

I have no specific comments to say since the area is outside of my field.

b) Specific Researches (on topics)

I have no specific comments to say since the area is outside of my field.

c) Future Plan

I have no specific comments to say since the area is outside of my field.

2. Others

I was truly impressed by the fact that under the excellent leadership of Director-General Motojima, NIFS carried out a drastic reorganization to steadily promote the LHD project, which comprises the heart of the National Institute for Fusion Science and also that the complexity simulation research for high-temperature plasmas were greatly extended and progressed.
Also, I got so fascinated and excited to witness that lots of excellent young researchers have been fostered through these researches.
Now, it is my best wish that, based on these achievements, a further progress and novel development in research will be made under the leadership of the next Director-General of NIFS. Among other things, I truly hope that a new academic development shall be brought forth through the collaboration with other NINS institutes.

Reviewer: D

1. Project Activities

(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

LHD device is the masterpiece of the art of fusion engineering.

Taking full advantage of LHD capabilities, important targets and achievements have been attained during the last 6 years. The highlights of major discoveries are the high ion temperature accompanied by important beneficial phenomena such as impurity hole, high density regime employing Internal Diffusion Barrier in open helical divertor configuration, high average beta of unprecedented 5.1 % and steady state operation of 54 minutes. These achievements resulted in the attainment of temperature of fusion reactor, world record of beta value and plasma density and the world record of injected energy. These impressive results are due to the fully integrated and coherent contributions of all teams and individual researchers working on LHD mastered by the present leadership. Furthermore, scientific and technological foundations have been laid down to improve the performance even further toward the goal of fusion.

b) Specific Researches (on topics)

Upgrade of heating capability consisting of NBI, ICRH and ECRH, the smart implementation of the closed divertor configuration and the deuterium operation should be employed to enhance the LHD performance even further in order to obtain simultaneously values of density, temperature and confinement time approaching the triple product relevant for stringent fusion requirements. Also, the steady state operation should be addressed to broaden the data base required by a fusion reactor. High beta can be increased even further by careful real time control of the Shafranov shift and the R_{ax} control. The closed divertor configuration may benefit confinement in the periphery thereby alleviating deterioration of confinement with an increase of beta values. Also, the synergy of the closed magnetic configuration with improved pellet injection system might yield further improvements of plasma parameters. More emphasis should be focused on studies of momentum transport in general and in particular on the correlation with the impurity transport. The emergence of the Impurity Hole deserves a close attention and further extension.

c) Future Plan

Nearest Future plans are well defined and properly funded. The physics program is well supported by a wide range of diagnostics available now and coming into operation in the near future. However, a more aggressive set of goals along the lines of the present strategy of NIFS is highly desirable. The current momentum achieving seemingly unattainable plasma parameters must be maintained. Hence, the fully integrated approach with ambitious goals must be employed. Novel subtle methods based on technical and computational excellence of NIFS in order to improve plasma parameters has to be sought and found. The recent successes (i.e. Li operation) obtained on smaller devices should be tested and exploited on LHD under conditions more relevant to fusion.

(2) Simulation Science Project

a) General View and Achievements

During the last years significant progress in amplifying the relevance and the predictive power for LHD experiments has been achieved. It occurs primarily due to the integration of the theory into the fabrics of LHD decision making and the attraction of the excellence of experimental results. The division is now focused on the fusion performance of LHD and supports major achievements carried out during experimental campaigns. However, Simulation Science must increase its impact by introducing many original suggestions for novel and fine improvements of LHD. A very wide range of sophisticated codes has been developed with a promise to improve the fusion outlook even further. New avenues of the LHD experiments due to come into operation are under the close attention of the Simulation Center. The impact is further extended by the Laser Fusion Simulation project and numerical studies of the plasma material interactions. The Simulation Project coordinates works at numerous universities in Japan involved in theoretical fusion research. This activity should be the subject of enhanced attention of SSC in order to provide an additional manpower required by a wide range of achievements of NIFS.

b) Specific Researches (on topics)

Targets encompassing the LHD relevant work are well defined. However, these must include the most timely and topical issues such as CDC, IDB and Impurity Holes as items of great importance. Simulation Center should strive at playing a major role in understanding and extending these experimental gains by all possible means. Furthermore, models should aim at achieving a highest possible degree of self consistency. To this end, a strong case should be made for employing the new computational center coming into operation in Japan for the benefit of the thermonuclear fusion research. Publication record of the SSC is excellent. Important subjects for general science such as self-organization, reconnection and holism project are addressed properly. These are important for the integration into the NINS infrastructure.

c) Future Plan

The Numerical Test Reactor project is very ambitious and should be commended. The fruitful collaboration and support of the ITER modeling group should be enhanced. The integration into the LHD interpretation and the decision making must continue and become more in depth. The broad range of issues addressed by the SSP has to be maintained.

Works should be carried out to amplify the computational power by invoking the large computer infrastructure existing in Japan. A large reservoir of the theoretical knowledge and skills at many universities associated with NIFS can be used to enhance the SSC impact. Scenarios focusing on the advantages of the De operation of LHD have to be worked out.

(3) Coordination Research

a) General View and Achievements

Research Coordination Center is the first – class activity increasing spin-offs of LHD experience to many fields of science and industry. It extends frontiers of fusion research by addressing future issues such as tritium inventory crucial for DEMO. PWI and atomic data problems are solved thereby benefitting present and future experiments on LHD. ITER related work is highly developed. Laser fusion works and collaborations with National Astronomical Observatory are valuable. Outreach efforts born out by Fusion Kids Energy Museum are highly welcomed. The CRC is a well organized entity making it a powerful tool within the NIFS infrastructure.

PWI activity has made a significant progress and is now well poised to contribute to future plans of the LHD and QUEST operations. Original ideas such as moving – surface plasma – facing components both solid and liquid must be tested first on QUEST and in case of success on the LHD. Plasma diagnostics methods based upon modern atomic physics advances must be implemented on the LHD and the Solar observing satellite" HINODE". Tritium studies should be emphasized as well given the shortage of information from other sources. R&D works employing the Microwave Steel Making important for industrial applications should be given a high priority. Manufacturing of mirrors for ITER is another important subject addressed by the CRC.

b) Future Plan

The CRC pursues to enhance and further integrate its activity into the LHD activities. Collaborations with ITER and the BA must be strengthen and broaden. Given the uncertainty of IFMIF the works on the tritium handling must be given a special emphasis. The outreach work can be extended to other groups of authorities and population. SC conductors for JT 60 – SA must be tested. The pioneering work on the DEMO relevant issues has to be given a high priority. Collaborations within both NIFS and NINS activities within the context of contributions delivered by universities in Japan must be employed given limitations of the available manpower.

(4) Fusion Engineering Research

a) General View and Achievements

FERC represents a relatively new activity addressing fusion engineering issues in depth. FERC has made important input already by specifying most outstanding issues to be confronted by a fusion reactor. Blanket issues based upon Flibe and Li were addressed. Tests on welding, irradiation, corrosion and coating of V –alloy and ferrite steel were carried out. Quick feedback 3D code system is under development in order to study neutronics of a reactor. 14 MeV mockup tests are carried out albeit their limitations in relevance.

b) Specific Researches (on topics)

Specific research in FERC consists of blanket material systems, neutronics and magnet material systems. Welding of vanadium alloys has been already shown possible by oxygen impurity reduction. High purity metal vanadium was developed for V alloy large heat loads. NIFS-HEAT -2 was welded in high purity Ar flow to avoid impurity contamination. Degradation of fracture energy was enhanced in weld material and later recovered by post-irradiation annealing. The degradation of the quality of welding appeared at neutron irradiation dose of 8.5 dpa. Design and feasibility studies for forced convection loop of molten salt Flibe and liquid Li were advanced. Advanced coating technologies and the emergence of the tritium permeation barrier have been demonstrated. Fast feedback systems were integrated in the neutronics design. Tritium breeding under sufficient shielding has been attained. Critical currents of varying Nb compounds were investigated after the 14 MeV neutron irradiation. Low activation superconducting wires have invoked to enhance the electron current in V_3Ga.

c) Future Plan

Asymmetric and fractal geometries of surrounding structures will be addressed in collaboration with ASIPP, China. In-situ observations during and after the 14 MeV irradiation will be carried out. All Nb_3Sn strands will be tested in order to facilitate ITER TF magnet fabrication. FERC issues relevant for DEMO will be performed. Collaborations with the Oarai center of the Tohoku University on the 15.5 T and 500 A current lead should be given a high priority. FERC should continue long-term creep tests in order to investigate thermal creeps on a very long time scale. Other options relevant for DEMO invoking fission experience and know-how must be sought and found.

2. Others

Present leadership has made NIFS the world-class leader at the cutting edge of fusion research.
This result has been achieved by a perfect coordination of a wide range of activities and the integration of all activities into the main goal of thermonuclear fusion. A detailed plan has to be worked out in order to maintain the current momentum achieved by NIFS under the present leadership.

Reviewer: E

1. Project Activities
(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

The Large Helical Device (LHD) continues to be the flagship machine of worldwide experimental stellarator research. LHD has achieved new record plasma parameters, though not simultaneously. It was demonstrated very high beta (at magnetic field strength reduced to 20%) without strong degradation by magneto-hydrodynamic (MHD) instability, ultra-high density by means of pellet injection, fusion-relevant ion temperatures and interesting new regimes with reduced impurity accumulation in the center. In this way, LHD continues to contribute to the physics understanding of helical plasma confinement. This is also of significant relevance for the international fusion project ITER, in particular certain aspects of edge magnetic field stochastisation and MHD stability by means of toroidal field shaping.

It is evident that LHD will remain Japan's most important fusion device until JT-60SA goes into routine operation. Until then the national activities in experimental fusion research will naturally focus on LHD and may contribute to important cross-fertilization between stellarator and tokamak research.

b) Specific Researches (on topics)

The LHD device is outperforming its initial expectations. This is a great achievement and makes a remarkable contribution to the regained trust in the stellarator concept for fusion power. The excellent plasma performance parameters were achieved thanks to optimized magnetic confinement (by shift of magnetic axis and by changing the plasma aspect ratio) but also to the systematic extension of the heating capabilities, namely the NBI (currently 23MW, additional 7MW are planned). Combined with fast pellet injection, new operation regimes were discovered which allow for very high density operation with steep edge gradients. Furthermore, interesting regimes were found where impurity accumulation is prevented by a shielding phenomenon in the ergodic layer. In this way high density, high pressure and – at low magnetic field – high beta plasmas could be successfully created and maintained. MHD equilibrium and stability issues at high beta were very successfully addressed by the team.

From the above it is evident that the LHD device is well on its way to accomplish its target values. In addition, unexpected discoveries are made and high-level basic research is performed (in particular MHD instabilities, Alfvén modes, zonal flows). To further pursue the excellent research on LHD, a few recommendations may be taken into consideration:

- The physics understanding of the discovered new regimes should be driven forward. The internal diffusion barrier (IDB), the core density collapse (CDC), and the impurity hole are exciting and highly relevant discoveries. Here a systematic approach that combines theory, computer simulations and dedicated experiments would be helpful.
- Electron and ion temperatures in the high density regimes are relatively low (around/below 1keV). Conversely, the temperature goals are achieved at densities that are one order of magnitude lower than required. Making use of the flexibility of the LHD device, integrated scenarios should be developed in order to obtain an optimum $n \cdot T_i \cdot \tau_E$.
- Steady-state operation of highly powered plasmas is – besides better stability – the main attraction of the stellarator concept in fusion research. The detailed design and the construction

of the closed divertor should be pushed forward as much as possible. An upgrade of the steady-state heating power to 4MW is planned and should be available together with the fully implemented the closed divertor.
- Fusion reactor studies should be closely linked to the present DEMO studies, which are all based on tokamaks. Here the pro's and con's should be highlighted. It is evident that the lack of a Greenwald limit opens for stellarators the perspective of ignition at higher densities and lower temperatures. It would be helpful to get a full picture of the role of thermal instabilities, neutral particle transport, impurity generation and transport under these reactor conditions. Here the "numerical test reactor" (see below) will surely play an important role.

c) Future Plan

The plan to explore the isotope effect by performing a dedicated Deuterium program is greatly appreciated. This will also result in better figures of merit of LHD. The main elements of the further development of the device are (I) the upgrade of NBI (to 32 MW) and ICRH (to 4MW) and (II) the development, construction, and integration of a closed helical divertor. In the latter, a step-wise approach is planned which appear to be reasonable in order to avoid a lengthy shut-down.

Recommendations:

- As soon as the detailed design of the closed divertor is available, a detailed design review with the participation of international experts (in particular in the field of engineering) should be conducted.
- The establishment of an MHD data base is greatly appreciated. It might be of advantage to embed these activities into the formal agreements of international collaboration.

(2) Simulation Science Project

a) General View and Achievements

From the view point of the experimental researcher, the simulation science project seems to be internationally competitive with highly regarded scientific works. As mentioned above, a dedicated effort to understand the newly discovered operation regimes of LHD is required. The simulation science project of NIFS seems to be well positioned to takes these challenges.

It was very nice to see the breadth of the NIFS simulation science program: The range spans from MHD and LHD simulations to laser plasmas to complexity in plasmas. This interdisciplinary approach is clearly in the sense of the NINS and fosters collaboration between the institutions involved.

b) Specific Researches (on topics)

No specific comments.

c) Future Plan

For the further development of codes, e.g. in the field of turbulence and zonal flows, the access to high performance computers is extremely important. The plans for new super computer and the NIFS plasma simulator are very much supported.

(3) Coordination Research

a) General View and Achievements

NIFS remains being very well embedded into the Japanese university environment. This is obviously of high mutual benefit. This is particularly the case for plasma-wall interaction, materials sciences, nuclear sciences, diagnostics and basic plasma research. However, the coordination research center makes also sure that the university facilities are well integrated into the LHD program, which is clearly an outstanding achievement.

b) Future Plan

The close contact to ITER and DEMO activities is absolutely mandatory for the stellarator community. The coordination research centre is right to go into this direction.

(4) Fusion Engineering Research

a) General View and Achievements

The engineering aspects of LHD are already covered in (1).

b) Specific Researches (on topics)

No specific comments.

c) Future Plan

No specific comments.

2. Others

The special review meeting was the best review meeting I ever had. It was a most appropriate summary of the great achievements of the NIFS during Prof. Motojima's service as the director general. His success must be recognized and applauded. I was pleased to learn that with Prof. Komori a well established a highly regarded scientist was identified to serve for the next term. I wish him all success and look forward to the next review.

The oral presentations during the review were of excellent quality. I was very impressed by quality the presentations of the "younger generation", Drs Sakakibara (high beta operation), Sakamoto (high density operation), Watanabe (zonal flows). It would be nice to see these younger scientists from the NIFS team on international conferences as invited speakers.

Reviewer: F

1. Project Activities

(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

LHD is an impressively large fusion experiment. It has made significant contributions to the advancement of high temperature plasma and fusion physics, and in particular to the understanding of stellarator / heliotron physics. The main technical achievements are the reliable operation of a complex superconducting device. Here, I would like to specifically note the further increase of the magnetic field. Also the demonstration of steady state plasma operation is very valuable for future developments. Very important scientific achievements are the demonstration of high density operation with improved confinement properties, high beta operation reaching impressive values of 5%, and plasma scenarios with low impurity content (so-called impurity holes).

b) Specific Researches (on topics)

High density operation: To achieve high power density in a fusion reactor high plasma density is indispensable. The internal diffusion barriers demonstrates both that stellarators / heliotrons can reach very high densities and that a simultaneous improvement of the confinement is possible. It is interesting to see that the density could be further increased if more heating power were available.

High beta operation: Also high beta is required for a stellarator / heliotron reactor. A volume average beta of 5% is envisaged, which has been achieved by LHD. Also the improved theoretical understanding of the beta-limiting MHD instabilities has to be mentioned. In particular against the background that the theoretical predictions of the MHD stability of LHD plasma were not very favourable, further studies in this direction have to be encouraged. In this context the adopted approach to consider the link between magnetic field topology and MHD stability, i.e. the link between stability and equilibrium limits, should be further pursued.

Impurity transport: Impurity accumulation is one of the major issues of stellarator research. LHD has shown that, at least under certain conditions, it is possible to avoid such accumulation. Further studies in these direction including different plasma scenarios (high density, low density, high beta, different plasma edge conditions, etc.) are strongly encouraged.

Diagnostics: Diagnostics were not specifically addressed. Nevertheless, I would like to use this opportunity to mention the very good quality of the presented experimental data which are a prerequisite for the analysis and understanding of the plasma experiments.

Altogether these results clearly show that significant progress has been made and that LHD is a major player in the international fusion research. Besides achieving high plasma performance, the very good analysis based on an increasing collaboration between experiment and theory has been noticed. This should be intensified. In addition, future studies should attempt a more integrated approach towards the development of high plasma performance.

c) Future Plan

Extension of heating systems and divertor:

The plans to extend the heating systems and to install an actively cooled divertor have been received very positively. In particular with respect to my earlier comment about the development plasma scenarios which combine favourable plasma properties this is a very important step. Additional heating power is required to remove limitations in particular at high density or to extend the operational space to high beta at higher magnetic field. This implies also a plasma exhaust which is capable of handling more power. Active cooling is required for steady state operation at higher power. The approach to extend the divertor in a modular way, in order to minimize the shut-down periods is fully supported.

(2) Simulation Science Project

a) General View and Achievements

Theory and plasma simulations are indispensable for the understanding of the increasingly complex phenomena observed in fusion experiments. Here, NIFS in conjunction with their collaborators have developed an impressive amount of tools and made significant advances also in first principle theory. This includes MHD stability and plasma transport reaching from the core of the plasma to the edge. Also the link to related fields is positively noted. Simulation science is an area which provides very good conditions for close collaborations with university groups. The involvement of such groups is well established.

b) Specific Researches (on topics)

An comprehensive number of research topics has been presented, including major topics in fusion research such as turbulent transport, MHD stability, including reconnection phenomena, and plasma wall interaction. A specific presentation has been devoted to turbulent transport, explaining that the inward shifted configuration of LHD shows improved confinement, not only because of better neoclassical confinement, but also because of reduced turbulent transport. This work is not only important since it can explain experimental trends, but also because it adopts the very important issue of the relationship between turbulent and neoclassical transport.

c) Future Plan

The LHD and magnetic confinement simulation project and the numerical test reactor project are important steps to develope the understanding of the running experiment and the basic properties of a fusion reactor. The presented plans are strongly encouraged. More heuristic simulations and first principle based theory are well balanced. The main recommendation is to further extend the link between theory and experiment in areas such as impurity transport and MHD stability.

(3) Coordination Research

a) General View and Achievements

Fusion requires stable long-term research and development. This makes the integration of universities for both education and participation in science and technology studies very valuable. An impressive number of collaborative research project has been presented covering a large number of topics. The approach to use NIFS and LHD as the centre of a large number of specific topics and research groups is the appropriate strategy to involve universities and other research groups.

b) Future Plan

Future plans, involving universities in ITER and DEMO developments, directly or indirectly via NIFS, are strongly encouraged. Such large scale facilities and development programmes require a broad academic basis not only for promotion of young scientist and engineers, but also for providing acceptance in the general population. In this context, it is very good to see that already the youngest generation is introduced to the topic of fusion research.

(4) Fusion Engineering Research

a) General View and Achievements

A very ambitious development plan for DEMO has been presented. The presented technology topics cover the main areas which need to be further developed: Blanket material system, neutronics, and magnet material system. The plans to construct systems which test as far as possible the integration of the individual components are strongly supported. For future discussions a more detailed analysis how the development plan depends on the ITER and IFMIF schedules, including decision making requirements, would be helpful.

b) Specific Researches (on topics)

Blanket material system: Interesting new results were presented indicating potential solutions for the blanket technology. A dedicated presentation explained the development of a liquid breeder blanket. In addition to the excellent presentation the main impression was that this research area is benefiting from very good collaboration work and a healthy nuclear industry. For the future a system integration for feasibility studies on the compatibility of hydrogen recovery and heat exchange in a flowing system is planed, which is strongly supported. It is recommended to further elaborate the plans to eventually test such a blanket on ITER.

Neutronics: The design of the FFHR is based on 3D neutron calculation for tritium breeding and neutron screening. It is very encouraging to see that these calculations are validated by DT neutron irradiation measurements. Future plans comprise improved neutron calculations for complicated geometries and further validation measurements.

Magnet material system: The effect of neutron irradiation on the magnet performance (critical magnetic field) has been discussed in detail for various types of superconductors. Future work will also include high-temperature superconductors, which is strongly encouraged, as this would significantly alleviate the requirements for the cryogenic systems.

2. Others

Finally, I would like to express my gratitude for the opportunity to take part in this special review. Not only did I learn a lot about NIFS and LHD, but I also enjoyed the very high quality of the presented work and the well-founded discussions. The younger researches taking part in this review demonstrated that NIFS is well prepared for the future. Sending these young researchers to major conferences should be encouraged.

Reviewer: G

1. Outline

Upon the establishment of the National Institute for Fusion Science (NIFS), a task force consisting of major researchers in Japan was placed under the Nuclear Fusion Group in the Academic Council to debate on major plans carried out in NIFS, and a series of in-depth discussions were made.

It was then concluded to pursue the following: 1) to adopt torus plasmas that were being conducted research with largest numbers of researchers on a global scale and that were best acknowledged academically at that point, and among those, to adopt the external conductor system that had a high-flexibility in the magnetic field configuration setting; and 2) to carry out the research in the torus plasma confinement physics including tokamaks.

The NIFS LHD research was first started from the device technology development including the superconducting magnet technology, and the LHD construction was successfully carried out based on the experiences in constructing another devices and their results. After that, a desired design and construction, studied from a broad perspective, were smoothly progressed; now, the device is making outstanding research achievements as the world leading large-scale torus device. This situation fits the initial expectations. As a person who has been witnessing the progress of its research ever since its start-up, I would like to begin my report by stating that the review of this time was extremely a satisfactory one with nothing to betray my expectations.

2. Large Helical Device (LHD) Project

The record of their steady-state operation (namely a high-ion temperature of 5.2 keV, high-density of $1.2\times10^{21}m^{-3}$, and a high β value of 5.1 %), which was achieved as its major research plan in NIFS, one of the Inter-University Research Institutes, under the proper research programs, should be highly evaluated as well as especially noted. Moreover, NIFS did not just pursue those data excellent as a record but that the institute made such notable achievements through a series of research and experimental campaigns to execute its original mission, which was to thoroughly research in the torus confinement characteristics as described above. This must be highly admired.

3. Activities as an a Inter-university Research Institute

(1) Simulation Science Project

While it is essential for NIFS to play its role as the inter-university research institute in executing the institute’s major plan addressed above as a matter of course, it is also desired that NIFS will make contributions to the entire field of fusion researches.
First of all, the simulation science to fully utilize the benefit of a rapid hardware / software progress made in the recent computer science is an important research method in the fusion researches. Besides, it will be a critical mission as the inter-university research institute for simulation researches to make the progress by communicating with wide fields deeply related to fusion researches.

Especially in the fusion research as a big science, simulation is also important method to apply its achievements to the confinement researches in other configurations like tokamaks by not only understanding the results of experimental research and predicting experimental results in the major plan in NIFS but also by analyzing its confinement characteristics.

In order to achieve the scientific results, except for simply utilizing the computer hardware performance as well as the ordinary software technology; the development of simulation methods based on characteristics inherent to fusion plasmas is extremely critical. Thus, the ability for that aspect is desired.

The theory and simulation science research in NIFS are evaluated as a quite high level, and the achievements up to now fully satisfied our initial expectations.

(2) Coordination Research

In a way, it is the matter of course that any major research like the nuclear fusion science, where a grand-scale budget is required, is expected to contribute to varieties of related areas of research along with the execution of its main plan. Therefore, a role of the newly established Coordination Research Center is much expected.
At the same time, it must be quite challenging to extract effective tasks among many related areas of research from a broad scientific, technological, or industrial perspective.

The newly established Coordination Research Center is extracting interesting topics and enabling the effective collaborative researches by surveying a broad field of research that deeply relates to surrounding areas as well as the industrial application. This will surely enhance the NIFS significance as the inter-university research institute, and thereto, possibly enhance a reputation toward the entire 'new energy source development research project' called 'nuclear fusion'. I should say that this new development deserves a special attention.
Now, a further development in this area is much expected.

By the way, the area of atoms and molecules in plasmas has been globally acknowledged as one of NIFS activities in the related fields. Though it may not be boldly recognized from the aspect of applications, the area of atoms and molecules has been making series of important achievements not only as a foundation to support various scientific technologies, namely many different industrial technologies like material science or diagnostic technology, but it has also built up a critical knowledge as a foundation of many academic fields.
Because of its rather unimposing existence, one may have to understand that no grand report was not made for their achievements this time; yet, I still cannot help hoping that they would further improve then develop their existing precious accumulations.

4. Others

Four presentations in the "Recent Research Report, Topics" by 4 young researchers in the afternoon were truly impressive since they proved that excellent young researchers were steadily brought up. It must be, needless to say, a wonderful opportunity for any young researchers to engage in their research in a great environment like NIFS.
Yet, I've seen many times that because of the severity of 'reviews' given to research, young human resources were wasted and the difficulty arose as to the improvement of promising young talents. Also, I often hear more than a few voices wondering whether such distinguished researchers who can be responsible for the academics in the future could really be fostered under such circumstances.

The fact that NIFS is in the process of successfully fostering such talented researchers definitely proves the healthiness of its research activities.

Thus, I should comment in addition that the future of nuclear fusion studies in Japan much depends on their effort.

5. Summary

As I have stated above, research activities by the National Institute for Fusion Science have made outstanding achievements as one of the leading magnetic field confinement nuclear fusion research in the world.
Their research fully satisfied our expectations, and thus it should be highly regarded.

6. Expectations

First of all, it is advisable that the present activity should be continuously carried out for further development as one of the major streams of the magnetic field confinement nuclear fusion research by the use of large-scale devices in the world.

On the other hand, the global trend is not necessarily focusing on the magnetic field confinement nuclear fusion only. It should be specially noted that in the Asian region, centers for the inertial confinement fusion research were constructed in China and Korea, respectively, to perform aggressive research activities.

The inertial confinement fusion research in Japan has been mainly carried out in the Institute of Laser Engineering (ILE), Osaka University up to today. Well, especially these days, many research groups have taken notice of the fast ignition developed by ILE, following them to carry out research along with the new development. Unfortunately, the fact is that it is not easy at this point for universities in Japan to compete each other on these activities.

Finally, I earnestly hope that NIFS will quickly devise a plan concerning how to deal with the inertial confinement fusion research in NIFS as the future nuclear fusion research plan in our country and moreover that the institute will consider adopting it as one of the NIFS plans.

Reviewer: H

1. Project Activities
(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

In General, the Large Helical Device Project has come long way after the "First Plasma", and it is now very mature fusion research program and leading experimental program world-wide. In my opinion, it is entirely due to leadership of NIFS and LHD Project, as well as dedicated professional staffs and technical members of the LHD Project. The LHD Project also provided and enhanced collaboration with domestic as well as international researchers and institutions for effective scientific program execution and human resource development in fusion science. It is also worthwhile to recognize the LHD experiment produced well-qualified world-class scientists by providing training and education in real world setting.

With new perpendicular NBI addition, the achievement of high ion temperature with high density is very impressive advancement since last review. In this series of experiment, the improvement of ion heat transport is attained level of neoclassical transport.

The achievement of high beta 5.1% and sustained value of 4.5% in steady-state, is also beyond initial design value as well as expectation. Detailed study of magnetic configuration and topology of flux surface has made such impressive achievement possible.

Along with high ion temperature experiment and high beta study, the achievement of high density, high pressure discharge due to internal diffusion barrier, is also very important progress. The measured diffusion coefficient under very high density gradient condition is studied very detailed manner.

In steady-state operation study, the control of heat-load on divertor plate as well as improvement of divertor plate heat conductivity had proven to be effective, so that the future planed upgrade could be more conclusive.

In conclusion of general view and achievement section of LHD Project, the achievements on ion temperature, electron temperature, higher-beta, electron density, and steady-state operation, all are surpassing initial expectation of LHD experiment targets, even though the operation of LHD is still moving forward strongly. So we could expect even better results after planed upgrade.

b) Specific Researches (on topics)

(i) High-Beta Research with 3D MHD Characteristics

As noted in general section, the high-beta study in LHD showed very high level of depth and maturity in all issues including MHD equilibrium, MHD stability and transport. The MHD equilibrium study with magnetic axis, aspect ratio variation compared with equilibrium topology, showed way to achieve higher-beta and way to avoid equilibrium beta-limit.

In MHD stability area, the study showed the clear dependence to the magnetic Reynolds number. Also the linear stability study made distinction from the resistive interchange mode stability prediction from real experimental environment. The ideal modes such as Mercier mode, low-n interchange mode, high-n ballooning mode, had been studied in detail. It derives possibility of common understanding of characteristics if MHD stability and relation to profiles as well as confinement.

(ii) High Density Operation

For achieving high density plasma, fueling with pellets and particle control has been studied in LHD. The results with various pellet injection methods also presented. In this high density study, the LHD Internal Diffusion Barrier plasma is produced with high density gradient. The reproducibility of IDB shots has been demonstrated and the transport properties of IDB shots had been studied in detail

In the high density study, the highest density is achieved and quasi-stationary sustainment of high density shots had been achieved by using repetitive pellet injection. The results showed way to improvement in future planned upgrade, as well as reactor studies.

c) Future Plan

In planned near term upgrades, the upgrade of heating capability in NBI, ICH and ECH is deemed very important to continue progress of LHD experiment that has been demonstrated in various areas. Also, the deployment of closed helical divertor would be very important to achieve better handling of particles and heat load to the plates.

The experimental capability with deuterium fuel would be very good compliment to the already impressive capability of LHD by providing tools for isotope effects.

(2) Simulation Science Project

a) General View and Achievements

In the report, the three major simulation efforts have been reported. The first effort, that is LHD and Magnetic Confinement Simulation with Numerical Test Reactor, is the most important among all three. The impressive progress in this first effort made LHD experiment much more consistent and strong in finding way to improve in the recent years. In my opinion, the fast growth in simulation area contributed and will contribute significantly to better understanding of experimental results as well as finding innovative new approach to the better performance of LHD experiment in future. It is also very much noted that the theoretical study and turbulence simulation worked very well and good feed-back to each other. These efforts will, no doubt, contribute to the LHD experiment and better understanding on confinement, so that the improvement on the target values.

It is worthwhile to noted that the fast ignition simulation of laser fusion, PIC-MHD simulation of magnetic reconnection phenomena, and PIC-MD simulation of plasma material interaction had made very good progress.

b) Specific Researches (on topics)

In Magnetic Confinement Simulation Project, the hierarchy-extended simulation with core-plasma fluid model, core-plasma kinetic model, and peripheral plasma model, as well as hierarchy-integrated simulation, have been presented with very strong progress and impressive results. Especially, the development of TASK3D code and application to the LHD Plasma analysis showed very important progress for future synergy between simulation and experiment.

The turbulence transport and zonal flow simulation showed NIFS' leading role in this effort in the world together with very strong collaboration with other leading groups. The fast growing capacity is very impressive and we would recommend to encourage higher priority in support.

c) Future Plan

The proposed future plan in magnetic confinement simulation project seems well posed. The improvement of hierarchy-extended simulation and integration to the level of numerical test reactor will be very challenging but worthwhile effort. It is recommend to make progress in turbulence simulation for particle transport, momentum transport along with electron transport studies in the present level of ITG related turbulence simulation.

(3) Coordination Research

a) General View and Achievements

In very short time, the Research Coordination Center made very good progress in many areas of cooperation activities, including Universities, Industries as well as other Research Institutions. The renewed efforts in atomic-molecular and edge-plasma data group made good results in plasma-wall interaction, moving-surface PFC studies, and plasma diagnostics using impurity ions.

The industrial cooperation with spin-off technology made big progress in many applications of microwave technology.

The cooperation with other research institutions including ZPF ceramics for large telescope is worth noting for fusion spin-off application.

b) Future Plan

The future plan for two cooperation areas such as industrial application and other research institutions is extension of what has been done, so far. But it would be recommendable to extend technologies aside from microwave application. The LHD has many other advanced technologies that have many spin-off potential, so it would be worthwhile to pursue systematic approach to cultivating new applications.

It is also recommendable to engage in much stronger way in ITER cooperation as well as BA. With accumulated engineering capability and technology know-how’s, NIFS is uniquely qualified to contribute ITER and BA project’s success. Therefore, the institutional priority to ITER engagement needs to push higher than up to now.

(4) Fusion Engineering Research

a) General View and Achievements

The main thrust of the Fusion Engineering Center is consisted with three areas including blanket material, neutronics and superconducting magnet materials. The blanket material system area has made steady progress with solid results. Neutronics area is now producing results. The superconducting magnet material area now produced important contribution to the neutron irradiation studies.

b) Specific Researches (on topics)

In specific contribution of FERC, the development of long-life liquid blanket is presented. The ITER

TBM related research including V-alloy, and Flibe, made steady progress. The detailed study and development is in progress.

c) Future Plan

The future direction of FERC's research plan is well placed to the system integration toward DEMO Reactor. However, the more effort and higher priority needs to be placed toward neutron material studies such as IFMIF or other neutron source.

2. Others

In concluding Special Review, the recognition of Professor O. Motojima's leadership to achieve this far, is on order. His contribution to the design, construction and operation of LHD before his DG position is well-known for long years, now. However, the his legacy of the six year tenure of NIFS DG is so distinguished, so the peers and followers would have very hard time to match in the future.

However, I strongly believe that the leaders of LHD experiments and younger generation scientists and engineers in NIFS will move into new territories of LHD experiment and beyond. To achieve this effectively, it will be important to have leadership with future vision, and empowerment of more active younger generation in leadership role.

Again, I am very honored to review such wonderful organization with leader like Professor Motojima.

Reviewer: I

1. Project Activities

(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

The plasma performance that has been achieved in the Large Helical Device (LHD) is most impressive. The target parameters for electron temperature and density, ion density, steady-state operation discharge time, and volume-averaged beta have all been either achieved or surpassed. The central ion temperature achieved to date (5.2 keV) is about half of its target (10 keV); it is to be noted, however, that a central ion temperature of 13.5 keV has been achieved with Argon gas.

b) Specific Researches (on topics)

The upgraded heating provided by the new 7 MW, 40 keV perpendicular neutral beam has resulted in higher ion temperature and improved ion thermal transport. Very interestingly, LHD also finds that, as the ion temperature gradient increases, a carbon impurity “hole” is formed, due to outward convection. The convection is apparently anomalous, contradicting neoclassical theory. This impurity hole is quite an impressive effect.

Also extremely impressive is the attainment of high volume-averaged beta (5.1% maximum, with 4.8% sustained for 85 energy confinement times and 4.5% sustained for 150 energy confinement times). The continued increase in achieved beta values with additional auxiliary heating is very promising for helical confinement systems.

The ultra-high density results achieved in LHD with the “internal diffusion barrier” are important in that they offer the possibility of a route to a force-free helical reactor. (This was a major topic of discussion at the 2008 International Toki Conference.) The continued optimization of pellet fueling is a necessary research topic for pursuing a high-density reactor scenario.

Transport in the ergodic layer at the plasma edge in high-density and high-beta LHD plasmas is an important research subject. The 3D edge transport code EMC3-EIRENE has been used to analyze the experimental data.

The measurement of fast-ion loss with scintillator probes, particularly in combination with code simulations of Alfven eigenmode-induced fast ion transport, has resulted in very nice data that is well interpreted.

I very much appreciated the specialized talks on high-beta MHD experiments (presented by Dr. Sakakibara) and on high-density operation for helical reactors (presented by Dr. Sakamoto). The lovely comparisons of experimental data with simulation results in both of these talks were especially well done. For example, the achievement of high precision MHD codes that allow the study of high-n ballooning modes has led to greatly improved predictions. In both talks, clear statements of next-step research plans were provided. Definitely I would encourage similar in-depth talks on special topics at future External Peer Review Committee meetings.

c) Future Plan

The LHD has four near-term future plans: (1) upgrading the auxiliary heating—in particular, adding a fifth neutral beam line, (2) installing a closed helical divertor, (3) operating deuterium plasma discharges, and (4) continuing the design study for the force-free helical reactor. These are important steps for moving forward and should be pursued vigorously. It would be interesting to hear more details about these future plans at a future External Peer Review Committee meeting.

(2) Simulation Science Project

a) General View and Achievements

The Department of Simulation Science has been very productive, with many results, invited talks, and publications. Consequently, the overview presentation on simulation science had to cover too many research topics, with little detail. The afternoon in-depth talk, however, compensated for this.

Particular examples of excellent research are the gyrokinetic simulations, multi-scale interaction between micro-turbulence and macro-MHD; energetic particle simulations; collisionless reconnection; and laser fusion simulations that led to new target designs for Fast Ignition.

The Department of Simulation Science appears to have good collaborations with the LHD Theory and Data Analysis Division. Collaborations with outside groups and scientists are also strong. In particular, I note a number of excellent papers written jointly with the JIFT visiting professors in recent years.

The annual Symposium on Simulation Science, which has now been held for two years (2007 and 2008), is developing into a solid meeting. The 2008 Symposium attracted 90 participants.

The replacement supercomputer (77 TFlop, 16 TByte) for simulation science was successfully selected and announced in September 2008. It will begin operation in March 2009. No doubt it will be put to heavy use for the Numerical Test Reactor Project.

As I had pointed out last year, the terminologies “hierarchy-extended,” “hierarchy-integrated,” and “hierarchy-normalized” are unclear. My suggestion is to use terminology that is more internationally accepted and understood.

With its world-class expertise in simulation science, it might be advisable for NIFS to participate in the Integrated Modeling Expert Group that is being newly formed for ITER.

b) Specific Researches (on topics)

The research on gyrokinetic simulations is internationally recognized as first class, as evidenced by the many recent publications (including a Physical Review Letter last year) and also by its having been selected for invited talks at three major international conferences in CY 2008 (American Physical Society, International Congress on Plasma Physics, and IAEA Fusion Energy Conference). The in-depth specialized talk on this research (given by Dr. Watanabe) was very well presented. Of particular interest, it has been found that inclusion of the radial drift motion of the particles trapped in helical ripples now leads to ITG heat transport results for inward-shifted plasmas that are in close agreement with the experimental observations. I recommend that these gyrokinetic simulations are now at a stage where specific experiments could be proposed on LHD to test its theoretical predictions. The proposed research on ETG turbulence and zonal flows is important. Studies of momentum transport and anomalous particle transport, in addition to heat transport, would also be advisable.

Considering the importance of the divertor to LHD high-density operation and of the ergodic surface layer in high-beta operation, it would be useful to strengthen the theoretical/simulation research on boundary plasma physics. In particular, the 1-D fluid modeling in the divertor leg for LHD should be extended to two or three dimensions and generalized to include kinetic effects.

For the laser simulations of FIREX, the new ideas of pre-pulse heating and additional foam in the cone should result in significantly improved performance.

Using the magnetic reconnection simulations to attack a real-life problem (viz., magnetospheric substorms) is commendable. Another significant real-life application for reconnection simulations would be solar coronal loops.

c) Future Plan

There are 14 targets in the Mid-Year Plan for the LHD and magnetic confinement simulation project. These targets are all reasonable. It would be helpful to hear more about how "hitting" these targets would impact LHD operation and/or understanding.

The Mid-Year Plan targets for the laser simulation project seem quite ambitious, especially in view of the fact that only one scientist at NIFS works on this project.

The Mid-Year Plan targets for the plasma complexity simulation project are reasonable.

The goal to develop a Numerical Test Reactor is exceeding ambitious. In addition to the flow chart describing this an all-encompassing code, it would be helpful to see a set of clearly defined concrete steps for the near-term plan.

The LHD experimental program is producing novel results—e.g., impurity holes, density barriers, ultra high beta operation—with interesting physics aspects, which could be clarified with simulations and theoretical interpretation. I recommend that the Department of Simulation Science continue to emphasize pursuing such studies.

(3) Coordination Research

a) General View and Achievements

The Coordination Research Center carries out a rather wide spectrum of interesting activities.

The internal structure of the Coordination Research Center was somewhat re-organized in 2008, with the conversion of the atomic and molecular effort from a Data Research Center into an Edge Plasma Data Group, the addition of a group on basic innovation science and technology within the Division of Industrial-Academic Research, and the addition of a new Division of Science Communication (which includes the new Fusion Kid's Energy Museum). In the revised organizational structure for the Coordination Research Center, it is unclear whether the terms "collaboration," "coordination," and "cooperation" have different or identical meanings.

In the area of plasma-wall interactions, the Coordination Research Center has a study on liquid and solid lithium moving-wall concepts. It would be interesting to hear how this study differs from corresponding investigations of lithium plasma-facing components by other world research groups. Also, it's not clear what are the new results; the most recent reference is to a paper by Nagayama that was presented at the 2008 Symposium on Fusion Technology (but he is not listed on the Coordination Research Center web page as a Center member).

The work on developing collisional radiative models for impurity ions is relevant to diagnostic measurements at the plasma edge in LHD. These models are said to form the basis for external collaborations to analyze solar plasma data.

The work on developing tritium recycling simulations that incorporate plasma physics, materials science, and atomic and molecular physics could be critically important for ITER and other burning plasma experiments. Two papers on this subject, presented at the recent PSI and ICPP conferences, have been accepted for journal publication. More work in this area would be advisable. Perhaps the Coordination Research Center activities on plasma wall interactions and on tritium inventory and recycling could be coordinated with similar activities in the Fusion Engineering Research Center.

It’s a bit confusing why the FIREX fast ignition simulations, already reported (as a collaborative effort) in the presentation concerning the work of the Department of Simulation Science, should also be included in the Coordination Research Center presentation.

The investigation of microwave sintering techniques for novel ceramics constitutes a major portion of the work done at the Coordination Research Center. This work has important applications for the construction of the mirror for the next-generation Extra Large Telescope. This work has also led to the establishment of significant collaborations with industry. Noteworthy in this connection are the Monte Carlo simulations on energy released by magnetic field changes, which led to the discovery of a very interesting result about the vanishing of spontaneous magnetization above the Curie temperature.

NIFS is to be commended for sponsoring the Fusion Science Archives, in which so far 18,000 documents have been collected. It is unclear why the number of events in the database, which had been increasing monotonically from about 1997, abruptly fell after 2005.

The Kids Fusion Science Museum, which began operation in late 2008, is an interesting new outreach program sponsored by NIFS through the Coordination Research Center. Personally, I walked through the exhibition room in the NIFS lobby and enjoyed looking at the various exhibits. I expect that students from local schools are similarly fascinated with the exhibits, as well as with the tours of the LHD device and the virtual reality simulation center.

The new course on “Science Communication” for teachers is also an excellent idea.

b) Future Plan

Except for a sentence about planning to develop a collisional-radiative model to examine solar coronal heating, no clear statements were provided about future plans. Presumably the current work described in the presentation will be continued forward.

(4) Fusion Engineering Research

a) General View and Achievements

The Fusion Engineering Research Center (FERC) is well equipped with good facilities, which will help to advance collaborations with university research groups.

The FERC is currently engaged in seven collaborations with groups at Japanese universities, in addition to working with scientists in other departments at NIFS on LHD engineering problems, on the force-free helical reactor, and on safety and cost evaluation. The increased emphasis on FFHR reactor design issues, especially blankets and irradiation, is commendable.

The FERC appears to be well managed.

b) Specific Researches (on topics)

In the area of blanket material systems, new results have been obtained for the welding of vanadium alloys, for forced convection of molten salt Flibe and liquid lithium, and for advanced coating technologies. Noteworthy was the young scientist award received from the Japanese Atomic Energy Society for the work on confirming the low corrosion rate of steel in high purity Flibe. The in-depth talk about the development of long-lived liquid breeder blankets (presented by Dr. Nagasaka) was quite interesting.

In the area of neutronics, both simulations and experiments are being performed. Importantly, this allows for validation of code modeling for Test Blanket Module and DEMO reactor designs.

In the area of magnet material systems, collaborations with universities, industry, and other national laboratories (NIMS and JAEA) are exploring the effect of neutronic irradiation on superconducting magnet materials.

I appreciated the tabular presentation about the number and various types of papers published during the past three years. For only having a staff of 7 scientists along with 3 students, the FERC has published prolifically during the past three years. Many of the papers were joint collaborations. The FERC has apparently made a conscious effort to promote the writing and publishing of papers.

c) Future Plan

Future plans were clearly presented for the three research areas of blankets, neutronics, and magnets.

2. Others

The National Institute for Fusion Science has a well-articulated statement about its three-fold mission goals. These goals are to carry out (1) research—experimental, theoretical, and engineering; (2) collaborations—national and international; and (3) training—graduate students and young researchers. Overall, NIFS is strongly fulfilling all three parts of its mission. The FY2004-09 Mid-Term Plans for the Large Helical Device project, for simulation research, and for fusion engineering are clearly stated. (It would be useful if there were also a similar statement of Mid-Term Plans for coordination research.)

The number of staff at NIFS increased marginally (2%) in FY 2008, compared to FY 2007. The budget decreased slightly from last year (less than 0.5%, which nevertheless amounted to 41 MYen in real money).

The number of research topics (and the number of collaborators) for general collaboration research, LHD collaboration research, and bilateral collaboration research all increased somewhat over the corresponding numbers for the previous year. However, the funding dropped slightly (by 21 MYen). Interestingly, the total number of universities and institutes involved in collaborations with NIFS decreased 8% from 157 to 144.

During 2008, no new governmental international collaborations or scientific agreements with foreign universities or institutes were established. Six of the former and 14 of the latter had previously been established, and this is already an impressively large number.

The number of students who are being trained through the Graduate University of Advanced Studies has remained constant, compared to last year, as have the number of students from associated universities doing degree work at NIFS and the number of student researchers working at NIFS through collaborative projects. The number of students from associated universities taking courses at NIFS has dropped by 50%. In 2008, the ITER International Summer School was held in Japan.

I appreciated the provision of 12 recent NIFS publications, as background information to the presentations at the meeting.

I recommend the inclusion of metrics in the overview presentations at future External Peer Review Committee meetings as measures of progress and activity for LHD, simulation science, research coordination, and fusion engineering. Examples of such metrics are the number of number of published papers, invited talks, patents, students graduated, collaborations, etc.). I have the impression that the NIFS publication record has been continuously increasing every year. The NIFS presence at the recent IAEA Meeting in Geneva was certainly very strong.

The excellent in-depth talks in the afternoon—very clear, very well organized—by the (comparatively) younger scientists bode well for having highly qualified staff members in the future at NIFS. Actually, I suspect that NIFS could have easily scheduled twice as many such talks, all reporting results at the same high level of achievement.

I have nothing but praise for Prof. Motojima as the NIFS director-general for the past six years. The Large Helical Device is now the best helical confinement fusion device in the world. NIFS is a world-leading center of excellence in fusion science, with a program that integrates experiments, theoretical simulations, and fusion engineering. The next director-general of NIFS will inherit an Institute that is functioning efficiently and productively, thanks to Prof. Motojima’s outstanding leadership.

3. Brief Summary

1. Project Activities

(Research objectives, Results and Topics, Research Quality, Suggestions for Improvements)

(1) Large Helical Device (LHD) Project

a) General View and Achievements

- The achievements of LHD project are very impressive and cover all the main issues for the successful development of fusion energy.
- The highlights of major discoveries during the last 6 years are the high ion temperature accompanied by an impurity hole, ultra-high density operation, high average beta without strong degradation by MHD instability, and steady state operation. These are promising results for helical confinement systems.
- Physics study has been emphasized, which is surely based on the NIFS's mission originally given at its establishment. They have also contributed to the progress of comprehensive understandings of toroidal plasmas.
- Reliable operation of a complex superconducting system is a great technical achievement.
- The LHD project has provided and enhanced collaborations for effective execution of science program and human resource development in fusion science.

b) Specific research

- The excellent plasma performances were achieved by optimizing magnetic configuration and the systematic extension of the heating capabilities. Combined with fast pellet injection, new operation regime, disruption-free high density operation, was discovered.
- Interesting regimes were found where impurity accumulation is prevented.
- MHD equilibrium and stability issues at high beta regime are very successfully addressed. It is recognized that good quality of diagnostics has driven the progress of the analysis and the understanding of the plasma experiments.
- Upgrade of heating capability, the smart implementation of the closed divertor configuration and the deuterium operation should be employed in order to extend the steady-state operation and to approach the triple product relevant for stringent fusion requirements.
- The physics understanding of new discoveries, such as internal diffusion barrier (IDB), the core density collapse (CDC), and the impurity hole, should be driven forward. More emphasis should be put on momentum transport and in particular on the correlation with the impurity transport.
- Beta value can be increased even further by careful real-time configuration control.
- The measurement of fast-ion loss and the corresponding simulations has resulted in very well interpreted nice data.
- Reactor studies should be closely linked to the present DEMO studies. It is evident that the lack of a Greenwald limit opens the perspective of ignition at higher densities and lower temperatures. It would be helpful to get a full picture of the role of thermal instabilities, neutral particle transport, impurity generation and transport under these reactor conditions.

c) Future plans

- Nearest future plans, such as the deuterium experiments, upgrade of the heating capability, closed helical divertor and continuation of the design study for the force-free helical reactor, are well defined.

- A step-wise implementation of a closed helical divertor is well planned not to affect the experimental schedule.
- It is recommended that all efforts should be made to take the machine to its physical limits.
- Novel subtle methods based on technical and computational excellence of NIFS has to be sought and found to improve plasma parameters.

(2) Simulation Science Project

a) General View and Achievements

- It is highly evaluated that the simulation group has grown up so as to develop three projects in parallel. Especially, LHD and magnetic confinement simulation project has steadily achieved internationally-competitive and highly-regarded results. The fast growth in simulation research has contributed and will do so to better understanding of experimental results and to find the better performance of LHD in future.
- It is the right way to develop “The Numerical Test Reactor Project” by integrating these activities and heavily utilizing the replaced supercomputer.
- The impact is further extended by the laser fusion simulation project and numerical studies of the plasma material interactions.
- These projects taking the interdisciplinary approach coordinate related works at numerous institutions.

b) Specific Researches (on topics)

- Research on ITG turbulence and zonal flow formation in helical plasmas is remarkably progressed. It has been clarified that the zonal flow is kept with higher amplitude in a configuration with smaller neoclassical transport. The effect of radial electric field has also been investigated. These simulations are now at a stage where specific experiments could be proposed on LHD to test its predictions.
- The development of TASK3D code and its application to the LHD experiment showed very important progress for the future synergy between simulation and experiment.
- Inclusion of quite detailed diagnostics data could be a good addition to the present excellent simulation results.
- Comparison with tokamaks should be taken into account.
- Targets encompassing the LHD experiment are well defined. These must include the most-timely and topical issues such as CDC, IDB, impurity hole and momentum transport.
- Important subjects for general science such as self-organization, reconnection and holism project are to be integrated into the NINS infrastructure.

c) Future Plan

- The Numerical Test Reactor project should be commended with a set of clear defined concrete steps for the near-term plan.
- The fruitful collaboration and support of the ITER modeling group should be enhanced.
- Scenarios focusing on the deuterium operation have to be worked out.
- The plans for new supercomputer are very much supported.
- It is strongly hoped that these simulation projects will play the pioneering role to promote the integrated research on hierarchical phenomena in a wide range of fields.

(3) Coordination Research

a) General View and Achievements

- Coordination Research Center is well-organized and performing the first-class activity increasing spin-offs of LHD experience to many fields of science and industry. This is particularly the case for atomic-molecular process, plasma-wall interaction, materials sciences, nuclear sciences, laser fusion, diagnostics and basic plasma research.
- Outreach efforts such as "Kids Fusion Energy Museum" are highly praised.
- The new course on "Science Communication" for teachers is also an excellent idea.

b) Future Plans

- Close contacts such as with ITER and BA, JAEA and ICF (FIREX) research are strongly encouraged. The pioneering work on the DEMO relevant issues has to be promoted.
- Tritium handling issues must be given a special emphasis.
- Further progress of atomic-molecular database activity should be emphasized as the basis of a wide range of scientific fields.
- The LHD has many advanced technology with spin-off potential to pursue systematic approach to cultivate new application.
- The outreach can be extended to other groups of authorities and population. These will be related to the future plans of NIFS so that discussions with related community should be promoted by exploiting NIFS's inter-university framework.
- It is also recommended to clarify the final object of each research topic, and what kind of "Boomerang" effect has been obtained.

(4) Fusion Engineering Research

a) General View and Achievements

- The research subjects were very well chosen and the obtained results are world-relevant. FERC (Fusion Engineering Research Center) has obtained important results by specifying most outstanding issues towards a fusion reactor, such as blanket, neutronics and magnets.
- Specification of the expected scale of a reactor would be worthwhile to understand their achievements.

b) Specific Researches (on topics)

- Researches in FERC consist of blanket material systems, neutronics and magnet material systems. Long-life liquid Flibe and Li blanket studies were impressive.
- NIFS-HEAT-2 was welded by avoiding impurity contamination.
- Fast feedback systems were integrated in the neutronics design. Neutronics studies are welcome in view of the approaching ITER operation.
- Developed results of superconductors are evaluated to be at high-level.

c) Future Plans

- Collaborations should be further promoted such as issues on the geometries of surrounding structures, and on the current lead.

- It should be continued long-term creep tests in order to investigate thermal creeps on a very long time scale.
- Improvement of neutron calculations for complicated geometries and further validation measurements and study on the high-temperature superconductors are expected.
- More efforts and higher priority needs to be placed towards neutron material studies such as IFMIF or other neutron source.
- More detailed analysis how the development plan depends on the ITER and IFMIF schedules would be helpful.
- The plans for helical reactor and comparison between tokamak and helical reactors are expected.

2. Others

- Outstanding leadership of Director-General Prof. O.Motojima has made NIFS the world-class leader at the cutting edge of fusion research. These results have been achieved by a perfect coordination of a wide range of activities and the integration of all activities into the main goal of thermonuclear fusion. They covered not only the world-relevant experimental results in LHD and simulation sciences, but all the accompanying programs in science, collaborations with many institutions, technology programs and public relations programs.
- The presentations were of the excellent quality. The quality of younger generation’s presentations is impressive. It is very encouraging to see they have been producing world-class results. It demonstrated that NIFS is well prepared for the future. It would be recommended that for the next review, special thought be given as to how to maintain such momentum and world leadership for the long term.
- Further progress of NIFS research and the germination of the new scientific paradigm are expected based on the present achievements and further extended collaborations.

(a) Translation into Japanese

和　訳

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In the case the reviews submitted in Japanese, the original text contents are included here and the translation of them into English is included in the main chapter (2. Reviews on NIFS Research Activities).

一部、オリジナルが和文のレビューがありましたが、このオリジナルを和訳に収録させていただき、その英訳を本文 (2. Reviews on NIFS Research Activities) に収録させていただきました。

目　次

1. 核融合科学研究所の研究活動に関する評価

評価者: A

1. プロジェクト活動
（研究の目的，成果と課題，研究の質，改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

1998 年以降 LHD 計画の功績には目を見張るものがあり，核融合エネルギー開発の成功に向けて解決されるべき主な課題を全て網羅している。同計画は，ヘリカルシステムに核融合エネルギー発生装置としての多大な可能性を生み出し，完全ではないにしろ，密度や圧力などにおいては効率的な核融合発電に必要とされるパラメーターを達成している。現在の課題はそれらを同時に達成することである。

さらに，より極端な運転領域の研究において，加熱源あるいは粒子／熱除去が原因の技術的制限によるものを除いては，根本的な物理的限界に達していないことを示した。また、これらの技術的性能についても向上が見込まれている。

私の意見では，LHD は核融合研究史において初めて，ヘリカルシステムが将来的に核融合エネルギー発電を担う重要な候補であることを，証明したと言える。同 LHD 装置は最新型トカマクシステムに類似した性質を持ちながら，強力なトロイダル電流に関連した難題（不安定性，ディスラプション，密度限界…等々）を抱えていない。

技術的観点から，1時間を越える定常プラズマ生成の可能性を証明したことは，より要求されるものに近い運転領域へと繋がり得る功績と言えるだろう。

b) （課題に順じた）専門研究

ディスラプションの無い，高密度運転領域の開拓は，近年核融合コミュニティが発展してきた中で，最も期待できる運転領域ではないだろうか。

<ß>値が 5%という核融合炉に相当する値に達したことは，繰り返すが躍進的進歩である。
と言うのも，磁場構造の実際の限界にはまだ達しておらず，明確な限界が見えないのは大変期待できる事実だと言える。

c) 将来計画

得られた研究成果から，装置の加熱容量向上，閉ヘリカルダイバータの採用，および重水素実験は絶対的に必要だと思われる。
また，装置を物理的限界まで高めるのに必要な資源を見定めることに，全力を尽くされたい。

(2) シミュレーション科学プロジェクト

a) 概要と功績

LHD に特化した閉じ込めシミュレーションおよびレーザー核融合シミュレーション分野をカバーした，大変意欲的なプロジェクトが提示され，既に有望な結果を残している。このグループが実験部門と密に連携し合っている現状を，個人的には大いに支持したい。若手世代が同分野において積極的に活動しているのが見られ，非常に好ましい。

b) （課題に順じた）専門研究

TJ-II のような，径電場に関して非常に詳細な計測を伴う他装置で得られたデータをシミュレーションデータに組み込むことは，今回提示された素晴らしい研究を更に拡張するだろう。

材料研究は将来の核融合装置にとって，ことさら重要である。

トカマク装置との比較も視野に入れておかれることをお薦めしたい。

c) 将来計画

今回提示された計画は意欲的であるが，同時に現実的でもある。
このタスクを成功させるには，最高水準の計算リソースを十分獲得するべきだろう。

(3) 連携研究

a) 概要と功績

本分野で積み重ねられた努力を賞賛したい。大型実験において，他のコミュニティから孤立するのが一般的な中，産業界や他の研究所，または核融合レーザーコミュニティや各種アウトリーチプログラムとの交流が進行中であるのを見るのは非常に喜ばしい。

特に，核融合用トリチウムに関する研究の強化を推進したい。ITER 稼動に近づきつつある今，これまで以上の問題解決を迫られており，本連携研究の努力は，これらの問題解決に大きく貢献してくれることだろう。首尾よく核融合エネルギーを導入するために，これは解決すべき重要課題である。

キッズ・エネルギー科学館設立に至る努力も高く評価したい。

b) 将来計画

ITER プロジェクト計画を視野に入れた現行の将来計画に，特別な注意を払っている。個人的には，ITER があらゆる世界的規模の核融合プログラムに強い影響力を持つことだろうと容易に伺えるため，成功への重要課題だろうと考える。

JAEA との密接な交流を推奨したい。

(4) 炉工学研究

a) 概要と功績

発表された研究課題は厳選されており，その成果は世界的に重要なものである。数多くの国際共同研究が実施されており，インパクトのある研究を行う上で強い自信に繋がっている。

論文数のような客観的指標を入れたことは，評価者にとっては大変役に立つ。

b) （課題に順じた）専門研究

長寿命溶融塩フリーベやリチウムブランケット研究は，目を見張るものである。ITER で試験する可能性が限ら

れているので，実際の環境でこれらのデザインを試す機会がどれくらいあるか，問題となるだろう。

中性子工学研究は，近づきつつある ITER 稼働（実験）に大変必要であり，歓迎される。

c) 将来計画

発表された将来計画のために，十分な資源を調達することが重要である。

2. その他

この場をお借りして，近年 NIFS が達成してきた功績をお祝いしたい。優れた成果は，世界記録を更新する LHD 実験結果のみに留まらず，科学研究において LHD を取り巻く全てのプログラム，国内外研究所との間で進行中の共同研究，各種技術プログラム，または，地道だが非常に重要な広報関連プログラム，これら全てに及ぶものである。

若手研究者や技術者が，すでに世界規模の成果を生み出していることは非常に頼もしく，素晴らしい。次期評価では，このような高水準かつ世界的なリーダーシップをどのような方法で長期間維持していくか，その辺りに焦点を当ててみてはいかがか。

NIFS チーム全体として，本島所長の指揮下に得られた成果を，誇りに感じていただきたい。グループ全員に私の祝辞が届けられるよう祈りつつ，本島所長に心から賞賛の辞を申し述べたい。

評価者: B

1. プロジェクト活動
（研究の目的, 成果と課題, 研究の質, 改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

核融合エネルギー研究は, これまで主にトカマク型装置を使用し, 実施されてきた。
TRIAM-1M は既に LHCD を使用した定常運転を実証しているが, トカマク型では効率的な継続運転を達成することが難しい。この点から, ヘリカル型装置が極めて望ましい。しかしながら, LHD 実験の開始以前にヘリカル型核融合炉研究は殆ど行われていない。過去 6 年の間に LHD 実験研究が精力的に行われ, 高温・高密度プラズマの達成に至った。特に 5%ベータ値の達成には感動させられた。
当初予測より高いパラメータに到達したことは, 高く評価できる。

b) （課題に順じた）専門研究

1. 高イオン温度: 5.2 keV at $n_{e=}$ $1.6x10^{19}$ m^{-3}

2. 最大 β =5.1%, 定常運転時(>100 τ_e)は 4.5%

3. 最大密度: 1.2 x 10^{21} m^{-3}

4. IDB（内部拡散障壁）の証明

さらに興味深い成果も数多く報告されている。

c) 将来計画

加熱機器の増強, 閉ヘリカルダイバータ, および DD 実験の準備が進んでおり, 今以上に優れた成果が期待される。 ヘリカルダイバータの設置が実験スケジュールに影響を及ぼさないよう, 上手く調整されている。

ヘリカル炉設計は, LHD の実験成果を参照しながら進行しているように思われる。 結果が上手く反映された設計を期待したい。

(2) シミュレーション科学プロジェクト

a) 概要と功績

シミュレーション研究が精力的に進められていることは賞賛に値する。
高温プラズマ中では多様な現象が共存し, 相関しあっている。よって, シミュレーション結果と実験結果が類似していたとしても, それが必ずしも実際のプラズマに該当するとは言えない。 この点を常に留意してほしい。

シミュレーショングループおよび計測グループは密な連携を取り合うべきだろう。

b) （課題に順じた）専門研究

c) 将来計画

シミュレーショングループにおいて，ヘリカル炉シミュレーションの重点的取り組みが望ましい。

(3) 連携研究

a) 概要と功績

数多くの業務に関して説明を受けたが，それらに関して，個々の最終目的を理解しづらかった。どのようなブーメラン効果が得られるのか示されておらず，現時点での評価は難しい。

b) 将来計画

ヘリカルダイバータ，DD 実験準備など，重要課題の選択が必要だろう。
最終目的も提示されるべきである。

(4) 炉工学研究

a) 概要と功績

ブランケット，中性子，マグネット等々に関して説明されたが，期待される炉のパラメータ（寸法，磁場強度，プラズマの規模）が示されていない。開発中とされている炉のスケールが公開されていれば，これまでに達成された段階も評価しやすいと思われる。

b) （課題に順じた）専門研究

超伝導の開発結果に強い関心がある。高く評価できる成果を上げた。

c) 将来計画

ヘリカル炉計画が期待される。ヘリカル炉／トカマク炉の長所・短所について，両者の比較研究が望まれる。また，それぞれの規模を示してほしい。

エネルギー問題を考慮すれば，規模や予算の問題はさて置き，まずは実現化が最重要視されるべきだろう。

2. その他

過去数年間で組織が改良され，研究所は数多くの傑出した功績を生み出してきた。特に LHD 実験の優れた成果に関しては，世界的評価に値する。

本島所長および研究所スタッフを賞賛したい。

評価者: C

1. **プロジェクト活動**
（研究の目的，成果と課題，研究の質，改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

大型ヘリカル装置LHDプロジェクトは，1986年，わが国のプラズマ・核融合研究者の間での純学問的討論に基づいて，大学関係がその総力を結集して取り組むべき次期大型研究計画として採択されたものである。採択に当っては，外部導体系ヘリカル磁場閉じ込め方式が，少ない還流エネルギーによる定常運転，高温・高ベータプラズマの長時間保持の可能性を持つことに留意し，当面 LHD が，内部電流系トカマク型装置を含む環状磁場閉じ込め方式におけるプラズマ物理の総合的理解へ寄与するという期待が込められた。具体的研究計画としては，①多様な磁場配位による高nτT プラズマ閉じ込めの最適化，②高ベータ領域での圧力駆動不安定性などの物理と閉じ込めへの影響の解明，③長時間運転による不純物制御，燃料給排気などの基礎資料の提供，④ヘリカルリップル磁場のもとでの高エネルギー粒子閉じ込め特性の研究，⑤核反応シミュレーション研究，などが挙げられた。

LHD は，1998 年 3 月，最初の着火以来，10 年間の間に，上記研究目標にしたがって着実に研究を進め，ほぼ所期の目的通りの成果を挙げ，世界の炉心プラズマ磁場閉じ込め研究において，ユニークな価値ある研究貢献を果たして来たと高く評価する。特に，高ベータプラズマの長時間保持を実現し，その MHD 特性，輸送，周辺制御などの面で，重要な基礎的な資料を提供したこと，また，ペレット入射による中心部ピーク高密度を維持する内部輸送障壁の発見など，核融合炉心を展望する環状磁場閉じ込め方式の総合的理解に大きな貢献を果たしてきた。

b) （課題に順じた）専門研究

・ 閉じ込め最適化について

磁気軸の位置，アスペクト比などを変化させて，MHD 特性，加熱効率，輸送の観点から，高ベータプラズマの閉じ込めの最適化をはかり，最大＜β＞＝5.1％を達成し，＜β＞＝4.8％でエネルギー閉じ込め時間の 85 倍の定常運転を実現した。また，圧力駆動不安定性や周辺磁気面の破壊に伴う MHD 平衡・安定性・輸送への影響を系統的に探求すると共に，垂直入射中性粒子ビームによる加熱を実現し，その閉じ込め特性を調べた。これらの成果は，環状磁場閉じ込めプラズマ物理の立場からも，また，炉を展望する観点からも，極めて優れた貢献であると判断する。

・ 内部拡散障壁(IDB)について

中心部への連続的ペレット入射の際，内部拡散障壁（IDB）形成による中心部ピーク高密度・高圧配位の生成・維持が，従来局所アイランド・ダイバーター配位で見出されていたが，磁気軸の外側シフトなどにより，通常のヘリカルダインバーター配位でも実現可能なことを見出し，その稼動領域(磁気軸・β)を同定した。これは，ヘリカル系における炉心プラズマ生成保持を展望する立場からも，重要な一歩であると判断する。実験結果によると，電子密度勾配が急峻なところでも，電子温度勾配はなだらかなままである。今後，IDB 形成に関わる拡散係数の物理機構の解明および CDC などの不安定性の同定と制御などに関して，理論・シミュレーションと協力した詳細な研究が期待される。

・ 周辺プラズマ制御

ベータ値の上昇に伴う周辺磁気面の乱れの効果の制御は，ヘリカル系プラズマ保持の定常化を図る上で，避けて通れない課題である。＜β＞～4.8％までの領域で，閉じ込め劣化が見られなかったことは，重要な成果である。また，高イオン温度下での不純物ホールの生成，高密度での衝突摩擦による不純物遮蔽，エルゴディック層の影響についての様々な解析，closed helical diverter 配位の設計など，多彩な研究が行われており，粒子・熱流束の周辺制御に見通しをつける研究として，今後の更なる進展が期待される。

c) 将来計画

最も望まれる将来計画は，重水素の導入である。地元の了解という難しい問題が絡んでいることは理解できるが，ここまで当初の計画が進行してきたことを考えると，重水素を用いた閉じ込め特性，特にイオンや不純物粒子の閉じ込め比例則への同位体効果などの研究，更に進んで，少量のHe^3を混入して，そのICRFマイノリティ加熱による核反応シミュレーション研究にまで発展することを期待したい。

ただし，現在の LHD 装置の大幅改造や，新たな大型ヘリカル装置の建設については，現段階では，時期尚早であると判断する。当面は，現在の LHD（加熱増力，ダイバーター配位の改造等の適度の増力・改造を含む）を活用した更なる研究の進展を図ることとし，次期計画については，ITER や ICF 関係の成果を見定めつつ，核融合研究全体の立場から，慎重に判断するべきであろうと考える。

(2) シミュレーション科学プロジェクト

a) 概要と功績

まず第 1 に，シミュレーション研究グループが大きな研究グループとして成長したことを高く評価したい。そして，①LHD and Magnetic Confinement Simulation Project ②Laser Fusion Simulation Project ③Plasma Complexity Simulation Project の三つのプロジェクトを同時に進行させることが出来るに至ったことを喜びたい。

この中で，中心となるプロジェクトは，①LHD and Magnetic Confinement Simulation Project である。このプロジェクトの中に，炉心プラズマについて，2流体モデルによる研究グループと，運動論的モデルによる研究グループ，そして周辺プラズマ研究の三つのサブグループが，それぞれ，2流体モデル，ジャイロキネティックモデル，及び境界のモデル化で，着実に研究成果を挙げている。そして，これら三つのサブグループの研究成果の統合により，多階層シミュレーションモデルを構築し，Numerical Test Reactor Project を推進しようとしているのは，適切な方策であると考える。同時に，この研究プロジェクトが，様々な分野における多階層現象に関するシミュレーション研究の魁としての役割を果たすことを期待したい。

b) （課題に順じた）専門研究

特筆すべき成果を挙げているのは，gyrokinetic Vlasov model を用いたヘリカル系での ITG 乱流と zonal flow に関する研究である。ITG 乱流とその zonal flow の形成による安定化については，軸対称トカマクでは既に多くの研究が行われ，非軸対称ヘリカル系でも，核融合科学研究所にあった小型ヘリカル装置 CHS において，zonal flow とその乱流抑制効果が実験的に確認されているが，ヘリカル系でのシミュレーション研究による詳細な解析は初めてであると思われる。非軸対称性に伴う径方向電場の効果も取り入れての解析であり，新古典リップル拡散を最小化する磁場配位で，zonal flow による乱流拡散抑制が強く働き，乱流拡散も抑えられることを明らかにした。径方向電場がどのような形に取り入れられているのか不明なところがあるが，粒子拡散束の非両極性により生成される電場をセルフコンシステントに取り入れた解析が望まれる。

c) 将来計画

シミュレーション研究では，モデル化とシミュレーション解析手法が鍵となっている。これらは，特定の対象(ヘリカル系プラズマ)に限定されるものではなく，様々な複雑系の解析に応用できるものである。現に，従来の理論・シミュレーション研究センターでの中心課題であった開放系での自己組織化に関する研究は，その後幅広い他分野への応用へと発展しており，自然界の複雑系研究手法に新しいパラダイムを切り開いてきたといえる。

多階層現象の統合的研究は，地球規模での気象現象や大気・海流等の研究，地球内部構造や地殻変動の研究，生命科学，宇宙科学等々の分野で，避けて通れない課題となっている。自然科学研究機構内の他の研究所を含む関連研究機関との意欲的な共同研究により，シミュレーション研究グループが，このような幅広い研

究分野を包括する新しいシミュレーション研究の潮流を導く魁としての役割を果たされることを，将来に期待したい。

(3) 連携研究

a) 概要と功績

連携研究センターが，限られたメンバーで，国際協力，ITER 関連研究連携，レーザー関連研究連携，原子・分子・周辺プラズマデータ収集・解析，産業連携，核融合子供科学館など多彩な活動を展開していることは評価に値する。

核融合科学という観点からは，従来，どちらかといえば，スピンオフ中心の活動であったのが，核融合炉を志向した活動に重点を移してきているのは，望ましいことである。

b) 将来計画

ヘリカル系と並んで，現状で核融合炉に最も早くつながると思われているトカマク(ITER，球状トカマク)や，ICF(FIREX)に関する連携研究に一層の力点がおかれることを期待する。これらの中には，核融合科学研究所の将来計画にも関わってくるものがあると思われるので，全国の核融合関連研究者の間での将来計画に関する学問的立場からの討論を，全国共同利用体制を活用して，喚起し・組織して行くことを勧めたい。

(4) 炉工学研究

a) 概要と功績

専門外でもあり，特に意見はありません。

b) （課題に順じた）専門研究および将来計画

専門外でもあり，特に意見はありません。

c) 将来計画

専門外でもあり，特に意見はありません。

2. その他

本島所長の卓越したリーダーシップのもと，思いきった組織の再編を行い，研究所の中核をなすLHDプロジェクトを着実に推進し，あわせて，高温プラズマという複雑系のシミュレーション研究を大幅に拡張，進展させてきていることに，深い感銘を受けた。また，これらの研究を通じて，優秀な若手研究者が続々育成されてきている姿に，心を奪われると共に，頼もしく感じた。

今後，この成果を基盤にして，次期所長のもとに，更なる研究の発展と，斬新な展開が行われることを期待したい。なかでも，母屋である自然科学研究機構の他の研究機関との連携による新たな学問的発展が芽生えて来ることを期待したい。

評価者: D

1. プロジェクト活動
（研究の目的, 成果と課題, 研究の質, 改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

LHD 装置は核融合工学における代表作である。
LHD 性能の利点を余すところなく活かし, 過去6年間で重要な目標を達成し、成果を納めてきた。大きな発見の主要なものとして, 不純物ホールなどの有用な現象をともなう高イオン温度, オープンヘリカルダイバータ配位における内部拡散障壁を伴う高密度運転, 5.1%という極めて高い平均ベータ値, また 54 分に及ぶ定常運転, 等があげられる。これらの成果によって核融合炉の温度に到達し, また, ベータ値やプラズマ密度, および入力エネルギーにおいても世界記録を樹立した。これらの素晴らしい成果は, LHD に従事する全チームおよび各研究者が現行のリーダーシップによって纏められて, 総合的かつ団結した貢献を成し得た結果である。さらに, 核融合の最終目標に向けて性能を益々向上させるよう, 科学技術の基礎が築かれてきている。

b) （課題に順じた）専門研究

厳しい核融合要件にを満たす三重積に近付く密度・温度・および閉じ込め時間を同時に達成するため, LHD 性能を更に向上させるには, NBI, ICRH, ECRHから構成されている加熱能力の増強, 閉ダイバータ配位の適切な導入, および重水素運転が採用されるべきだろう。また, 定常運転に関しても, 核融合炉に求められるデータベースを拡大することに取り組むべきである。高ベータは, シャフラノフシフトを注意深くリアルタイム制御したりR_{ax}制御することで, さらに上昇させ得る。閉ダイバータ配位は, 周辺部の閉じ込めを改善する可能性があり, よって, ベータ値の上昇に伴う閉じ込め性能の低下を軽減すると思われる。また, 改良されたペレット入射システムと閉じた磁場配位の相乗効果により, プラズマパラメータが更に向上すると思われる。さらに, 全般的な運動量輸送の研究, 特に不純物輸送との相関に注目していただきたい。不純物ホールの発生には, 細密な考察と更なる進展が求められる。

c) 将来計画

直近の将来計画は明確に定められており, 適切に予算措置がなされている。物理プログラムは, 現在利用可能または近い将来運転が見込まれている幅広い計測により十分にサポートされている。しかしながら, NIFS の現在の戦略に沿った, より積極的な目標が強く求められる。不可能と思われるほどのプラズマパラメータを達成している現在の研究の勢いを, 絶対に維持してほしい。故に, 大きな目標を掲げた統合的アプローチの採用が不可欠である。プラズマパラメータ向上のため, NIFS の秀逸な工学と計算技術に基づく斬新で繊細な方法を模索されたい。小規模装置で近年達成した成果（例：Li 運転）に関しては, より核融合に近い条件の LHD を用いて試験し, 利用すべきだろう。

(2) シミュレーション科学プロジェクト

a) 概要と功績

現在に至るまで, LHD 実験の適用性および予測性の向上という点で, 目を見張る発展が遂げられた。これは主に, LHD の意思決定, および優れた実験結果という魅力に理論を統合させた結果である。各研究系は現在 LHD の核融合性能に着目しており, 実験期間中に達成した主な功績を支えている。しかしながら, シミュレーション科学は斬新で傑出した LHD 性能の向上に向けた様々な独自提案を出していくことで, その意義を更に高めていく必要がある。核融合の展望を更に広げるため, 極めて多岐にわたる複雑なコードが開発された。LHD 実験の新たな流れは, シミュレーション科学研究部によって充分に注目されている。レーザー核融合シミュレーションプロジェクトやプラズマ-材料相互作用の数値的研究によって, 益々共同研究の効果が広まること

だろう。シミュレーションプロジェクトは，理論核融合研究に携わる国内の数多くの大学と連携し，研究を行っている。これらの活動は，NIFS の幅広い業績に益々求められるだろう人材を提供するためにも，シミュレーション科学研究部が特に注力すべき課題だろう。

b)　（課題に順じた）専門研究

LHD 関連研究を含んだ目標は的確に定義されている。しかしながら，これらは大変重要な項目として CDC，IDB，そして不純物ホールなどの最新かつ話題の課題を含んでいるべきである。シミュレーション科学研究部は，これらの実験の進展を理解し，その成果をより発展させる上で主役を担えるよう，あらゆる手段を用いて尽力してほしい。さらに，モデルは自己矛盾のない可能な限り最高レベルのものとなるよう目指すべきである。この目的を達成する上で，熱核融合研究のために日本で稼動する新計算機の稼働にあたって充分配慮されるべきである。シミュレーション科学研究部の出版歴は素晴らしい。自己組織化，リコネクション，ホリズムプロジェクトと言った，一般科学に関わる重要課題は，適切に取り組まれている。 これらは NINS インフラへの統合という点で非常に重要である。

c)　将来計画

数値試験炉プロジェクトは非常に積極的で賞賛に値する。ITER モデリンググループとの実り多い研究協力や支援はさらに強化されたい。LHD 実験結果の理解や意思決定への統合を継続し，さらに追及すべきだろう。SSP が取り組んでいる広範囲の課題を維持する必要がある。
日本に存在する大型計算機基盤を使い，計算パワーの拡大を図る研究を実施してもらいたい。 NIFS と連携している多くの大学が有する理論知識やスキルの蓄積は，シミュレーション科学研究部の効果拡大に利用できるだろう。LHD 重水素実験の利点に注目したシナリオに取り組む必要があるだろう。

(3) 連携研究

a)　概要と功績

連携研究推進センターでは傑出した活動が行われ，LHD の経験から得た知識の産業科学各分野への波及効果を高めている。同センターは DEMO 計画にとって重要なトリチウムインベントリーと言った将来的課題を提示することで，核融合研究の新領域を拡大している。また，PWI や原子データに関する問題を解決することにより，現行および将来の LHD 実験に貢献している。ITER 関連研究にも大きな進展が見られる。レーザー核融合研究や国立天文台との共同研究は，非常に高く評価できる。NIFS キッズ・エネルギー科学館に始まるアウトリーチ活動は非常に好感が持てる。
連携研究推進センターはよく整備された組織であり，NIFS インフラにおける強力なツールである。
PWI 活動は目覚しい発展を遂げ，既に将来の LHD および QUEST オペレーションに貢献する用意が整っている。移動表面式プラズマ対向機器（MS-PFC）などのオリジナル概念は，固体・液体双方とも先ずは QUEST で試験した上，成功したならば LHD での試験が必須である。現代の原子物理学進歩に基づくプラズマ計測方法を，LHD および太陽観測衛星「ひので」に導入するべきである。他の研究資源からの情報不足という点を鑑みれば，トリチウム研究にもより重点を置くべきである。産業応用に重要な，マイクロ波加熱による製鋼技術を用いた研究開発を，優先的に考えるべきである。ITER 用ミラーの製造も，連携研究推進センターが提示した重要テーマである。

b)　将来計画

連携研究推進センターはセンターの活動を向上させ，LHD 計画への更なる統合を図っている。ITER および BA との協力関係を強化，発展させることが不可欠である。IFMIF（国際核融合材料照射施設）の不確実性を考慮した上で，トリチウム処理に関する研究は，ことさら重要視されるべきだろう。アウトリーチ研究を他の専門家集団や民間グループに拡大してみてもいいだろう。JT60-SA 用超伝導コンダクターの試験は絶対必要である。

DEMO 関連問題に関する新たな研究は，率先して行うべきだと思われる。人材に限りがあることを考慮すると，国内大学がもたらし得る貢献という観点から，NIFS および NINS 活動内での研究協力は不可欠である。

(4) 炉工学研究

a) 概要と功績

炉工学研究センターは，比較的新しい活動に代表され，核融合工学の問題に深く取り組んでいる。同センターは，既に重要な情報を提示しており，核融合炉が直面するだろう最も重要な課題を指摘した。フリーベやリチウムに基づくブランケットの問題に取り組んでいる。V（バナジウム）合金やフェライト鉄の溶着，照射，腐食，またはコーティングに関する試験が実施された。炉のニュートロニクス（中性子工学）研究用に，高速フィードバック 3D コードシステムが開発途上である。適用性に限界はあるだろうが，14MeV モックアップ試験が実施されている。

b) （課題に順じた）専門研究

炉工学研究センターの専門研究は，ブランケット材料システム，ニュートロニクス，およびマグネット材料システムで構成されている。バナジウム合金の溶着に関しては，酸素不純物除去により，既に可能性が示唆された。高純度金属バナジウムがV合金高熱負荷に対して開発された。NIFS-HEAT-2 は，不純物混入を防ぐため，高純度Arフローで溶接された。溶接材料において破壊エネルギー減少が進んだが，照射後焼鈍によって回復した。溶接クオリティの低下は中性子照射 8.5dpaで現れた。溶融塩フリーベや液体リチウムの強制対流ループに関する設計や実現性研究が進んだ。高度コーティング技術やトリチウム浸透バリアの発生を実証してきた。高速フィードバックシステムがニュートロニクス設計に統合された。十分な遮蔽下でのトリチウム増殖に成功した。14MeVニュートロン照射後，多様なNb化合物の臨界電流が調査された。V_3Gaの電子電流を向上させるため，低活性化型超伝導ワイヤが使用された

c) 将来計画

周辺構造の非対称・フラクタル配置に関して，中国ASIPPと共同で取り組む予定である。14MeV照射中および後のその場観測の実施を予定している。ITER TFマグネット製造を円滑化させるため，全Nb_3Sn素線に関して試験を予定している。東北大学大洗センターとの間で実施予定の 15.5Tおよび 500A電流リードに関する共同研究に重点を置かれたい。炉工学研究センターは，超長時間スケールでの熱クリープを調査するための長期クリープ試験を継続すべきである。核分裂での経験やノウハウを参照しながら，DEMO炉に関わる他の選択肢を追求・発見していくことが不可欠である。

2. その他

現所長は核融合研究の最先端で，NIFS の世界的リーダーとしての地位を築き上げた。
この成果は幅広い研究活動の完全なる調和，そして，これらの活動を熱核融合炉という共通課題に統合したことにより，達成されたものである。現所長の指揮下で達成された今の勢いを維持するため，詳細な計画を考えていく必要がある。

評価者: E

1. プロジェクト活動
（研究の目的，成果と課題，研究の質，改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

LHD は，世界中のステラレータ実験研究の最重要装置であり続けている。同時ではないにしろ，LHD はプラズマパラメータの新たな記録を達成しており，これらは MHD 不安定性による過度な劣化の見られない超高ベータ（磁場強度を 20%に減少時），ペレット入射による超高密度，核融合条件に匹敵するイオン温度，および中心部不純物の蓄積軽減を伴う興味深い新領域などにより，実証された。このように LHD は，ヘリカルプラズマ閉じ込めの物理的理解に貢献し続けている。これはまた，国際的な核融合プロジェクト ITER に，特に周辺磁場のストキャスティック化およびトロイダル磁場制御による MHD 安定化において，深く関連している。

JT-60SA が定期運転を開始するまでは，LHD は日本の最重要核融合装置であり続けるだろう。よってその時まで，核融合実験研究の国内活動は，自ずとLHD に集中し，ステラレータとトカマク研究の間での重要な相互発展を生み出すだろう。

b) （課題に順じた）専門研究

LHD は，当初の予測を上回る性能を示している。これは偉大な功績であり，核融合エネルギーに向けたステラレータ概念の信頼度に大きく寄与するものである。（磁気軸の移動およびプラズマアスペクト比の変更により）最適化された磁気閉じ込めのみに留まらず，NBI（現在 23MW，7MW の追加を計画中）に代表される加熱パワーの体系的拡充にも支えられた結果，傑出したプラズマ性能が達成された。高速ペレット入射と相まって，急なエッジ勾配で超高密度運転を可能にする新たな運転領域が発見された。さらには，エルゴディック層での遮蔽効果によって，不純物蓄積が妨げられるという，興味深い運転領域も見出された。これにより，超高密度・高圧，および（低磁場状態で）高ベータプラズマが首尾よく生成され，維持できている。高ベータ時の MHD 平衡および安定性の問題について，LHD チームは極めて成功裏に取り組んだ。

上記のことから，LHD が目標値の達成に向かっていることは明らかである。加えて予想外の発見にも恵まれ，高レベルな基礎研究（特に MHD 不安定性，アルヴェンモード，ゾーナルフロー等）を実施している。秀でた LHD 研究の更なる追求に向けて，いくつか提案するので検討していただきたい。

- 発見された新たな運転領域の物理的理解を急ぐべきである。IDB，CDC，および不純物ホールは大変有望で，大いに意義のある発見である。ここにおいて，理論，計算機シミュレーション，特化した実験を組み合わせた体系的アプローチが有用だろうと思われる。
- 高密度領域における電子・イオン温度は比較的低い（概ね 1keV前後）。逆に，目標温度は必要な値より一桁低い密度で達成されている。LHD装置の柔軟性を活かし，最適な$n{\cdot}T_i{\cdot}\tau_E$を達成するため統合シナリオを策定されたい。
- ハイパワープラズマの定常運転は，更なる安定性向上のほか，核融合研究におけるステラレータ概念の魅力である。閉ダイバータの詳しい設計および建設を可能な限り急ぐべきである。定常加熱パワーの 4MW への改善が計画されており，閉ダイバータの完全導入とともに，実現されたい。
- 核融合炉研究は，トカマクに基づく現行の DEMO 研究と密接に結びつくべきである。そしてそれらの長所、短所が明確に示されるべきである。ステラレータに関しては，グリーンワルド限界が無いことによって，より高密度・低温での燃焼への展望が開かれたことは明白である。これらの炉条件下における熱不安定性，中性粒子輸送，不純物生成および輸送のもつ役割について，全貌が分かればより有益だろう。つまり，「数値試験炉」（以下参照）が非常に重要な役割を担うことになる。

c) 将来計画

重水素プログラムの実施により，同位体効果を探求する計画は，高く評価される。これは LHD の性能向上にも繋がるだろう。装置の更なる開発に関しては，主に，(I) NBI（32MW へ）および ICRH（4MW へ）の増強，(II) 閉ヘリカルダイバータの開発，製作，および組立が考えられる。 後者に関しては，段階的アプローチが計画されており，長期的な実験休止を防ぐ意味合いでも，合理的だと思われる。

推奨：

- 閉ダイバータの詳細設計の公開と同時に，国際専門家（特に工学分野）を交えた詳しい設計評価の実施が望ましい。
- MHD データベースの確立は高い賞賛に値する。これらの活動を正式な国際協力協定に盛り込むことも，有益であろう。

(2) シミュレーション科学プロジェクト

a) 概要と功績

実験側に立つ研究者の視点から見た場合，シミュレーション科学プロジェクトには高く評価される科学研究があり，国際的競争力を持つと思われる。上記で述べたとおり，LHD で新たに発見された運転レジームを理解するために，集中した取り組みが求められる。NIFS シミュレーション科学プロジェクトは，これら課題の取り組みに向けて，合理的に配置されているように見受けられる。MHD や LHD シミュレーションからレーザープラズマ，複雑性プラズマまでに至る NIFS シミュレーション科学プログラムの奥行きを拝見できて光栄に思う。この学際的アプローチは明らかに NINS の方針であり，機構研究所間の連携協力を育成している。

b) （課題に順じた）専門研究

特になし

c) 将来計画

例えば，乱流やゾーナルフロー分野などにおけるコードを更に発展させていく上で，高性能コンピュータへのアクセスは極めて重要である。新たなスーパーコンピュータおよび NIFS プラズマシミュレータ計画は，高く支持できる。

(3) 連携研究

a) 概要と功績

NIFS は，日本の大学環境に非常に上手く溶け込んでおり，それが高い相互利益を生むことは明白である。特に PWI，材料科学，原子物理学，計測，および基礎プラズマ研究などの場合が挙げられる。一方で，連携研究推進センターは，大学施設が LHD プログラムに適切に統合されていることも確認しており，これは言うまでもなく素晴らしい功績である。

b) 将来計画

ITER および DEMO 活動との密接な関わりは，ステラレータコミュニティにとって絶対的不可欠であり，連携研究推進センターが進もうとする方向性は，極めて正しい。

(4) 炉工学研究

a) 概要と功績

LHD の工学的観点に関しては，(1)で既に記述済みである。

b) （課題に順じた）専門研究

特になし

c) 将来計画

特になし

2. その他

本特別評価会合は，私がこれまで参加した中で，最高の評価会合であった。本島教授が所長任期中に積み上げられた，NIFS の傑出した成果の数々について，最も端的に述べられていたと思う。彼の成功は高く評価され，また，賞賛されるべきものである。また，高い見識を持ち，周囲の尊敬を集める小森教授が次期所長を務めると伺って，心から喜ばしい気持ちである。小森教授の成功とともに，次の評価会合に参加するのが待ち遠しい。

会議中の口頭発表も大変素晴らしかった。取り分け，若手世代によるプレゼンテーションにおいて，榊原博士（高ベータ運転），坂本博士（高密度運転），渡邉博士（ゾーナルフロー）の発表の質の高さに驚かされた。NIFS 所属のこれら若手研究者が，国際会議で招待講演者として登場する姿をいつの日か拝見してみたいものである。

評価者: F

1. プロジェクト活動
（研究の目的, 成果と課題, 研究の質, 改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

LHD は巨大核融合実験であり，高温プラズマや核融合物理の発展に大きく貢献した。また，特にステラレータ・ヘリオトロン物理理解への寄与は計り知れない。主な技術的成果は，複雑な超伝導装置の安定した運転に拠るところが大きい。ここで，磁場の更なる増強について特に注目しておきたい。また，定常プラズマ運転の実証は，今後の発展を考慮する上で非常に有意義である。大変貴重な科学的成果として，改良された閉じ込め特性を使った高密度運転の実証，5%という驚異的な数値に達した高ベータ運転，および低不純物含量（いわゆる不純物ホール）でのプラズマシナリオ，などが挙げられる。

b) （課題に順じた）専門研究

高密度運転: 核融合炉でハイパワー密度を達成しようとする場合，高プラズマ密度が必要不可欠になる。内部拡散バリアは，ステラレータ／ヘリオトロンで非常に高い密度が達成でき，閉じ込めの同時改良が可能である，という2点を実証している。加熱パワーの増加が見込めれば，更なる密度向上も可能だとする結果は大変興味深い。

高ベータ運転: 高ベータもまた，ステラレータ／ヘリオトロン炉に求められる。5%の体積平均ベータ値が認識されており，これは LHD により達成された値である。さらに，ベータ限界（beta-limiting）MHD 不安定性について，より向上した理論的理解を言及されたい。特に，LHD プラズマの MHD 安定性に関する理論的予測があまり良くなかった状況に反して，この方向について更なる研究が奨励されるべきである。この観点から，磁場トポロジーと MHD 安定性（つまり安定性と平衡点上限）の関連性を研究するのに採用されたアプローチを更に追及されたい。

不純物輸送: 不純物の蓄積は，ステラレータ研究が重要課題とするものの一つである。LHD は，少なくともある一定の条件下において，不純物蓄積を回避できることを示した。多彩なプラズマシナリオ（高密度，低密度，高ベータ，様々な境界プラズマ条件，等々）を含む同方面の研究推進を大いに期待したい。

計測: 計測に関しては特に言及されなかったが，敢えて，発表された実験データの秀逸さを書き添えておきたい。なお，これらはプラズマ実験を解析・理解する上で，前提となるものである。

全体として，これらの成果は顕著な発展がなされ，また，LHD が国際核融合研究を率いている事実を明示している。また，高プラズマ性能の達成以外にも，実験・理論グループ間の協力強化に基づく優れた解析力が注目されてきた。これについても更なる強化が望まれる。さらに，今後の研究においては高プラズマ性能の発展に向けて，より統合的アプローチを目指されたい。

c) 将来計画

加熱システム増強とダイバータ:
加熱システム増強，およびアクティブクーリングされたダイバータを採用する計画は，非常に肯定的に受け取られてきた。特に，開発に関して先に述べたコメント「好ましいプラズマ特性を組み合わせたプラズマシナリオ」に関して，これは大変重要なステップである。特に高密度状態での上限をなくし，また，運転領域をより高磁場での高ベータに拡大するためには，加熱パワーの増強が求められる。これは，より大きいパワーの処理が可能なプラズマ排気を示唆している。アクティブクーリングは高パワー定常運転の実現に必要である。シャットダウン期間の最小化を目指し，モジュラ方式でダイバータを拡張するというアプローチは十分支持されるものである。

(2) シミュレーション科学プロジェクト

a) 概要と功績

理論とプラズマシミュレーションは，核融合実験で見られる複雑現象を理解する上で，必要不可欠である。ここで，NIFS は共同研究者と連携し，たくさんのツールを開発した上に，第一原理に基づく理論において目覚しい発展を遂げた。これには MHD 不安定性，およびプラズマ中心から境界に渡るプラズマ輸送が含まれる。また，関連各分野との繋がりにも注目したい。シミュレーション科学は，大学グループと密な連携を取り合う上で，非常に適した条件を提供しうる分野である。これらグループの協力参加が上手く機能している。

b) （課題に順じた）専門研究

乱流輸送，MHD 安定性，リコネクション現象，PWI といった，核融合研究における重要課題を含む，多数の研究トピックが発表された。個別発表では乱流輸送が取り上げられ，LHD の内寄せ配位が優れた新古典的閉じ込めだけに拠らず，乱流輸送の軽減によっても，閉じ込めを向上させたことを説明した。この研究は実験結果を説明するというだけでなく，乱流と新古典的輸送の関係という重要課題を取り上げている点で，非常に貴重である。

c) 将来計画

LHD・磁場閉じ込めシミュレーションプロジェクト，および数値試験炉計画は，既存実験および核融合炉の基本特性への理解を深める上で，重要なステップである。発表された計画を強く支持したい。より発見的なシミュレーションと，第一原理に基づく理論の均整が上手く保たれている。今後に関しては，不純物輸送・MHD 安定性といった分野の実験と理論間の連携強化を推進することを推奨したい。

(3) 連携研究

a) 概要と功績

核融合には，安定した長期的研究と開発が求められる。このことから，教育および科学技術研究への参加，双方に関して大学の統合化が貴重になる。数々のトピックを網羅した大変な数の共同研究計画が発表された。多様な専門トピックや研究グループの中心として，NIFS や LHD を利用するというアプローチ方法は，大学や他の研究グループの参画を仰ぐ上で適切な戦略である。

b) 将来計画

NIFS の直接的・間接的関与を問わず，大学の ITER および DEMO 開発への関与を含む将来計画が強く求められる。
このような大型施設および開発プログラムには，若手研究者やエンジニアの人材開発のみならず，市民の理解を得る上でも，幅広い学術的基盤が必要になる。
この観点から言えば，若年層により核融合研究関連トピックが紹介されている現状は，非常に素晴らしい。

(4) 炉工学研究

a) 概要と功績

DEMO に関して非常に積極的な開発計画が発表された。紹介された技術関連トピックは，開発が必要とされる主な分野を網羅している：ブランケット材料システム，ニュートロニクス，マグネット材料システム。個々の要素の統合を可能な限り試験するシステムを構築する計画が，強力にサポートされている。将来的なことになるが，

開発計画について，意思決定要件を含めどの程度ITERおよびIMFIFスケジュールに依存すべきか，より詳細な解析が有用になるだろう。

b)　（課題に順じた）専門研究および将来計画

ブランケット材料システム：ブランケット技術の解決策となり得る興味深い新成果が発表された。発表は，液体増殖ブランケットの開発に特定して行われた。素晴らしい発表に加え，同研究分野が，優れた共同研究，および健全な原子力産業界の恩恵を大いに受けているように感じられた。今後に関しては，水素回収の整合性に関するフィージビリティスタディや，フローシステムにおける熱交換といった分野でのシステム統合が計画されており，これは強力に支持できる。将来的にはこれらのブランケットをITERで試験できるよう，同計画をより精密に練り上げることを推奨したい。

ニュートロニクス：FFHR の設計は，トリチウム増殖および中性子遮蔽用3次元中性子計算に基づいている。これらの計算は，DT 中性子照射計測によって検証されており，非常に頼もしい。将来計画には，複雑配置および更なる検証できる計測に対応する改良中性子計算が含まれる。

マグネット材料システム：中性子照射によるマグネット性能（臨界磁場）への影響について，多様な超伝導体に関して詳しく議論された。今後の研究に高温超伝導体が含まれているが，これは低温システムの要件を大幅に軽減させるため，強く望まれている。

2.　その他

最後になるが，今回評価委員に加えていただけたことを心から感謝したい。NIFS や LHD について多くを学んだばかりでなく，ハイレベルな研究発表や，正しい根拠に基づく討論を非常に楽しませていただいた。本評価に参加している若手研究者は，NIFS が将来に向けて準備万端であることを実証した。是非，これら若手研究者の主要会議出席を奨励していただきたい。

評価者: G

1. はじめに

核融合科学研究所（以下NIFS）の設立に当たって、そこで行われるべき主計画について論議するために、学術審議会核融合部会の下に国内の主要な研究者によって構成される作業部会が置かれ、学術的立場から徹底的な論議が行われた。

その結論として、世界的にも最も多くの研究者が研究に携わり、その時点において学術的知見の最も豊富な環状系プラズマを取り上げ、その中でも磁場の配位設定の自由度の高い外部導体系を取り上げることとし、トカマクを含む環状プラズマの閉じ込めの物理の研究を行うこととした。

NIFS における大型ヘリカル系の研究は、先ず超伝導マグネット技術を含む装置技術開発に始まり、装置建設とそれらの成果を踏まえて順調に装置の建設が進行し、広い視野で見据えた所期の設計・建設が順調に進み、世界を代表する大型環状装置として優れた研究成果を挙げている状況は、初期の期待に沿うものであって、当初からその研究の進行を期待の下に見守ってきた一人として、今回の報告は、期待を裏切ることのない、極めて満足すべきものであったことを先ず申し述べたい。

2. 大型ヘリカル装置研究について

共同利用研究所であるNIFSにおける主計画として、適切な計画の下に、高イオン温度(5.2keV)、高密度($1.2\times10^{21}m^{-3}$)、高β(5.1%)の定常運転の記録は特記すべき優れた成果と考えられる。更に、記録として良好なデータを追求すると言うのでなく、上にも述べたように、環状系の閉じ込めの特性を詳細に研究するという当初与えられた使命を十分に考慮した活動の成果としてこのような良いデータを得たことは大いに称揚されるに値する。

3. 共同利用研究機関としての活動について

① シミュレーション科学

上に述べた主計画の遂行においても、共同利用機関としての機能を果たすことはいうまでもなく重要であるが、それのみでなく、核融合分野全体への寄与が求められるのは当然である。先ず最近の計算機科学の、ハードウェアとソフトウェアの急速な進歩の恩恵を十分に活用するためのシミュレーション科学は核融合研究の重要な研究手段であると共に、それと深い関係を持つ広大な領域と交流することによってその進歩を図ることは、共同利用研究所の重要な使命である。

特にシミュレーションは、巨大科学としての核融合研究においては、主計画における実験的研究の成果を理解し、その将来を予測するのみでなく、その閉じ込め特性を解析する事によって、トカマクなど、他の配位による閉じ込めにその成果を活かす手段としても重要である。

またその成果は単に計算機ハードウェアの性能や一般的なソフトウェア技術だけでなく、核融合プラズマ固有の特性を考慮した上で開発されるシミュレーション手法の開発が極めて重要であり、その面での能力が要求される。

NIFS における理論・シミュレーション科学の評価は極めて高いものがあり、今回の成果にも、我々の当初の期待を十分に満たすものであった。

② 連携研究

核融合科学のように、大規模な予算を必要とする研究には、その主たる計画の遂行と同時に、その周辺に在る広大な関連分野への貢献が同時に期待されるのは当然の成り行きと考えられる。その意味で、最近設立

された連携研究センターに対する期待は大きい。同時に、広い科学的・技術的・更には産業的視野で、関連する諸分野の中から有効な仮題を拾い出すことは極めて困難な作業である。

最近設立された連携研究センターは、周辺分野に深く関連し、産業応用にも深く関わる広範な領域を広い視野で見渡した上で、興味深い課題を抽出し、有効な共同研究を可能にしている。このことは共同利用センターとしてのNIFSの存在意義を高めるとともに、核融合という新エネルギー源開発研究事業全体の評価を高める可能性を持ち、特筆すべき新展開である。この領域での今後の発展を大いに期待した。

なお、以前から、関連分野の NIFS 活動として世界的に高い評価を受けて来たものとして、プラズマ中に於ける原子・分子過程がある。これは応用の立場からは地味な存在ではあるが、広範囲の科学技術の基盤として、特に材料科学や計測技術など、諸産業技術の基盤として重要な領域を支えるために必要なばかりでなく、諸学術分野の基盤として不可欠な知見を蓄積してきた。今回の報告においては地味な存在ゆえに目立つ形での成果報告は行われなかったことはやむを得ぬとして、やはりNIFSの地味ではあるが有意義な学術貢献の一つとして、従来の貴重な蓄積をさらに充実・発展させることを期待したい。

4．　その他の特筆すべきこと

午後に行われた報告「最近の研究成果、トピックス」において行われた4件の若手研究者の報告は、優れた若手研究者の育成が確実に進んでいることを示すものとして特に印象的であった。NIFS のような恵まれた環境で研究に従事することは、若手研究者にとって極めて恵まれたことであるに違いないが、最近の情勢は、研究の「評価」の厳しさ故にともすれば若い人材が浪費され、優れた資質を伸ばすことが困難になる場合を数多く見て、このような情勢下で果たして将来の学術を担う優れた研究者が育成し得るのか不安になる場合を少なからず見聞する。

NIFS がこれらの優れた研究者を育成に成功しつつあることは、その研究活動の健全さを示すものであって、わが国の核融合研究の未来を期待させるものであることを付記したい。

5．　全体的評価

以上のように、核融合科学研究所の研究活動は、磁場閉じ込め核融合研究の世界の中心の一つとして、優れた成果を挙げ、我々の期待に十分沿うものとして高く評価する。

6．　今後への期待

今後も世界の大型装置による磁場閉じ込め核融合研究の中心の一つとして現在の活動を益々発展させる方向で進むべきと考える。

一方で、世界の情勢は必ずしも磁場閉じ込め核融合にのみ集中しているわけではない。特にアジア地区においては、中国と韓国において慣性核融合研究の拠点が作られ、活発な研究活動が行われつつあることは注目に値する。

わが国の慣性核融合研究は、今日まで主として大阪大学レーザーエネルギー学研究センターで行われ、特に最近同グループが発見した高速点火方式には多くの研究グループが注目し、その線に沿った研究が行われつつある。しかし、現状の日本国内の大学でこれらの活動に競うことは極めて困難な状況にある。

NIFS に於いて慣性核融合をどう取り扱うかを、わが国の核融合研究計画の将来計画として早急に策定し、NIFS の計画の一つとして取り上げる方向で検討されることを切実に期待したい。

評価者: H

1. プロジェクト活動
（研究の目的，成果と課題，研究の質，改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

総評として，LHD プロジェクトはファーストプラズマ後，長きに渡り継続されてきた結果，非常に成熟した核融合研究プログラムとなり，現在世界中の実験プログラムを代表するものである。私的観点を述べると，これはひとえに NIFS および LHD プロジェクトの指導力，また，LHD プロジェクトを支える NIFS 専門職員や技術職員の努力の結果であると思う。LHD プロジェクトはまた，国内外の研究者や研究機関に研究協力を促し，繋がりを深め，核融合科学における効率的科学プログラムの実施および人材開発に取り組んできた。さらに，LHD 実験という現実的環境の中で指導と教育を行うことにより，世界に通用する一流の科学者を輩出したことについて，大いに評価したい。

新たに設置された垂直方向 NBI とともに，高密度状態での高イオン温度達成は，前回の評価会議から大きく飛躍した成果である。 今期の実験でイオン温度輸送が改良され，新古典輸送のレベルに到達している。

5.1％という高ベータ達成および定常運転時の持続値 4.5%は，ともに当初目標あるいは予測を上回る結果である。磁場構成およびトポロジーに関する詳細研究では，非常に優れた成果を上げてきた。

高イオン温度実験，高ベータ研究とともに，IDB による高密度，高圧力放電の達成も極めて重要な進展である。超高密度勾配条件下で計測された拡散係数は，詳細に研究されている。

定常運転研究において，ダイバータ板上にかかる熱負荷の制御，およびダイバータ板熱伝導率改良が効果的であったことが証明され，よって，今後計画されている改良はより確信的なものとなるだろう。

総評および LHD プロジェクトに関する功績のまとめとして，LHD 運転は未だ力強い前進の途にあるが，イオン温度，電子温度，改良高ベータ，電子密度，定常運転，これら全てが LHD 実験目標の当初予測を上回っている。よって計画中の改良が実施されれば，更に優れた結果をも望めるだろう。

b) （課題に順じた）専門研究

(i) 3D-MHD 特性を用いた高ベータ研究

上記で述べたとおり，LHD の高ベータ研究は，MHD 平衡，MHD 安定性および輸送を含む全ての課題において，研究の深さおよび成熟度を実証している。磁気軸を用いた MHD 平衡研究，平衡位相と比較したアスペクト比変化により，高ベータの達成方法および平衡ベータ限界を避ける方法が示された。

MHD 安定性分野では，磁場レイノルズ数への明確な依存性を明らかにした。また，線形安定性研究によって，抵抗性交換型モード安定性予測と実際の実験環境の区別が可能になった。Mercier モード，低 n 交換性モード，高 n バルーニングモードといった理想的モードの詳細研究が継続されており，MHD 安定性の特性，および分布や閉じ込めとの関係に関する共通理解への可能性が生まれた。

(ii) 高密度運転

高密度プラズマ達成に関しては，ペレット入射と粒子制御が LHD で研究されてきた。多様なペレット入射方法とともに，それらの成果が発表された。この高密度研究において，LHD の IDB プラズマは高密度勾配で生成される。IDB ショットの再現性が実証され，IDB の輸送特性が詳しく研究されてきた。

高密度研究において最高密度が達成され，連続ペレット入射を用いて高密度ショットの準定常保持が実現された。これらの成果によって，将来的アップグレードおよび炉研究における改善点が示された。

c) 将来計画

近い将来実施予定のアップグレードにおいて，NBI, ICH, ECH 加熱パワーの拡充は，これまで様々な分野で実証されてきた LHD 実験の進展を継続していく上で，極めて重要である。また，閉ヘリカルダイバータの展開も，ダイバータ板への粒子熱負荷の制御性を向上させる上で重要になるだろう。

重水素燃料を用いた実験を行うことで，同位体効果を理解する機会となり，既に素晴しい性能を実証済みの LHD の性能を更に引き立てるに違いない。

(2) シミュレーション科学プロジェクト

a) 概要と功績

報告の中で，3 つの主要なシミュレーションの取り組みが紹介された。第一の取り組み，数値試験炉を使った LHD・磁場閉じ込めシミュレーションが，3 件の中で 1 番の重要性を占める。この取り組みの目覚しい進展があり，LHD 実験において，近年性能向上を行う上で、首尾一貫性があり、より強力なものとなった。私個人の意見では，シミュレーション分野の急成長は，実験結果の理解向上や LHD 実験の性能向上に大きく貢献し，将来的にも貢献し続けるだろうと思われる。さらに，理論研究と乱流シミュレーションが非常に上手く作用し，互いに良いフィードバックを生み出したことにも注目したい。これらの取り組みが LHD 実験，そして閉じ込めに関する理解向上に貢献したことは疑いようがなく，よって，目標値の向上も当然のことだと考えられる。

レーザー核融合の高速点火シミュレーション，磁気再結合現象の PIC-MHD シミュレーション，およびプラズマ材料相互作用の PIC-MHD シミュレーションが，大きく進展したことは注目に値する。

b) （課題に順じた）専門研究

磁場閉じ込めシミュレーションプロジェクトにおいて，炉心プラズマ流体モデル，炉心プラズマ運動モデル，周辺プラズマモデル，および多階層統合シミュレーションを使った階層拡張シミュレーションの成果が発表され，大きな進展と素晴しい成果が紹介された。特に TASK3D コードの開発および LHD プラズマ解析への応用は，シミュレーションと実験の将来的な相乗効果を考える上で，極めて重要な進展を遂げた。

乱流輸送とゾーナルフローシミュレーションにおいては，他の主要グループとの強力な研究連携とともに，NIFS のこの取り組みにおける世界的役割が示された。急成長した能力は極めて素晴らしく，支援の面でも優先度を高くするようお勧めしたい。

c) 将来計画

提案された磁場閉じ込めシミュレーションプロジェクトの将来計画は，よく提起されていると思う。階層拡張シミュレーションの改良および数値試験炉レベルへの統合には相当の努力を強いられるだろうが，挑戦し甲斐もあるだろう。現行レベルの ITG 関連乱流シミュレーションに関する電子輸送研究とともに，粒子輸送のための乱流シミュレーションおよび運動量輸送に関する進展を期待したい。

(3) 連携研究

a) 概要と功績

連携研究推進センターは，非常に短期間の内に大学，産業界，また，他の研究機関と行ってきた多方面での連携活動において，非常に素晴らしい発展を遂げた。原子分子および境界プラズマデータグループの再編成は，PWI，移動表面式プラズマ対向壁概念研究，および不純物イオンを用いたプラズマ計測などにおいて良い成果に繋がった。

スピンオフ技術を生かした産業連携では，マイクロ波技術の数々の応用により，大きな進展が見られた。

大型望遠鏡の ZPF セラミックを含む他研究機関との連携協力は，核融合スピンオフ応用という面で注目に値する。

b) 将来計画

産業や他の研究機関といった 2 つの研究協力分野の将来計画に関しては，これまでの実績の延長である。しかしながら，マイクロ波応用の他にも技術を展開していくことが望ましい。LHD は多様なスピンオフが可能な先進機能を多数備えた装置であり，新たな応用方法を開拓していくための体系的アプローチの追及は，価値あるものである。

ITER 協力および BA プロジェクトにおいて，更に強力な姿勢で従事することも期待される。これまでに蓄積されたエンジニアリング能力と技術的ノウハウを活かし，NIFS は ITER および BA プロジェクトの成功に向けて，大いにその貢献が期待される。よって，ITER 活動に対する所内優先順位を現在以上に上げることが求められる。

(4) 炉工学研究

a) 概要と功績

炉工学研究センターは，ブランケット材料，ニュートロニクス，および超伝導マグネット材料の 3 分野を主軸として研究を行っている。ブランケット材料システム分野は，素晴らしい成果とともに着実な進歩を遂げてきた。ニュートロニクス分野は，現在発展の真っ只中にあり，成果を生み出している。超伝導マグネット材料に関しては，現在，中性子照射研究に大きく貢献しているところである。

b) （課題に順じた）専門研究

炉工学研究センター独自の貢献として，長寿命液体ブランケットの開発が報告された。V 合金やフリーベなど ITER TBM 関連の研究は，着実に発展してきた。詳細研究や開発も現在進行中である。

c) 将来計画

炉工学研究センターの将来計画の方向性は，DEMO 炉に向けたシステム統合をよく考慮されている。しかしながら，IFMIF および他の中性子源などの中性子材料研究のために，今以上に努力および優先する必要があるだろう。

2. その他

特別評価の締めくくりに当たり，NIFS をここまで発展させた本島修教授の指導力を賞賛したい。所長任期以前の彼の LHD 設計，建設，および運転に向けた貢献に関しては，今では広く知られているところであるが，NIFS 所長として 6 年間の任期中に築き上げた功績は比類なきもので，彼に並ぶ研究者となることは，決して容易ではないだろう。

しかしながら，LHD 実験や NIFS 若手研究者およびエンジニアの指導者は，LHD 実験の新たな領域そして，

その先に突入していくと強く信じている。効果的な進化を遂げるには先見の明をもつ指導力が求められ，活発な若手世代に責任職への門戸を開いていくことが重要になるだろう。

繰り返しになるが，本島教授のような素晴らしい指導者を持つ研究機関を評価させていただく機会に恵まれ，心から光栄に思う。

評価者: I

1. プロジェクト活動
（研究の目的，成果と課題，研究の質，改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

大型ヘリカル装置（LHD）で達成したプラズマ性能は，非常に素晴らしい。電子温度と密度の目標パラメータ，イオン密度，定常運転放電時間，そして，体積平均ベータが達成もしくは更新された。現在記録されている中心部イオン温度（5.2keV）は，目標（10keV）の約半分であるが，アルゴンガスを使用した場合の中心部イオン温度が 13.5keV を記録したことは，注目に値する。

b) （課題に順じた）専門研究

新しく増設された 7MW，40keV 垂直方向 NBI により，イオン温度およびイオン熱輸送向上に繋がった。非常に興味深いこととして，イオン温度勾配が増加するに連れ，外向き対流によって炭素不純物ホールが形成されることが発見された。対流は新古典的理論に矛盾しており，明らかに異常輸送である。不純物ホールは，非常に印象的な効果である。

また，高体積平均ベータ値（最大 5.1%，エネルギー閉じ込め時間の 85 倍持続値 4.8%，同 150 倍で 4.5%）の達成は驚異的である。追加熱機器増設によるベータ値の継続的向上は，ヘリカル型閉じ込めシステムにとって，非常に有望な結果だといえる。

「内部拡散バリア」によって，LHD が達成した超高密度に関しては，FFHR への可能性を繋ぐものとして，非常に重要である。（これは，2008 年国際土岐コンファレンスでの主要トピックであった。）ペレット入射の連続最適化は，高密度核融合炉シナリオを追求していく上で，不可欠な研究課題である。

高密度・高ベータプラズマ境界面のエルゴディック層における輸送は，重要な研究テーマである。3 次元境界輸送コード EMC3-EIRENE が，実験データ解析用に使用された。

とりわけ，アルヴェン固有モードに起因する高速イオン輸送のコードシミュレーションとコンビで実施されたシンチレータプローブを使った高速イオン損失計測では，非常に上質のデータが得られた。

個人的には，高ベータ MHD 実験に関する専門的発表（榊原博士）およびヘリカル炉用高密度運転に関する発表（坂本博士）を高く評価したい。これら双方に見られた実験データとシミュレーション結果の比較は，高く評価できる。例えば，高-n バルーニング・モードの研究を可能にする高精度 MHD コードの開発により，予測範囲が大幅に拡大された。両発表において，次の段階の研究計画が明確に示された。当然ながら，今後の外部評価委員会においても同様な特定のトピックスに関する説明を期待したい。

c) 将来計画

LHD には 4 つの短期計画がある。: (1) 追加熱機器の向上，特に 5 台目の NBI ライン増設，(2) 閉ヘリカルダイバータの設置，(3) 重水素プラズマ放電の開始，(4) FFHR に向けた設計研究の継続，これらは前進する上で，重要なステップであり，積極的な追求姿勢が望まれる。今後の外部評価委員会において，これらの将来計画の更に詳しい内容を伺ってみたい。

(2) シミュレーション科学プロジェクト

a) 概要と功績

シミュレーション科学研究部は，多数の成果を上げ，招待講演や出版物においても，極めて生産的である。結果として，同研究部の概要説明は多岐にわたる研究トピックを取り上げねばならず，詳細にまで至らなかったわけだが，午後の詳細な発表は，これらの不足を補完するものであった。

とりわけ，傑出した研究例として，ジャイロキネティックシミュレーション，マイクロ乱流およびマクロ MHD 間の多階層相関，高エネルギー粒子シミュレーション，無衝突リコネクション，高速点火の新たな目標設計に導いたレーザー核融合シミュレーション，などが挙げられる。

同研究部は，理論・データ解析部門と上手く連携しているように思われる。外部グループや研究者との連携協力にも尽力している。近年，JIFT の客員教授と共著で発表した論文の数々は，非常に素晴らしく，注目に値する。

シミュレーション科学に関する年次シンポジウムは，過去 2007，2008 年に開催され，より中身の濃い会議へと発展し続けている。2008 年のシンポジウムには，約 90 名が参加した。

シミュレーション科学のためのスーパーコンピュータのリプレイス（77 TFlop, 16 TByte）の選定が完了したと，2008 年 9 月に発表された。2009 年 3 月より，運転開始を見込んでいる。 数値試験炉プロジェクトの進行に当たって多用されるだろうことは言うまでもない。

昨年も指摘したとおり，「hierarchy-extended（階層拡張）」，「hierarchy -integrated（階層統合）」「hierarchy-normalized（階層繰り込み）」の意味が未だ不明瞭である。もう少し国際的に許容され，理解されている専門用語の使用を提案したい。

超一流のシミュレーション科学知識を持つ研究所として，NIFS には，近年 ITER 用に新設されつつある統合モデル専門家グループへの参加が望まれる。

b) （課題に順じた）専門研究

近年発行された数々の出版物（昨年の Physical Review Letter を含む）または 2008 年度に開催された 3 つの国際的に大きな会議（American Physical Society, International Congress on Plasma Physics, and IAEA Fusion Energy Conference）で招待講演に選ばれたことから証明されるとおり，ジャイロキネティックシミュレーション研究は，世界的に認められている。本研究についての専門発表（渡邉博士）は素晴らしかった。特に，ヘリカルリップルに閉じ込められた粒子の径方向ドリフト運動の効果を導入したことにより，内寄せプラズマでの実験観測と非常によく合致する ITG 熱輸送が導かれたという発見は，非常に興味深い。これらのジャイロキネティックシミュレーションは，現在その理論的予測を実際に LHD でテストするための，具体的な実験を提案できる段階にあると思われる。 計画されている ETG 乱流やゾーナルフローに関する研究は，非常に重要である。 熱輸送に加え，運動量輸送や異常粒子輸送研究も考慮されたい。

LHD 高密度運転におけるダイバータ，高ベータ運転におけるエルゴディック境界層の重要性を考慮すると，境界プラズマ物理に関する理論・シミュレーション研究の強化が有益だと思われる。特に，LHD 用ダイバータレッグの一次元流体モデルは，二次元あるいは三次元モデルに拡張し，キネティック効果を加えるために一般化すべきである。

FIREX のレーザーシミュレーションに関しては，pre-pulse 加熱およびコーンのフォーム構造の追加という新たな構想により，性能は大幅に向上するだろう。

現実問題（磁気圏サブストーム等）を解決するため，磁気リコネクションシミュレーションを用いることを推奨したい。リコネクションシミュレーションの現実的適用例として，他には太陽コロナループが挙げられる。

c) 将来計画

LHD・磁場閉じ込めシミュレーションプロジェクトに関する中間計画に，14 の目標が掲げられている。これらは全て妥当だと思われる。目標達成が LHD 運転または理解に与える影響について，更にお聞かせいただきたい。

レーザーシミュレーションプロジェクトの中期計画目標は，NIFS で 1 人の研究者のみが同プロジェクトに携わっていることを考えれば，大変野心的だと思われる。

プラズマ複雑性シミュレーションプロジェクトの中期計画目標は，妥当である。

数値試験炉開発への目標は，極めて意欲的である。この包括的コードを表示しているフローチャートに加え，短期計画への具体的ステップが明示された構想を拝見したい。

LHD 実験プログラムは，シミュレーション・理論的解釈で解明されるだろう興味深い物理的側面から，不純物ホール，密度バリア，超高ベータ運転等々，斬新な成果を上げ続けている。シミュレーション科学研究部には，これらの研究にさらに着目し，追求し続けていただきたい。

(3) 連携研究

a) 概要と功績

連携研究推進センターでは，幅広い分野で多彩な活動が行われている。

同センターの内部組織は，研究センター内にあった原子分子グループを境界プラズマデータグループへ変更，産学連携推進室内に基礎イノベーション科学技術関連グループを追加，（キッズ・エネルギー科学館を含む）サイエンスコミュニケーション部門の新設など，2008 年に一部改組された。
改組後のセンター組織図において，「collaboration」，「coordination」，「cooperation」が，それぞれ違う意味で用いられているのか，また，同じ単語として認識されているのか分からない。

PWI の分野では，連携研究推進センターは，液体・固体リチウム移動壁コンセプトに関して研究を行っている。本研究が，各国研究グループが実施しているリチウムプラズマ対向壁研究と如何に異なるのか伺ってみたい。また，新たな成果が明確にされていない。最近では 2008 年核融合技術シンポジウムで長山博士が論文を発表している（が，同センターの Web ページ上に彼の名前は見当たらない）。

不純物イオンの衝突輻射モデル開発研究は，LHD の境界プラズマ診断計測と関連する。これらのモデルが太陽プラズマデータを分析する外部連携の基礎を築いたとのことである。

プラズマ物理，材料科学，および原子分子物理を組み込んだトリチウムリサイクリングのシミュレーション開発研究は，ITER および他の燃焼プラズマ実験にとって，極めて重大な課題だと言えよう。PSI および ICPP 会議で発表された本テーマに関する 2 本の論文は，何れもジャーナル出版が認められた。同分野での更なる研究発展が望まれる。PWI やトリチウムインベントリーおよびリサイクリングに関する同センターの研究活動は，炉工学研究センターが実施する同様の研究と調整・統一化できるのではないだろうか。

FIREX 高速点火シミュレーションに関しては，既にシミュレーション科学研究部が研究発表の場で（共同研究として）報告しており，新たに連携研究推進センターの報告に含まれる理由が不明瞭である。

新しいセラミックを目指したマイクロ波焼結技術の研究が，同センター活動の大部分を占めている。同研究は，次世代型巨大望遠鏡用ミラーの建設に応用できるものとして，非常に重要である。また，本研究を通して，産業界と強固な連携協力体制を築くに至った。これに関連して，磁場変化によって発生したエネルギーに関するモンテカルロ・シミュレーションは，高い注目に値する。これにより，キュリー温度以上での自発的磁化消失に関する興味深い結果が見出された。

NIFS が核融合アーカイブズを支援していることは高く評価される。同アーカイブズは，これまで 18,000 の文書を収集してきた。データベース上のイベント数について，1997 年から単調に増加していたものが，なぜ 2005 年以降，突然落ち込んでしまったのか疑問である。

2008 年後半に開館したキッズ・エネルギー科学館は，NIFS において連携研究推進センターが運営する新たなアウトリーチプログラムであり，非常に興味深い。NIFS のロビーに設けられている展示室をゆっくり観覧して回り，様々な展示を楽しませてもらった。地元学生や，LHD／バーチャルツアーに訪れた見学者も各展示物に心奪われることだろう。

新たに設けられた，教員のための「サイエンス・コミュニケーション」コースも，斬新で素晴らしいアイデアである。

b) 将来計画

コロナ加熱を調査するための衝突輻射モデル開発計画に関する記述を除き，将来計画に関して明確に記述されていなかった。プレゼンテーション上で報告された現在の研究が，継続されるのだろうと推測される。

(4) 炉工学研究

a) 概要と功績

炉工学研究センターには素晴らしい設備が整えられており，大学研究グループとの研究協力推進に役立つだろう。

同センターは，LHD の工学的課題，FFHR，および安全コスト評価の面で，炉工センター外に所属する NIFS 研究者と連携研究を進めているほか，国内大学の研究グループと 7 件の共同研究に携わっている。FFHR 炉設計問題，取り分け，ブランケットおよび照射に着目した研究は，賞賛に値する。

炉工学研究センターは，非常に建設的に運営されていると思う。

b) （課題に順じた）専門研究

ブランケット材料システム分野においては，バナジウム合金溶接，溶融塩フリーベ・液体リチウムの強制対流，および先進コーティング技術といった方面で，新たな成果が達成された。特に，高純度フリーベ下におけるスチールの低腐食速度を確かめる研究で，日本原子力学会から若手研究者賞を賜ったことは大いに注目したい。長寿命液体増殖ブランケットの開発に関する詳細な報告（長坂博士）は，非常に興味深かった。

ニュートロニクスの分野では，シミュレーション，実験ともに行われている。重要なこととして，これにより試験ブランケットモジュールおよび DEMO 炉設計に関するコードモデリングの妥当性が確認できる。

マグネット材料システムの分野では，大学，産業界，および他の国立研究所（物質・材料研究機構，日本原子力研究開発機構）との連携協力を通して，超伝導マグネット材料への中性子照射効果を調査している。

過去 3 年間に発表された多数に及ぶ各種論文を，表を用いて発表していただけてありがたかった。研究者 7 名と学生 3 名しか在籍しないことを考慮すれば，炉工学研究センターは 3 年間で非常に多くの論文を発表してきた。これら論文の多くは共著である。同センターが論文執筆および出版の推進に，意識的に取り組んできたことが伺える。

c) 将来計画

ブランケット，ニュートロニクス，およびマグネットの 3 研究分野ともに，明確な将来計画が提示された。

2. その他

核融合科学研究所は，同研究所が掲げる三重のミッション目標について明瞭に記述している。これらは，(1) 研究－実験，理論および工学, (2) 共同研究－国内および国際協力, (3) 教育－大学院生および若手の3項目に分かれている。総体的にNIFSは，これら全てのミッションを強力に遂行している。2004－2009年度のLHD／シミュレーション／炉工学中期計画は，それぞれ明瞭に述べられている。（共同研究に関しても，同様の中期計画があれば良かったかもしれない。）

NIFS職員の数は，2007年度から比べれば，2008年度は2%と僅かに増加した。予算は昨年度から若干減少した。（数値上は0.5％減であるが，実質値では4,100万円のマイナスになる）

一般共同研究，LHD 共同研究，双方向型共同研究それぞれの研究テーマ数（および共同研究者数）は，前年に比べて若干ながら，全てにおいて増加した。しかしながら，研究資金は2,100万円減少した。また，興味深いことであるが，NIFSとの共同研究に携わった大学および研究機関の総数は，157校から144校へ8%減少した。

2008 年においては，新たな政府間、外国の大学や研究機関との国際連携，あるいは科学協定は締結されなかった。政府間協定として6件，外国の大学や研究機関とは14機関，これまでに学術交流協定が結ばれており，これだけでも目を見張る数だと言える。

総合研究大学院大学の学生数は，連携大学の学生がNIFSで博士研究を行ったり，共同研究プロジェクトを通して NIFS で研究している学生研究者がいることから，前年比とほぼ同じ数に留まった。連携大学の学生がNIFSで授業を受ける数は50%減少した。2008年にはITER国際サマースクールが日本で開講された。

特別評価会合での発表のバックグラウンド情報として，NIFS の最新出版物 12 件を提供していただけたことに感謝したい。

今後の外部評価委員会の概要発表において，LHD，シミュレーション科学，共同研究，および炉工学研究センターの活動および進展の度合いを測るものとして，数値基準の導入をお薦めしたい。数値基準の一例として，発表論文，招待講演，特許，卒業学生，共同研究の数等が挙げられる。
私の印象では，NIFS の出版物は年々増加を重ねてきた。近年ジェノバで開催された IAEA 会議の場でも，NIFSの存在が注目を集めていたことは明白である。

午後に設けられた（比較的）若手研究者による詳細発表は，明瞭かつ整然として非常に素晴らしく，このような高い資質を持った人材がいる NIFS の明るい未来を象徴している。実際のところ，今回と同等の高い質の成果報告の数を2倍に増やすことも，今のNIFSなら容易にできるのではないかと推測している。

6年間NIFSの所長を務めた本島教授には賞賛の言葉以外見つからない。LHDは，現在世界で最高のヘリカル型閉じ込め核融合装置であり，NIFS は実験，理論シミュレーション，および炉工学を統合したプログラムとともに，世界の核融合科学界をリードする存在である。次期所長におかれては，本島所長が発揮してこられた見事な指導力に則って，効率的かつ生産的に機能している現研究所を引き継がれることだろう。

2. 評 価 の 概 要

1. プロジェクト活動
（研究の目的，成果と課題，研究の質，改善点の提案）

(1) 大型ヘリカル装置（LHD）プロジェクト

a) 概要と功績

- LHD プロジェクトの成果は大変優れたものであり，核融合エネルギー開発を成功裡に進める上での主要課題を全て網羅している。
- 過去 6 年間における主な発見のハイライトとして，不純物ホールを伴う高イオン温度，超高密度運転，MHD 不安定性による大幅な劣化が見られない高平均ベータ，および定常運転などが挙げられる。これらはヘリカル閉じ込め方式核融合にとって，非常に有望な成果であるといえる。
- 物理研究も重要視され，これは言うまでもなく，設立当初 NIFS に課された使命に基づいている。また，研究所はトロイダルプラズマの総合理解の前進にも貢献した。
- 複雑な超伝導システムの安定運転も，優れた技術的成果である。
- LHD プロジェクトは，科学プログラムの効率的実践，および核融合科学分野における人材開発に，向けて貢献し，共同研究を強化した。

b) （課題に順じた）専門研究

- 磁場配位の最適化および加熱機器の体系的増強により，素晴らしいプラズマ性能が達成された。 高速ペレット入射とあいまって，新たな運転領域，ディスラプションの無い高密度運転が発見された。
- 不純物蓄積が抑制された興味深い現象も見出された。
- 高ベータ領域におけるMHD 平衡および安定性の問題に対しては，大変成功裡に取り組まれている。 質の高いプラズマ計測技術によって，プラズマ実験の分析および理解の前進に繋がったものと考えられる。
- 定常運転の発展および核融合条件を満たす核融合三重積を実現するためにも，加熱機器の増強，閉ダイバータ構成および重水素運転の効率的導入を実践すべきである。
- 内部拡散障壁(IDB)，コア密度崩壊(CDC)，不純物ホールといった新発見の物理的理解について，更なる追究が求められる。運動量輸送について，特に不純物輸送との相関性について，更に重点を置いて取り組まれたい。
- 注意深い実時間配位制御によって，ベータ値は更に向上すると思われる。
- 高速イオン損失の計測および関連するシミュレーションの知見により，実験データの解釈が大きく進展した。
- 炉研究は，現在の DEMO 研究との密切な関連性を持つべきである。グリーンワルト限界が無いことで，より高密度・低温状態での点火に関する展望が拓けたことは明白である。これらの炉条件下における熱不安定性，中性粒子輸送，不純物生成および輸送の役割について，全貌の理解を得ることは有益だろう。

c) 将来計画

- 重水素実験，加熱能力増強，閉ヘリカルダイバータ，FFHR 設計研究の継続といった直近の将来計画は，よく定義されている。
- 閉ヘリカルダイバータの段階的導入に関しても，実験スケジュールに影響を及ぼさないよう，よく計画されている。
- 装置の物理的限界への挑戦を目標に，全力投入していくことが望まれる。
- プラズマパラメータの改善に向けて，NIFS の傑出した技術力・計算機能力に基づく斬新かつ詳細な方法を模索していただきたい。

(2) シミュレーション科学プロジェクト

a) 概要と功績

- 3 件のプロジェクトを平行して進められるようになる程，シミュレーショングループが発展してきたことは高く評価される。特に LHD 磁場閉じ込めプロジェクトにおいては，国際的競争力をもつ高レベルな成果を着実に積み上げてきた。シミュレーション研究の急成長は，実験成果の理解を深めるとともに，今後の LHD 性能向上に貢献し，また，将来的にもそうあり続けるだろう。
- これらの活動を統合し，新たなスーパーコンピュータを最大限に活用することによって，「数値試験炉プロジェクト」を展開させていくという方向性は理にかなっている。
- レーザー核融合シミュレーションプロジェクトおよびプラズマ材料相互作用に関する数値研究により，同グループの影響力は更に拡大されるだろう。
- 学際的アプローチをとるこれらのプロジェクトは，様々な研究機関における関連事業を取り纏めている。

b) （課題に順じた）専門研究

- ヘリカルプラズマにおける ITG 乱流およびゾーナルフロー形成の研究は，目覚しい進展を遂げている。新古典輸送の小さい配位では，ゾーナルフローが高い振幅で維持されることが明らかにされた。また，径電場効果においても研究が進められた。これらのシミュレーションは現在，予測の検証的 LHD 実験を提案できる段階にまで到達している。
- TASK3D コードの開発および同コードの LHD 実験への応用は，シミュレーションと実験の将来的な相乗効果に向けて，大変貴重な進歩を遂げた。
- 詳細な計測データを含めることは，現在の傑出したシミュレーション成果の更なる増補に繋がるだろう。
- トカマクとの対比に気を配られたい。
- LHD 実験に関連した目標は，適切に定義されている。CDC, IDB, 不純物ホール，また，運動量輸送といった最新かつ話題の問題が，これらに含まれていることは必須である。
- 一般科学に関する重要課題（自己組織性，磁力線再結合，および全体統合プロジェクトなど）については，NINS における取り組みの統合がなされつつある。

c) 将来計画

- 数値試験炉プロジェクトは，直近の計画に関して，明確に定義された具体的段階が準備されており，高く評価される。
- ITER モデリンググループとの実りある協力，支援が望まれる。
- 重水素実験に焦点をあてたシナリオの取り組みが必要である。
- 新たなスーパーコンピュータに関する計画は，高く支持できる。
- これらのシミュレーションプロジェクトが，幅広い分野における階層現象の統合研究を推進する上で，先駆者的役割を担っていくことを強く期待したい。

(3) 連携研究

a) 概要と功績

- 連携研究推進センターは，適切に組織されており，多方面の科学・産業分野に LHD 実験の波及効果を高めつつ，トップクラスの活動を行っている。このことは，原子分子過程，PWI，材料科学，原子物理学，レーザー核融合，計測，および基礎プラズマ研究の分野で特に顕著である。
- キッズ・エネルギー科学館のようなアウトリーチ活動も高く評価される。
- 新たに開設された教師のための「サイエンスコミュニケーション部門」も，素晴らしいアイディアである。

b) 将来計画

- ITER，BA，JAEA，および ICF(FIREX)研究との密切な連携が強く推奨される。DEMO 関連課題に関するした先駆的研究の推進が必要である。
- トリチウムの取り扱いに関する問題に殊更重点を置くべきである。
- 幅広い科学分野の基礎として，原子分子データベース活動の更なる前進を強化されたい。
- LHD はスピンオフの可能性を秘めた多彩な先進技術を兼ね備え，新用途の開拓に必要な体系的アプローチを追究している。
- アウトリーチを様々な団体や市民にまで拡大することも可能だろう。これらは NIFS の将来計画に関わるものであり，NIFS の大学共同利用体制を活用しつつ，関連コミュニティとの議論を進めるべきである。
- また，各研究トピックの最終目標，どのようなブーメラン効果が得られたのかについて，明確にすることをお勧めしたい。

(4) 炉工学研究

a) 概要と功績

- 研究課題は適切に選択されており，国際的にも価値のある成果を上げている。炉工学研究センターは，核融合炉に向けた最大の懸案事項（ブランケット，ニュートロニクス，マグネット等）を選定することにより，重要な成果を上げてきた。
- 彼らの功績を理解する上で，予想される炉スケールを明確化してみる価値はあるだろう。

b) （課題に順じた）専門研究

- 炉工学研究センターは，ブランケット材料システム，ニュートロニクス，およびマグネット材料システム分野の専門家で構成されている。長寿命フリーべおよび Li ブランケット研究は極めて素晴らしい。
- NIFS-HEAT-2 は，不純物汚染を防いで溶接することに成功している。
- 高速フィードバックシステムが，ニュートロニクス設計に統合された。 ニュートロニクス研究は，間近に迫っている ITER 運転にとっても，歓迎される。
- 超伝導開発でハイレベルな成果を上げており，高く評価できる。

c) 将来計画

- 周辺構造，電流リードに関する課題等について，更なる研究協力の推進が求められる。
- 超長時間での熱クリープの研究のために，長期間のクリープ試験を継続する必要がある。
- 複雑形状における中性子計算の向上，および高温超伝導に関する更なる検証計測や研究が望まれる。
- IFMIF や他の中性子源といった中性子照射下での材料研究に向けて，さらに尽力し，優先順位をあげられたい。
- 開発計画がどの程度 ITER および IFMIF スケジュールに左右されるかについて，更に詳しく分析するとよいだろう。
- ヘリカル炉計画およびトカマク／ヘリカル炉間の対比が望まれる。

2. その他

- 本島修所長の優れたリーダーシップにより，NIFS は最先端核融合研究における国際的先導者としての地位を確立した。これらの成果は，幅広い研究活動の周到な協調，および同研究を熱核融合という主要目標に集約させたことにより達成された。これらは世界的関心を集める LHD 実験成果やシミュレーション科学の成果のみならず，付随する全ての科学プログラム，多数の研究機関との連携協力，技術プログラム，および広報関係プログラムまでも網羅してきている。
- 成果報告のクオリティは素晴らしく，若手世代の発表には目を見張るものがある。彼らのような若い研究者が世界に通用する成果を上げているのは，大変心強いことである。また，これは NIFS が将来に向けて準

備万端であることの証でもある。次回の評価会議では，現在の勢いや世界的先導力をいかにして長期間保ち続けていくかについて，着目していただきたい。
- 現在の成果と更なる連携協力の発展に基づく NIFS における研究の進展，新たな科学的潮流の萌芽を期待したい。

(b) Attached Documents

Contents

1. Participants List of NIFS Special Review Meeting

No.	Name	Title, Affiliation
Reviewers		
1	Dr. Carlos Alejaldre	Deputy Director-General for Safety and Security, ITER, France
2	Dr. Gyung-Su Lee	President, National Fusion Research Institute, Republic of Korea
3	Prof. Hiroshi Takuma	Advisor (Emeritus Professor, the University of Electro-Communications)
4	Prof. James W. Van Dam	Director, Institute for Fusion Studies in the University of Texas at Austin, USA
5	Prof. Kyoji Nishikawa	Advisor (Emeritus Professor, Hiroshima University)
6	Prof. Michael Tendler	Advisor (Professor, Royal Institute of Technology, Sweden)
7	Prof. Robert Wolf	Professor, Max-Planck-Institute for Plasma Physics, Germany
8	Prof. Satoshi Itoh	Advisor (Emeritus Professor, Kyushu University)
9	Prof. Thomas Klinger	Professor, Scientific Director of Max-Planck-Institute for Plasma Physics, Germany
NIFS members		
10	Prof. Osamu Motojima	Director-General
11	Prof. Shigeru Sudo	Deputy Director-General / Executive Director, Department of Simulation Science
12	Prof. Akio Komori	Executive Director, Department of Large Helical Device Project
13	Prof. Hiroshi Yamada	Director, Research Operations Division, Department of Large Helical Device Project
14	Prof. Shinsaku Imagawa	Director, Fusion and Advanced Technology Systems Division, Department of Large Helical Device Project
15	Prof. Noriyoshi Nakajima	Director, LHD and Magnetic Confinement Simulation Division, Department of Simulation Science
16	Prof. Shoichi Okamura	Director, Fusion Frontier Simulation Division, Department of Simulation Science
17	Prof. Motoyasu Sato	Director, Coordination Research Center
18	Prof. Akio Sagara	Director, Fusion Engineering Research Center
19	Assoc. Prof. Satoru Sakakibara	Associate Professor, Research Operations Division, Department of Large Helical Device Project
20	Assoc. Prof. Ryuichi Sakamoto	Associate Professor, Research Operations Division, Department of Large Helical Device Project
21	Assoc. Prof. Masayuki Yokoyama	Associate Professor, Theory and Date Analysis Division, Department of Large Helical Device Project
22	Assoc. Prof. Tomohiko Watanabe	Associate Professor, LHD and Magnetic Confinement Simulation Division, Department of Simulation Science
23	Assoc. Prof. Takuya Nagasaka	Associate Professor, Fusion Engineering Research Center
24	Mr. Yasuo Kainai	Director, Department of Administration
25	Mr. Yutaka Fukui	Head, Planning and External Affairs Division, Department of Administration
26	Mr. Sadao Azuma	Leader, Planning Office, Planning and External Affairs Division, Department of Administration
27	Mr. Makoto Tsuda	Chief, Objective Planning and Evaluation Section, Planning Office, Planning and External Affairs Division, Department of Administration
28	Mr. Kazuma Shimizu	Staff, International Affairs Section, External Affairs Office, Planning and External Affairs Division, Department of Administration
29	Ms. Shihoko Soga	Staff, Press and Community Relations Section, External Affairs Office, Planning and External Affairs Division, Department of Administration

2. Program of NIFS Special Review Meeting

December 13, 2008 (Sat.)
Special Room, Restaurant and Conference Rooms 3F, HIDA Earth Wisdom Center

8:30	Opening
8:30 -	Opening Address (5 min) Director-General, Osamu Motojima
8:35 -	Introduction of NIFS Activities (20 min) Deputy Director-General, Shigeru Sudo
8:55 -	Current status and research subjects, future plans of NIFS (160 min) [40 min / item (Report 25 min + Q&A 15 min)] 8:55 - 9:35 Large Helical Device (LHD) Project Executive Director, Akio Komori 9:35 - 10:15 Simulation Science Project Director, Noriyoshi Nakajima ---- Coffee Break (15 min) ---- 10:30 - 11:10 Coordination Research Director, Motoyasu Sato 11:10 - 11:50 Fusion Engineering Research Director, Akio Sagara

---- Lunch Break (60 min) ----

12:50 -	Recent results and topics (240 min) [60 min / item (Report 40 min + Q&A 20 min)] 12:50 - 13:50 High Beta and Related 3-D MHD Characteristics Assoc. Prof. Satoru Sakakibara 13:50 - 14:50 High Density Operation and Its Prospect for Helical Reactor Assoc. Prof. Ryuichi Sakamoto ---- Coffee Break (15 min) ---- 15:05 - 16:05 Turbulent Transport and Zonal Flows Assoc. Prof. Tomohiko Watanabe 16:05 - 17:05 Development of long-life liquid blanket Assoc. Prof. Takuya Nagasaka
17:05 -	General comments from reviewers (40 min)
17:45 -	Closing Address (5 min) Director-General, Osamu Motojima
17:50	Closing

3. Viewgraphs

3-1 Introduction of NIFS Activities

Introduction of NIFS Activities

National Institute for Fusion Science, NINS
Shigeru SUDO
自然科学研究機構 核融合科学研究所
Presentation to the Special Review Meeting
December 13, 2008, Takayama, Japan

Introduction of NIFS Activities

1. **Mission of NIFS**
2. **Organization**
3. **Collaboration Research**
4. **Training and Education of Young Researchers**
5. **Recent NIFS Research Activities**
6. **Overview of Review Process**

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1. Mission of NIFS

To promote nuclear fusion science and research on its application, NIFS was established as an Inter-University Research Institute in 1989.

(1) To promote both experimental research based on the world largest superconducting device: Large Helical Device (LHD), theoretical and simulation research, and fusion engineering research.

(2) To promote collaboration research with universities and institutes all over the country and also international collaborations, and to bring up young researchers.

(3) To educate graduate students in the department of nuclear fusion science of the Graduate University for Advanced Studies, and also in the other universities.

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Transparency and Accountability of Research Activity

- Mid-Term Goal (FY2004-2009)
- Mid-Term Plan (FY2004-2009)
- Annual Plan (done for 2004-2008 every year)

- Annual Achievements Report 2004-2007 every year
- Annual review by the evaluation committee organized by MEXT (done in 2004-2007 every year)

- Research activities are being reviewed by National Institution for Academic Degrees and University Evaluation in 2008

NIFS
Number of Staff: 225 (Researchers:133, Technical Staff: 45, Administrative Staff: 47) (FY2008)
Annual Budget: 10616 MYen (FY2008)

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Mid-Term Plan (FY2004-2009) Related to LHD

LHD project

- To maximally utilize the performance of LHD and conduct scientific researches in an effort to achieve comprehensive understanding of toroidal plasmas and actualize fusion reactor plasmas. Therefore, NIFS strives to maintain, develop, and improve plasma heating devices and diagnostics equipments as well as to increase the performance of LHD plasmas that foresee fusion core plasmas.

Bilateral collaboration researches

- To work on the clarification of physical mechanism necessary to boost up the plasma performance as part of bilateral collaboration researches by efficiently utilizing devices and equipments of research institutions, universities, affiliate institutions, and centers. With a view to improve confinement property, to actively promote a development of the next-generation experimental device with an advanced magnetic configuration as a common subject of the research community.

Internal structure to achieve goals

- In order to produce an intensive research outcome, to establish organizations capable of operating flexibly and effectively. To review functions of research departments and centers and carry out organizational changes.
- To strengthen collaboration systems with universities and to enhance supporting systems for researches in universities.

Relevance to inter-university research activities

- To improve the research environment with a view to promote inter-university research activities and collaboration researches that utilize experimental devices like LHD.

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Mid-Term Plan (FY2004-2009) Related to Simulation Research and Fusion Engineering

Simulation Research

(1) Understanding of the Plasma

To understand and systematize physics mechanism of fusion plasmas

To explore complexity science (nonlinear, non-equilibrium, open system) as basic researches to support fusion plasma studies

(2) Simulation Science

To aim at establishing "Simulation Science" as a new interdisciplinary field

To promote collaborative researches, utilizing large-scale simulators

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Fusion Engineering

To contribute progress toward establishment of fusion reactors by leading activities and summarizing results in the fusion engineering studies through collaborations among universities, to enrich facilities and functions for these studies, to obtain most advanced results in this field with own activities.

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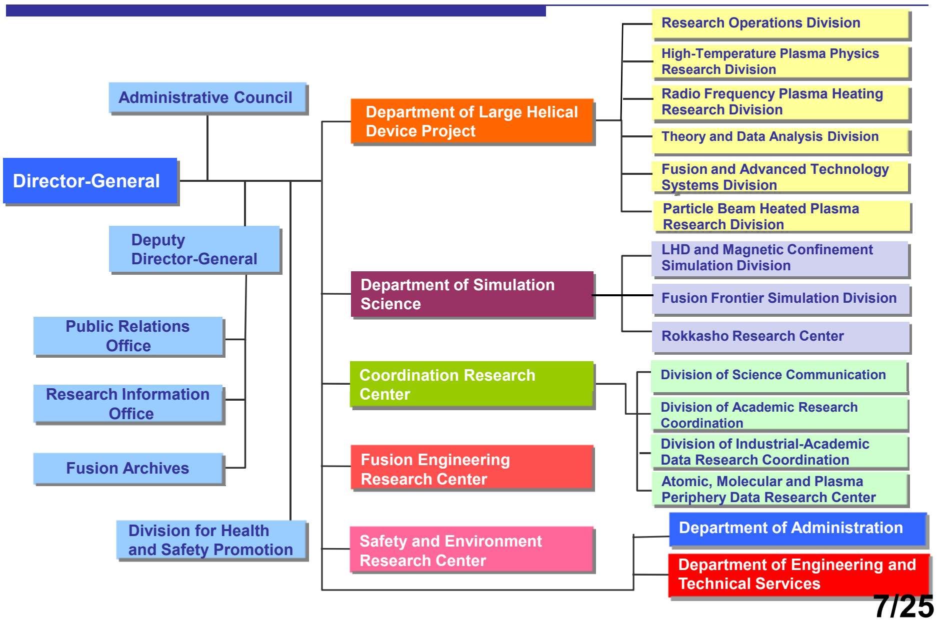
2.Organization

(2008)



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3. Collaboration Researches conducted by NIFS as an Inter-University Research Institute

The collaboration researches conducted by NIFS are categorized into:

(1) General collaboration research

339 Research Subjects, 80 MYen

(2) LHD collaboration research

34 Research Subjects, 170 MYen

(3) Bilateral collaboration research

68 Research Subjects, 654 MYen

for FY 2008

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Bilateral Collaboration

Number of subjects & collaborators

JFY	2004	2005	2006	2007	2008
Subjects	43	52	53	59	68
Collaborators	495	625	671	777	866

for FY 2008

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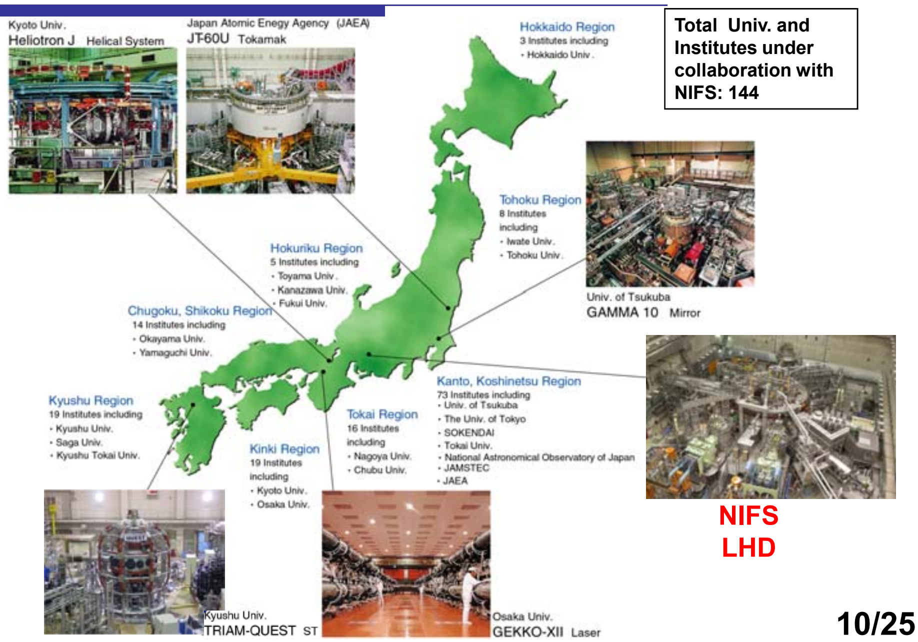
Japanese Fusion Activities



Total Univ. and Institutes under collaboration with NIFS: 144

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International Research Collaboration

1. Academic Agreement

To promote international research collaborations the following agreements have been concluded:

(between governments) US-Japan, China-Japan, Korea-Japan, IEA Stellarator, IEA TEXTOR, IEA Spherical Tori: These agreements cover fusion community in Japan. NIFS contributes to support domestic researchers

(between institutions) ASIPP-,Max Planck-, Kurchatov-, Kharkov-, ANU-, KBSI-, FZK-, PPPL-, IFS ,Univ.Texas-, ORNL-, UCLA-, Univ. Provence-, GPI- NIFS,

LIA (Kyushu Univ. NIFS, Osaka Univ. – CNRS, Univ. Provence)

2. Collaborative Research Framework for ITER

To promote ITER-related collaboration researches, the organization has been established in NIFS.

3. International Conferences

To support research activities of domestic researchers by holding international conferences and symposia. **International Toki Conference (ITC)** has been held annually, selecting current topics as the main theme. In 2007, the ITC was held jointly with International Stellarator/Heliotron Workshop with the topics of “Physics of Flows and Turbulence in Plasmas.” The theme of the ITC in 2008 was “Development of Physics and Technology of Stellarator/Heliotrons en route to Demo.” The 6th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research in Inuyama, the PET conference in Takayama, the international LAPD conference in Takayama, US-Japan Workshops were held in 2007.

4. Personal Exchange

To strengthen research activities guest professors have been invited and researchers have been sent to foreign institutes. To promote mutual understanding and to cultivate young scientists, graduate students have been accepted from foreign countries.

International Cooperation

Governmental Cooperation	Date of Conclusion
IEA Implementing Agreement for a Programme of Research and Development on Plasma Wall Interaction in TEXTOR	Apr. 13 1978
Agreement between the Government of Japan and the Government of United States of America on Cooperation in Research and Development in Energy and Related Fields	May 2 1979 (Changing to new scheme)
International Energy Agency Implementing Agreement for Co-Operation in Development of the Stellarator Concept	Oct. 2 1992
Core University China-Japan Collaboration Program (CUP) Researches on Core Plasma & Reactor Technology for Advanced Fusion Reactor	Oct. 16 2000
Japan-Korea Cooperation in the Area of Fusion Energy Research and Related Fields	Nov. 16 2004
IEA Implementing Agreement for Cooperation on Spherical Tori	Feb. 20 2007

Scientific Agreements of NIFS with Foreign *Universities/Institutes*

Agreement Conclusion Facility	Country	Conclusion Date
Institute of Plasma Physics, Academic Sinica	China	Jun. 27 1992
Max-Planck-Institut für Plasmaphysik	Germany	May 11 1993
Russian Research Centre, Kurchatov Institute	Russia	May 15 1993
National Science Centre, Kharkov Institute of Physics and Technology	Ukraine	Oct. 7 1994
The Australian National University	Australia	May 8 1995
Korea Basic Science Institute	Korea	Mar. 6 1996
Forschungszentrum Karlsruhe GmbH, Institut für Technische Physik	Germany	Oct. 6 2005
Princeton Plasma Physics Laboratory	USA	Mar. 3 2006
Institute for Fusion Studies, The University of Texas at Austin	USA	Mar. 6 2006
Oak Ridge National Laboratory	USA	May 25 2006
Institute of Plasma and Fusion Research, University of California, Los Angeles	USA	Nov. 28 2006
University of Provence	France	Jul. 19 2007
A. M. Prokhorov General Physics Institute, Russian Academy of Sciences	Russia	Oct. 15 2007
Agreement for the Creation of an Associated International Laboratory (LIA): Japan (Kyushu Univ., NIFS, Osaka Univ.) – France (CNRS, Univ. Provence)	France	Oct. 22 2007

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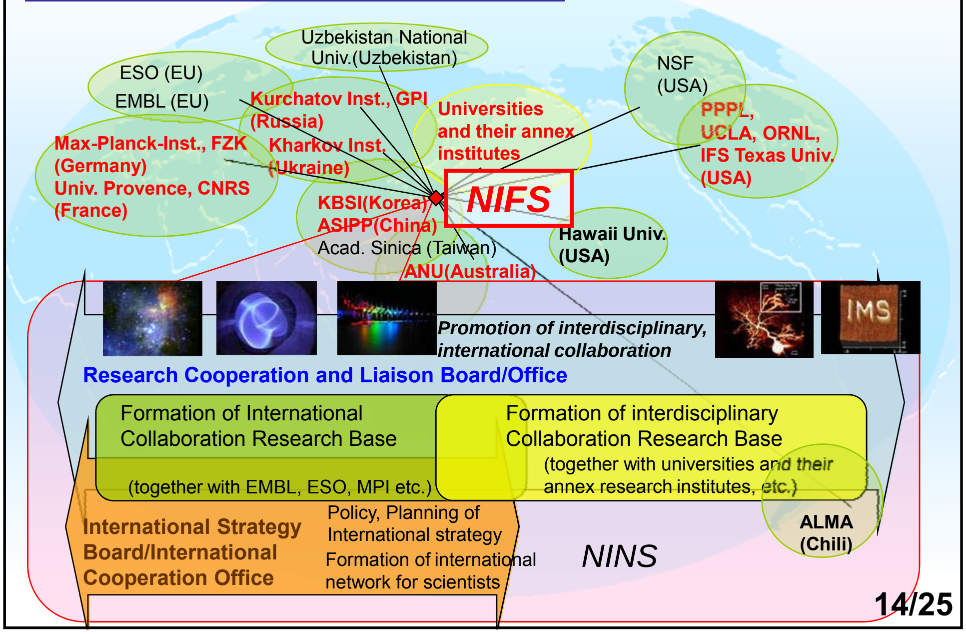
Formation of Interdisciplinary and International Network of Research Bases as a member of NINS



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4. Training and Education of Young Researchers at NIFS

Postgraduate Education — at 2008.11.01

	FY2005	FY2006	FY2007	FY2008
Summer / Winter Schools				
Seminar in Kashikojima	Jul.28-30	Jul.27-29, Jul.31-Aug.2	Jul.29-Aug.1	Jul.31-Aug.2
Summer Introductory School	Aug.18-24	Aug.7-11	Aug.8-10	Aug.4-8
Asian Winter School	Dec.12-16	Feb.27-Mar.2	Jan.26-29	Feb.3-6
ITER Int. Summer School			Jul.16-20	Jul.22-25
Graduate University for Advanced Studies (SOKENDAI)				
Number of students	25	21	22	18
Number of Ph. D awardees	12	4	8	2
Students from associated universities doing degree courses at NIFS				
Grad School of Eng., Nagoya U.	11	10	6	6
Grad School of Sci., Nagoya U.	7	4	5	7
Grad School of Eng., Hokkaido U.	1	2	2	2
Students from associated universities taking courses at NIFS				
Grad School of Sci. and Eng., U. Toyama	14	20	15	7
Student researchers at NIFS under the collaboration research programs				
From national universities	22 (Tohoku U., U.Tokyo, Tokyo Inst. of Tech., Yokohama Ntnl. U., Shinshu U., Nagoya U., Osaka U., Yamaguchi U., Kyushu U., Kagoshima U.)	23 (Tohoku U., Saitama U., U.Tokyo, Yokohama Ntnl. U., Shinshu U., Nagoya U., Kyushu U., Kagoshima U.)	20 (Tohoku U., U.Tokyo, Yokohama Ntnl. U., Niigata U., Fukui U., Shinshu U., Nagoya U., Kyoto U., Kyushu U.)	21 (Tohoku U., U.Tokyo, Tokyo Inst. of Tech., Yamagata U., Yokohama Ntnl. U., Fukui U., Kyoto Inst. of Tech., Osaka U., U. Tokushima, Kyushu U., Kagoshima U.)
From prefectural or city universities	0	0	1 (Toyama Prefectural U.)	0
From private universities	4 (Sophia U., Seikei U., Tokai U., Rikkyo U.)	4 (Sophia U., Seikei U., Tokai U., Fujita Health U.)	5 (Sophia U., Seikei U., Tokai U., Fukuoka Inst. of Tech., Fujita Health U.)	4 (Sophia U., Seikei U., Doshisha U., Fukuoka Inst. of Tech.)

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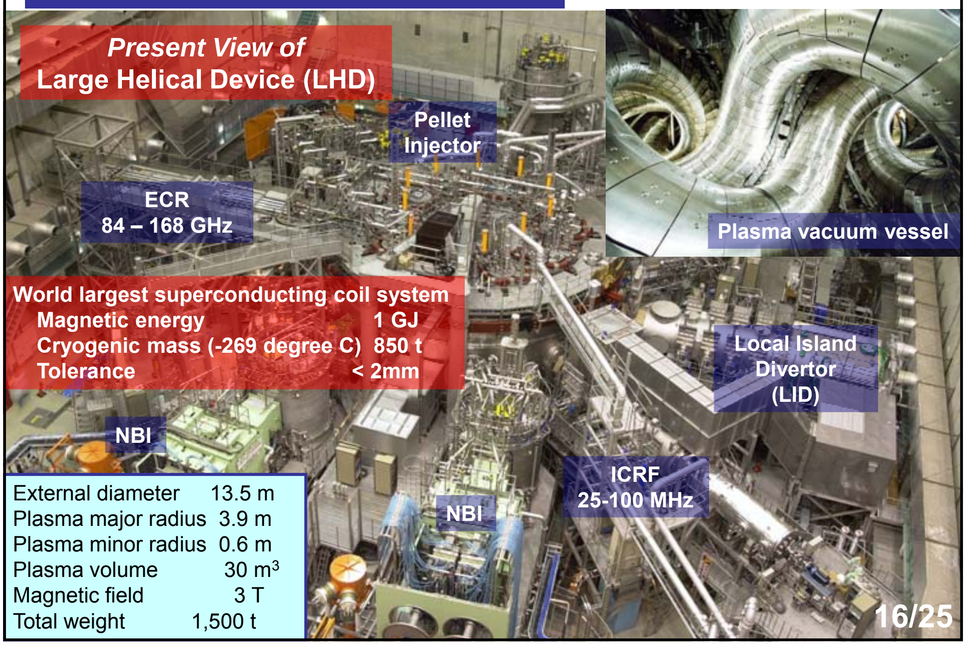
5. Recent NIFS Research Activities



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Target and Achievements in LHD

Achievements [Final target]

Ion Temperature
Central T_i 13.5 keV
Density $3\times10^{18}m^{-3}$ (Ar gas)

Attainment of temperature of fusion reactor

Electron Temperature
Central T_e 10 keV [10 keV]
Density $5\times10^{18}m^{-3}$ [$2\times10^{19}m^{-3}$]

World record of beta value approaching to plasma pressure condition

Volume Averaged β
5.1 % (magnetic field of 0.425T)
[≥ 5 % (1-2 T)]

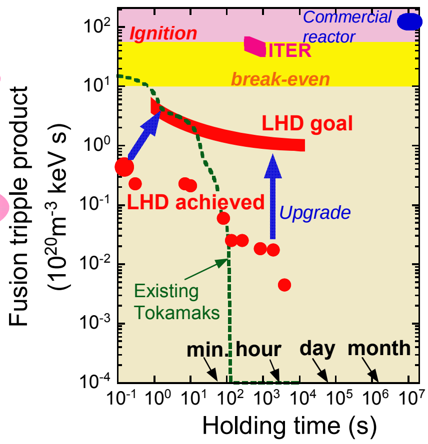
Electron Density
$1.2\times10^{21}m^{-3}$

World record of plasma density

Stored Energy
1.66 MJ [4.0 MJ]

Steady State Operation
31min.45sec. (680 kW) 1.3GJ [1 hour (3,000 kW)]
54min.28sec. (490 kW) 1.6GJ

World record of injected energy



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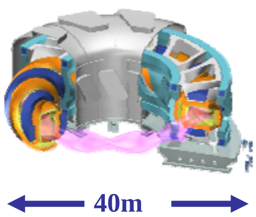
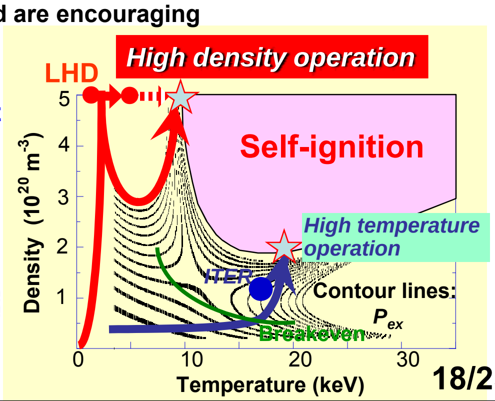
IDB Scenario and Super Dense Core Reactor

- **Edge Control**
  - Core fueling by pellet injector
  - Particle pumping by LID ➔ Low edge density
- **Confinement Improvement (IDB)**
  - Present Interests : Position sensitivity of IDB foot & MHD stability
- **New Ignition Scenario (SDCR)**
  - High Density and Lower Temperature Core
  - Parameters (n, T, β) obtained are encouraging

Reduced engineering demand and neoclassical ripple transport

FFHR
1,000 MW
6Tesla
25,000 ton





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Establishment of Dept. of Simulation Science

- New organization: Department of Simulation Science was established on April 1, 2007

▪ Organization of the Department of Simulation Science

Department of Simulation Science consists of 2 division and 1 center, by unifying the previous theory and computer center, and computer and network center

LHD and magnetic confinement simulation division,
Fusion frontiers simulation division,
Rokkasyo research center

Promote three simulation projects under the collaboration with universities and institutes: (a) LHD and magnetic confinement, (b) Laser fusion, (c) Complex plasma

▪ **Symposium of Simulation Science was held every year**: at Ceratopia, Toki on September 6-7, 2007, and at Tajimi on September 24-25, 2008

▪ **New computer and computer-related resource**

New supercomputer has been selected and its operation will start in March 2009
Image analysis system ComplexCope has been developed

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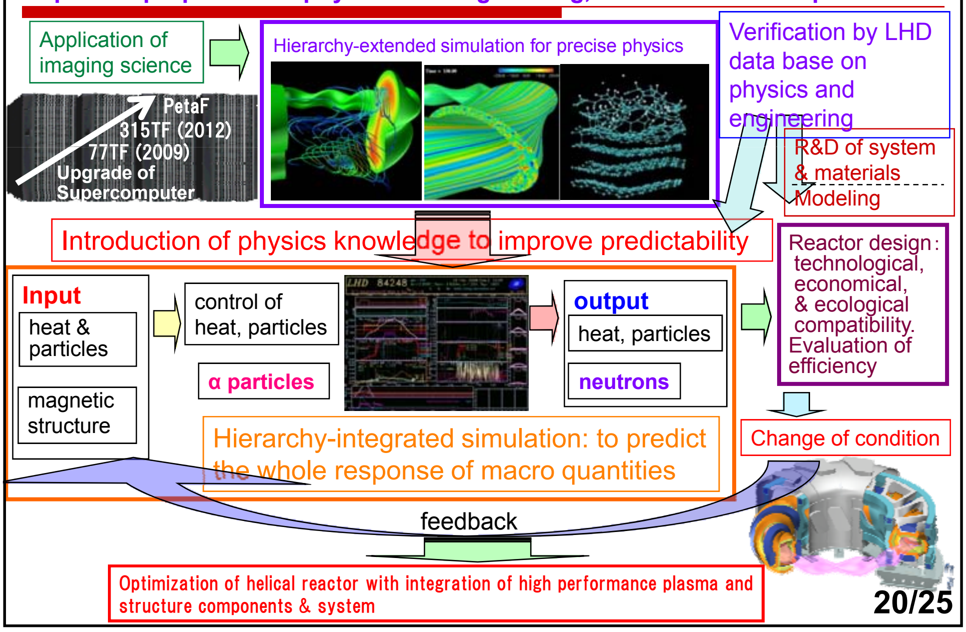
Numerical Test Reactor Project

To create a fusion energy reactor in a virtual space (computer) in order to optimize properties on physics and engineering, and economical aspects



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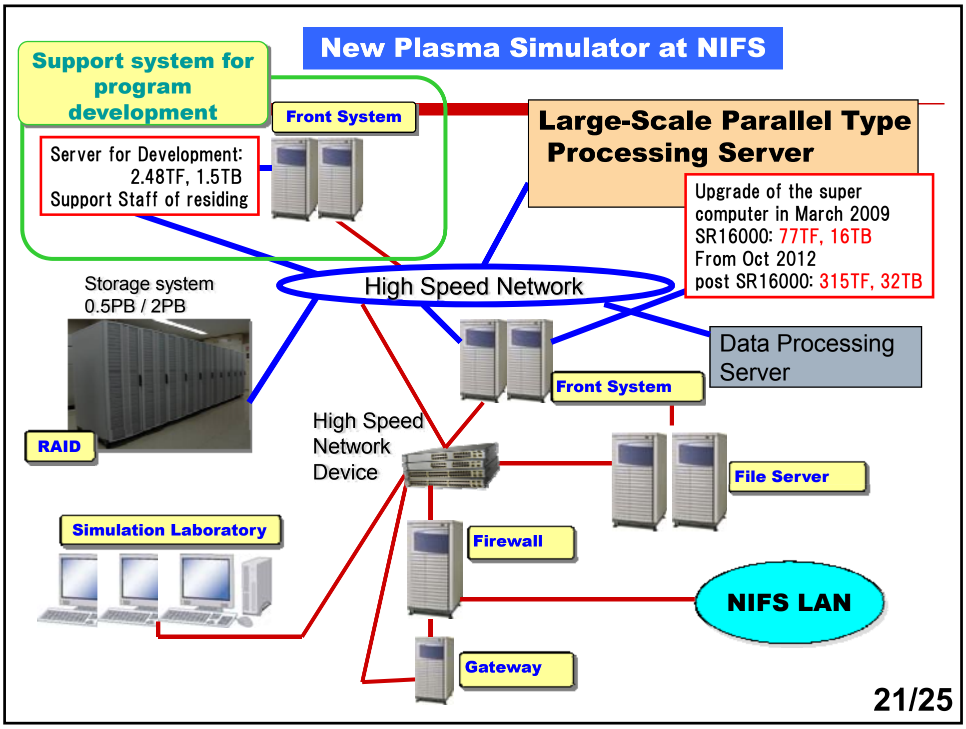

New Plasma Simulator at NIFS
Support system for program development
Front System
Server for Development: 2.48TF, 1.5TB
Support Staff of residing
Large-Scale Parallel Type Processing Server
Upgrade of the super computer in March 2009
SR16000: 77TF, 16TB
From Oct 2012
post SR16000: 315TF, 32TB
Storage system
0.5PB / 2PB
High Speed Network
Data Processing Server
Front System
RAID
High Speed Network Device
File Server
Simulation Laboratory
Firewall
NIFS LAN
Gateway
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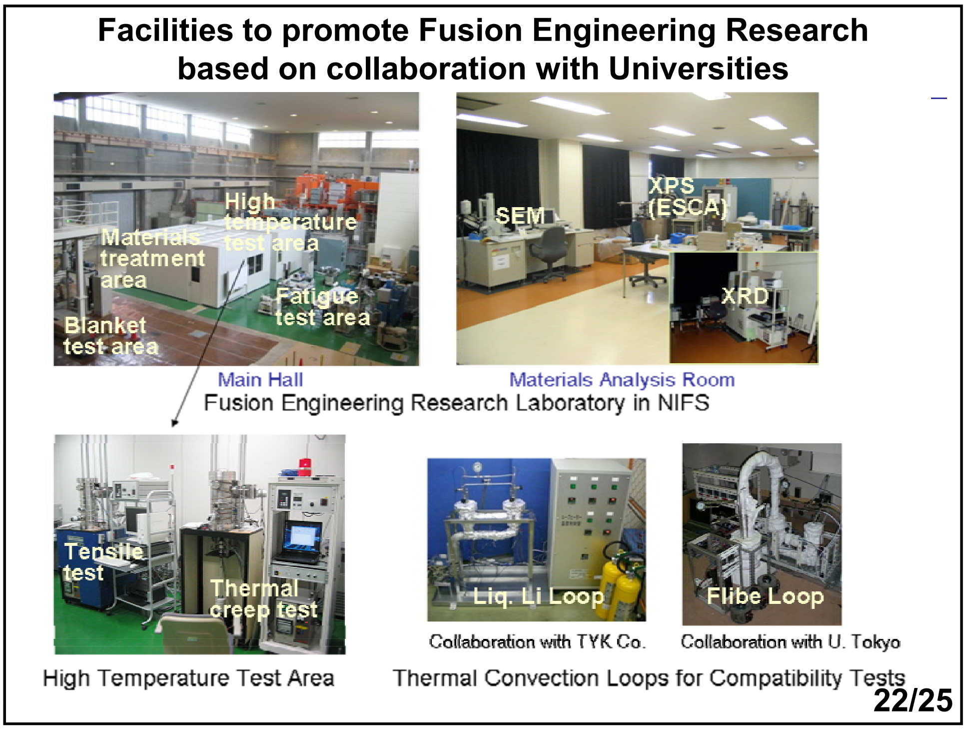

Facilities to promote Fusion Engineering Research based on collaboration with Universities
High temperature test area
Materials treatment area
Fatigue test area
Blanket test area
SEM
XPS (ESCA)
XRD
Main Hall
Materials Analysis Room
Fusion Engineering Research Laboratory in NIFS
Tensile test
Thermal creep test
Liq. Li Loop
Flibe Loop
Collaboration with TYK Co.
Collaboration with U. Tokyo
High Temperature Test Area
Thermal Convection Loops for Compatibility Tests
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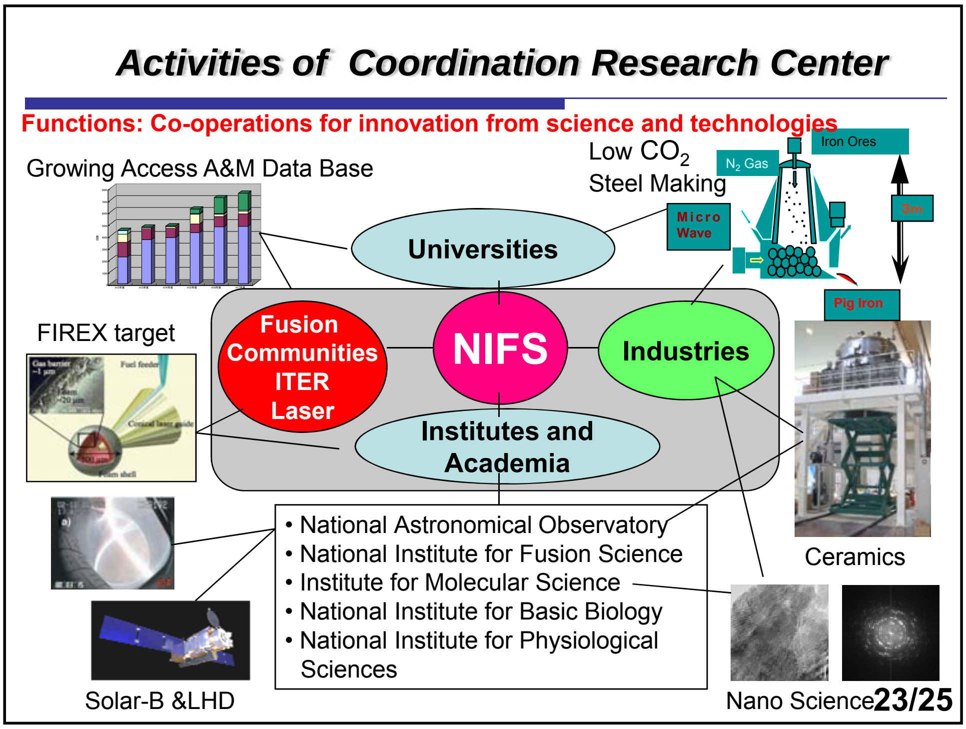
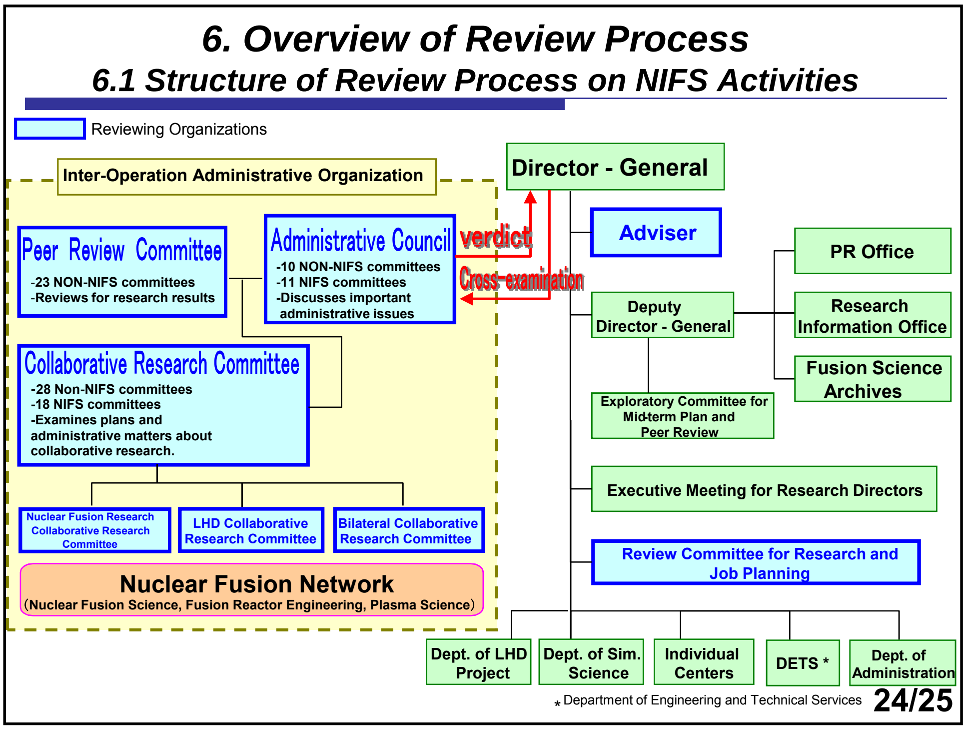

Activities of Coordination Research Center
Functions: Co-operations for innovation from science and technologies
Growing Access A&M Data Base
Low CO_2 Steel Making
Iron Ores
N_2 Gas
Micro Wave
Pig Iron
Universities
Fusion Communities ITER Laser
NIFS
Industries
Institutes and Academia
FIREX target
Ceramics
• National Astronomical Observatory
• National Institute for Fusion Science
• Institute for Molecular Science
• National Institute for Basic Biology
• National Institute for Physiological Sciences
Solar-B &LHD
Nano Science
23/25


6. Overview of Review Process
6.1 Structure of Review Process on NIFS Activities
Reviewing Organizations
Inter-Operation Administrative Organization
Director - General
Peer Review Committee
-23 NON-NIFS committees
-Reviews for research results
Administrative Council
-10 NON-NIFS committees
-11 NIFS committees
-Discusses important administrative issues
verdict
Cross-examination
Adviser
PR Office
Deputy Director - General
Research Information Office
Fusion Science Archives
Collaborative Research Committee
-28 Non-NIFS committees
-18 NIFS committees
-Examines plans and administrative matters about collaborative research.
Exploratory Committee for Mid-term Plan and Peer Review
Executive Meeting for Research Directors
Nuclear Fusion Research Collaborative Research Committee
LHD Collaborative Research Committee
Bilateral Collaborative Research Committee
Review Committee for Research and Job Planning
Nuclear Fusion Network
(Nuclear Fusion Science, Fusion Reactor Engineering, Plasma Science)
Dept. of LHD Project
Dept. of Sim. Science
Individual Centers
DETS *
Dept. of Administration
* Department of Engineering and Technical Services
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6.2 Review System and Process of NIFS

1. Third-Party Review

① **Review as the National Institutes of Natural Sciences** (annually)
② **Review by the Council for Science and Technology Policy** (annually)

2. Peer Review and other reviews

① **Review by the External Peer Review Committee under the Administrative Council in the National Institute for Fusion Science**
- Large Helical Device (LHD) Research (2004)
- Simulation Science (2004)
- Collaboration Research & Joint Activity (2005)
- Fusion Engineering Research Center (2005)
- Safety and Environmental Research Center (2005)
- International Collaboration Activities (2006)
- Coordination Research Center (2006)
- Department of Engineering and Technical Services (2006)
- Large Helical Device (LHD) Research (2007)
- Simulation Science (2007)
- Bilateral Collaboration Research (2007-2008)
- Special Review Committee (2008)

② **Other Review**
- Reviews by the special advisers for the National Institute for Fusion Science (2004)
- Reviews by the Cryogenic Association of Japan (2005)
- Reviews by the Internal Review Committee for Research and Job Planning (annually)

③ **Review made by the nuclear fusion research workgroup within the Science and Technology Council**
- The report submitted on January 8th 2003 by the nuclear fusion research workgroup within the Special Committee for Basic Problems, Science and Technology Subcommittee, Science and Technology Council, was checked and reviewed for the promotion of the future nuclear fusion research (2006)

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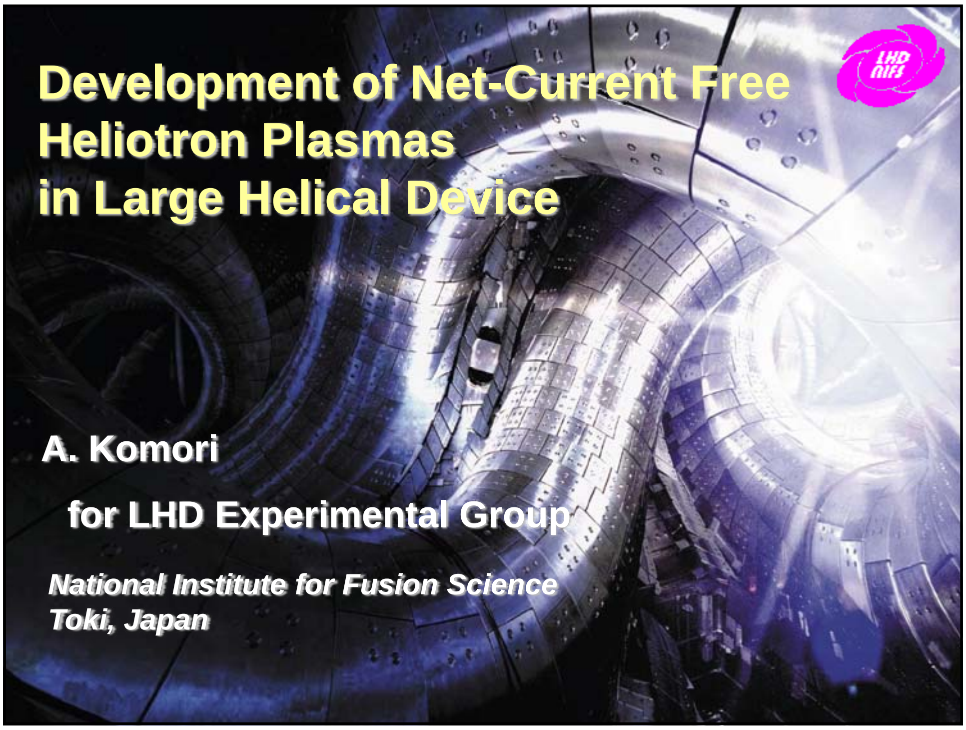
3-2 Development of Net-Current Free Heliotron Plasmas in Large Helical Device



Outline

1. High ion temperature 5.2 keV at n_e = 1.6×10^{19} m^{-3} accompanied by *Impurity hole*

2. High density n_e (0) = 1.2×$10^{21}$$m^{-3}$ at B = 2.5 T with *Internal Diffusion Barrier (IDB)* in Helical Divertor

3. High beta <β> = 5.1 %, <β> > 4.5 % for > 100τ_E

4. Steady state

5. Summary

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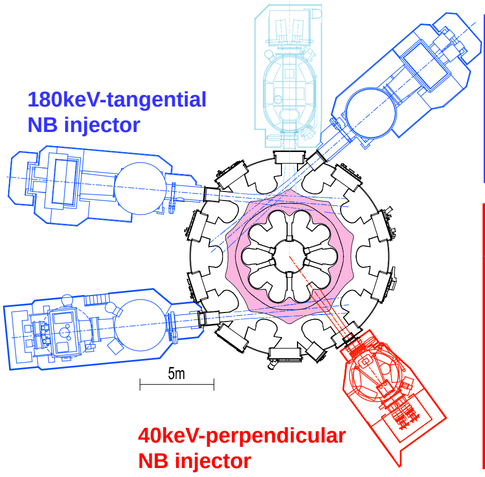
New perpendicular NBI much improves ion transport study

- High-power NBI of 23 MW in total -

✓ 4 beam lines of NBI
= 3 tangential + 1 perpendicular (+ 1perpendicular in 2010)



Tangential beams
- 16 MW in total, E_{NBI} = 180 keV with negative-ion sources
- Primarily electron heating
- Less fraction of trapped particles

Perpendicular beam
- 7 MW, E_{NBI} = 40keV with positive-ion sources
- **Ion heating ($T_i(0)$ = 5.2 keV)**
- works as a diagnostic beam for **CXRS (T_i, V_ϕ, V_θ, E_r)**
- Confinement of trapped particles secured by geometrical optimization

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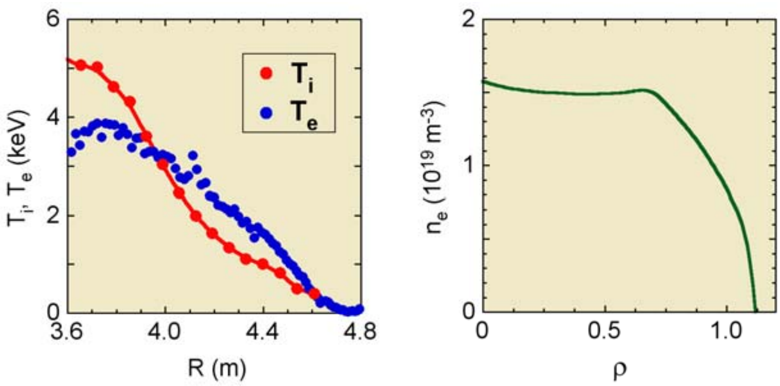
High T_i plasma realized by upgrade of ion heating power

T_i (0) reaches 5.2 keV at $\bar{n}_e = 1.6\times10^{19}$m^{-3}



✓ Heating Power N-NBI: 12 MW, P-NBI: 3.5 MW for high-T_i
✓ $T_i > T_e$ in core and $T_i < T_e$ in edge

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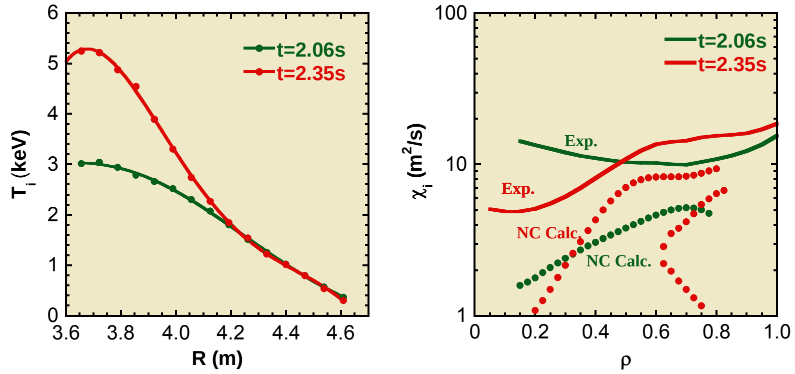
Improvement of ion heat transport



✓Reduction of χ_{i_exp} appears in the core

✓ Ion root ($E_r < 0$) in core and Electron root ($E_r > 0$) in edge
-> core transport is improved to NC level

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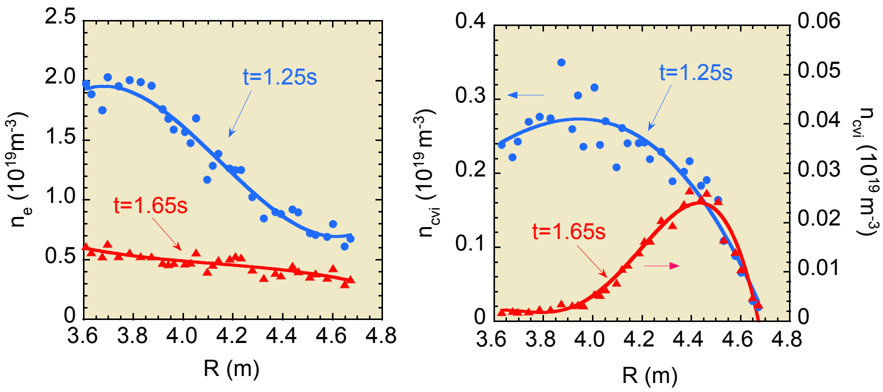
Carbon impurity is expelled due to outward convection : Impurity Hole



- ✓ More hollow as the ion temperature gradient is increased
- ✓ Steep Ti gradient ➔ Extremely hollow carbon profile "**impurity hole**", which is quite different electron density profile.
- ✓ Contradicting NC prediction ➔ suggests anomalous convection

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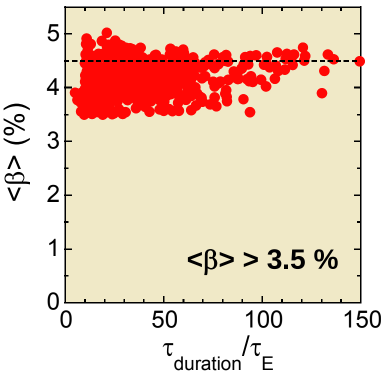
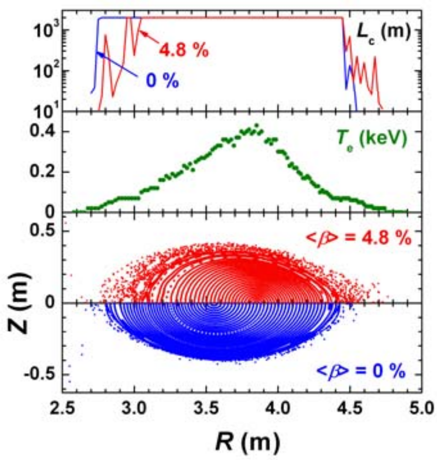
β of 5.1 % has been achieved and β of 4.5 % has been maintained in steady state



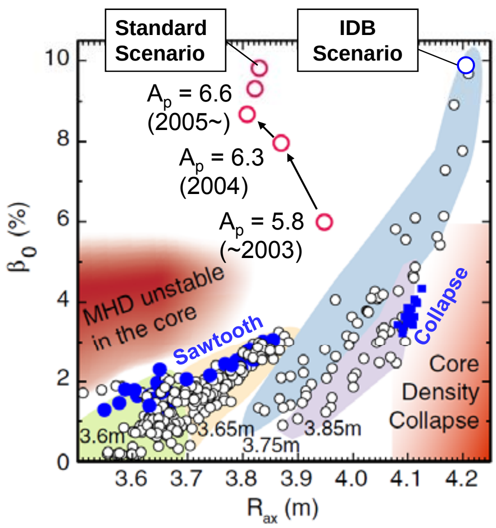
3-D equilibrium calculated by HINT



- ✓ Beta limit
- ✓ Transport in the ergodic layer
- ✓ Change of magnetic topology, e.g., magnetic island dynamics

Effect of stochasiticity has been investigated in detail

Operational Regime of high-β



Magnetic axis position is a key parameter for high-beta

✓ **Standard Scenario**

(broad pressure profile)

- restrict of the plasma outward shift for keeping good heating efficiency in low-field

→ increase plasma aspect ratio

→ <β> = 5.1 %, β_0 ~ 10 %

✓ **IDB Scenario**

(peaked pressure profile)

- overcome the core density collapse

→ <β> = 2 %, β_0 ~ 10 %

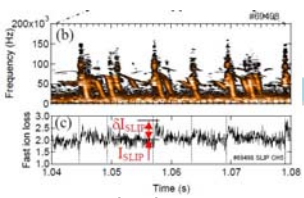
Real time control of B_v

✓ Much higher beta with this operational window

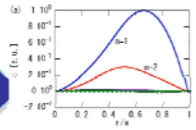
✓ extension of operational regime

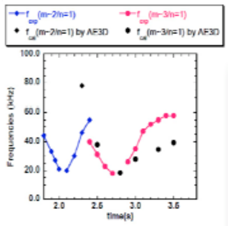
Interaction between Alfvén eigenmodes and energetic-particles in LHD

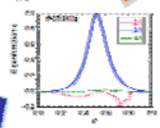
TAE-induced fast-ion loss measurement with scintillator probe (SLIP)



Analysis in collaboration with AE3D code

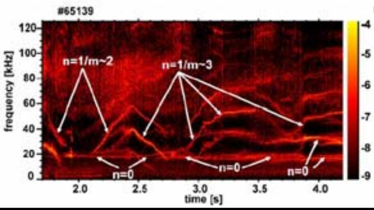


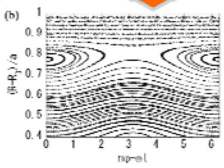




Understanding of RSAE freq. sweeping with MHD theory

Impact of Alfvén eigemodes on GAM





Phase space structure analysis of TAE-induced fast-ion transport

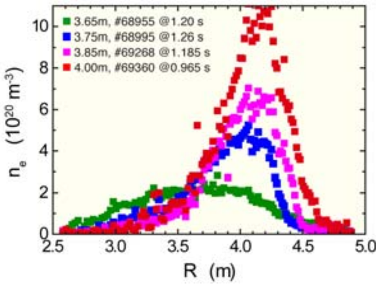
Achievements of High Density High Pressure Discharges with Internal Diffusion Barrier

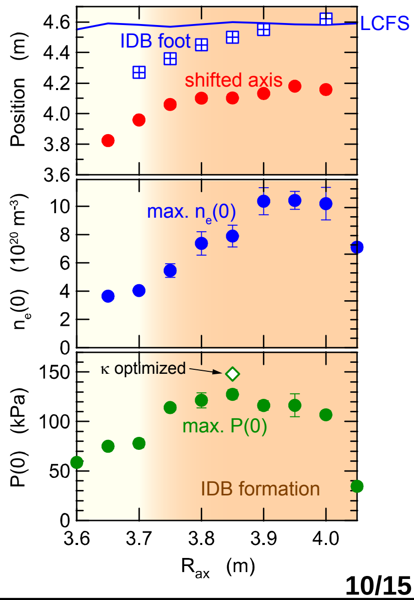
✓ **Maximum $n_e(0)$ exceeds 1×10^{21} m^{-3}**

Maximum P(0) =130 kPa

- Pressure rise is limited by ***Core Density Collapse*** (CDC)
- CDC mitigated by elongation ➔ P(0) = 150 kPa

✓ IDB width widens as the preset magnetic axis is put outward and IDB foot reaches to LCFS with R_{ax}= 4.0 m

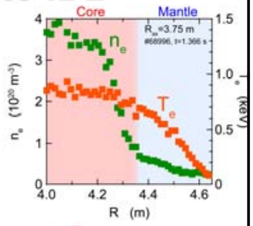




Diffusion Coefficient kept at tolerable level under large density gradient due to IDB

Relationship between time evolution and gradient of density profiles

$$\frac{\Gamma_e}{n_e} = -\frac{D_e}{a}\frac{1}{n_e}\frac{\partial n_e}{\partial \rho} + v_e$$



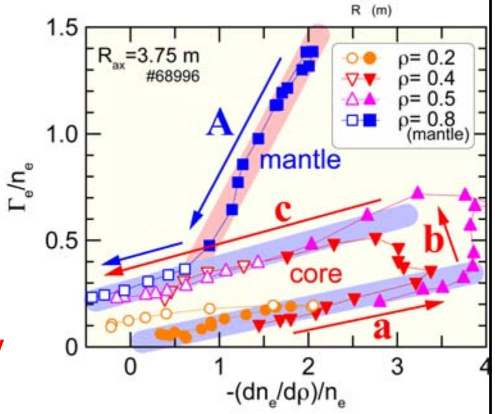
Core plasma

- **a** (pressure rise): $dn_e/d\rho$ increases with IDB formation, D≈0.05 m²/s
- **b** (maximum pressure): flux increase without $dn_e/d\rho$ change
- **c** (pressure decline): $dn_e/d\rho$ decrease with density decay, D≈0.05 m²/s

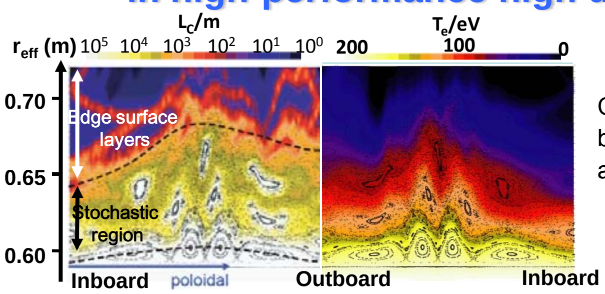
Mantle plasma

- **A** (IDB formation period): Can not reach large $dn_e/d\rho$during high flux IDB phase, D≈0.43 m²/s
- (after IDB disappearance): merge into **c**, D≈0.05 m²/s

Thermal transport is unaffected by particle transport



Transport in ergodic layer is a key in high-performance high density plasma



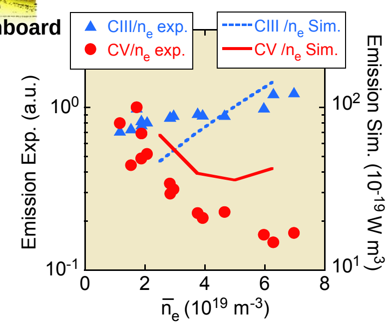
Core plasma is surrounded by ergodic layer by stretch and fold of magnetic islands

3-D edge transport code : EMC3-EIRENE

✓ **Impurity screening** in stochastic region by friction with bulk plasma flow

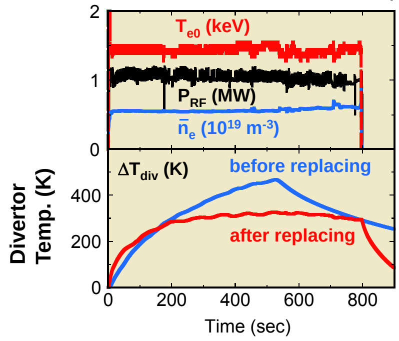
✓ Retention of impurities via shot flux tube in edge surface layer

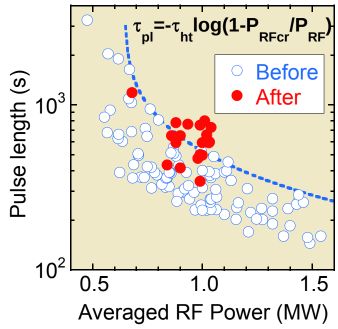
➔ **Remarkable reduction of impurity contamination in high density operation**



Control of heat load on divertor plate is a major key for steady state operation

Critical P_{RF}=0.65 MW : Penetration of metal impurities from deposited layer on divertor plate ← can be simulated by small Fe pellet





P_{RF} = 1.1 MW (P_{ICH} = 1 MW, P_{ECH} = 0.1 MW)

- ✓ Divertor plates with significant temperature increase
  - → replaced by ones with better heat conductivity
  - → critical P_{RF} is mitigated
- ✓ Mode-conversion heating not to produce energetic ions

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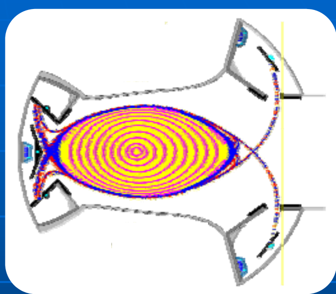
Nearest Future Plan

1. Upgrade of heating capability
   - NBI 5th beam line 7 MW, 60 keV
   - ICH 3 MW steady state
   - ECH 1 MW steady state



2. Closed helical divertor

3. Deuterium
   - Identification and documentation of isotope effect
   - Upgrade of NBI (32 MW in total)

4. Reactor design study
   FFHR :
   Force-Free Helical Reactor

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Summary

1. **High ion temperature 5.2 keV at $n_e = 1.6\times10^{19}\ m^{-3}$ with confinement improvement**

2. **High beta $\langle\beta\rangle = 5.1\ \%$, $\langle\beta\rangle > 4.5\ \%$ for $> 100\tau_E$**

3. **High density $n_e(0) = 1.2\times10^{21} m^{-3}$ at B = 2.5 T with *Internal Diffusion Barrier (IDB)***

4. **Steady state 1MW for 800 s**

5. **Near-term upgrade package**
   closed helical divertor, heating capability, deuterium

6. **3-D effect inspiring new advanced physics model and theory which are to be validated in LHD experiment**

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Simulation Science in NIFS

N.Nakajima and DSS members

Outline

I. Purposes
II. 3 projects
  LHD and Magnetic Confinement Simulation Project
  Laser Fusion Simulation Project
  Plasma Complexity Simulation Project
III. Future plan
IV. Summary

Purposes

To clarify and systematize the confinement physics of fusion plasmas and to promote the basic science based on the simulations, by developing predictive simulation codes like a Numerical Test Reactor based on hierarchy-renormalized model, leading to establishing simulation science

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3 projects

I. LHD and Magnetic Confinement Simulation Project

  Hierarchy-extended simulation
    Core plasma fluid model group
    Core plasma kinetic model group
    Peripheral plasma model group
  Hierarchy-integrated simulation

  } Hierarchy-renormalized simulation
  +
  Reactor design
  ⇓
  Numerical Test Reactor Project

II. Laser Fusion Simulation Project

  related to FIREX project at Osaka University

III. Plasma Complexity Simulation Project

  Magnetic reconnection
  Plasma material interaction

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LHD and Magnetic Confinement Simulation Project

Purpose: To exploit and understand the physics on cross-hierarchy interactions of compound physics processes by developing a predictive hierarchy-renormalized simulation model under the domestic and international collaborations, leading to an Numerical Test Reactor (simulation code) predicting overall behaviors of fusion plasmas

Hierarchy-renormalized simulation

Hierarchy-integrated simulation To predict the whole temporal behaviors of experimentally observable macroscopic quantities (M.Sato, A.Fukuyama, Y.Nakamura, S.Murakami, K-Y,Watanabe, M.Yokoyama, S.Toda, Y.Funaba, N.Nakajima)

Knowledge (theoretical model, database, modules) for improving predictability

Hierarchy-extended simulation To exploit and understand the physics on cross-hierarchy interactions of compound physics processes

- core plasma fluid model group : (Y.Todo, H.Miura, R.Ishizaki, A.Ishizawa, A.Ito, M.Sato, K.Uzawa, N.Nakajima)
- core plasma kinetic model group : (T-H.Watanabe, H.Sugama)
- peripheral plasma model group : (Y.Tomita, G.Kawamura, M.Kobayashi, A.Takayama, D.Kato, K,Ohya, D.Tskhakaya, A.Kirschner)

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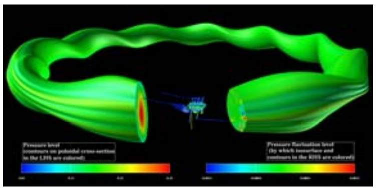
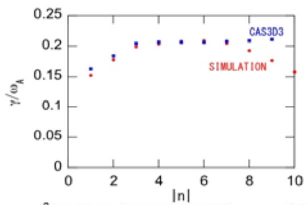
Hierarchy-extended simulation (Core plasma fluid model group)

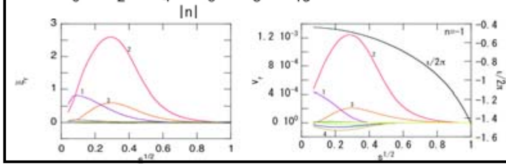
- MHD
  - I. MHD Infrastructural code for Plasma Simulation (MIPS) (Y.Todo,N.Nakajima) common source for collaborators (in this FY)
  - II. High precision MHD simulation in LHD (MINOS) (H.Miura)
- Extended-MHD
  - I. Pellet dynamics (CAP) (R.Ishizaki)
  - II. Long time AE simulation in LHD (MEGA) (Y.Todo)

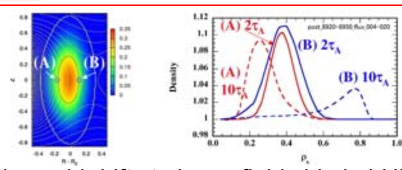


Perturbed pressure profile with multiple ballooning modes ($\chi_{||}$ reduces them)

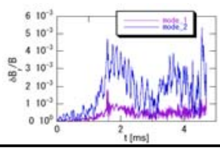


Comparison of MIPS and CAS3D results of ballooning modes in LHD





Plasmoid drifts to lower field side in LHD.



Alfvén eigenmode burst in LHD(#47645) was found with reduced simulation code.

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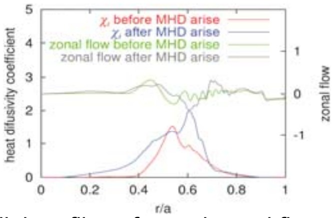
Hierarchy-extended simulation (Core plasma fluid model group)

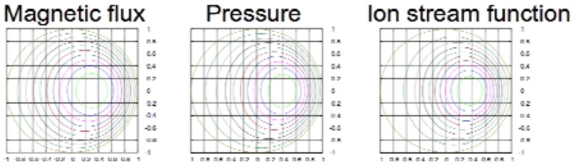
- Extended-MHD (Two-fluid model)
  - I. Two-fluid equilibrium with flows and ion Larmor radius effects (A.Ito)
  - II. Turbulent transport in externally heated plasma (A.Ishizawa)
- Full implicit algorithm
  Development of full implicit method by extending 2D spectral finite element code (SEL) to 3D (HiFi) (M.Sato, A.Glasser)



Radial profiles of χ_i and zonal flow. χ_i increases around magnetic island (r/a=0.6), which partially comes from macro-scale convective cell flow.

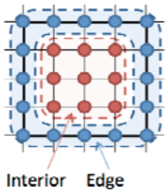
✓Singularity at the boundary is regularized due to the ion FLR effects

Magnetic flux　Pressure　Ion stream function



✓Isosurfaces of each quantity do not coincide because of the flow and the two-fluid effects

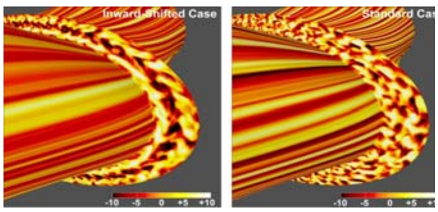
2D static condensation subroutine has been improved and extended to 3D subroutine.



Hierarchy-extended simulation (Core plasma kinetic model group)

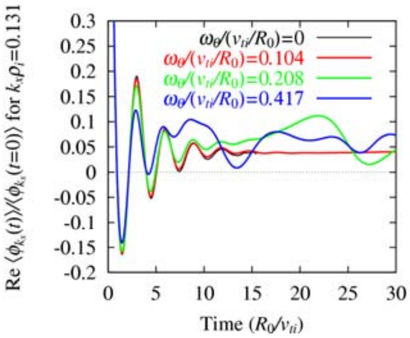
- Progresses in gyrokinetic theory and simulations for toroidal plasmas (T.-H.Watanabe, H.Sugama)
  - Zonal flow enhancement and turbulent transport reduction in helical systems is confirmed by GKV simulations. (Watanabe, et al., PRL 2008)
  - Zonal-flow response in case with equilibrium radial electric field (E_r) is theoretically derived. (Sugama et al., invited talk@APS/DPP 2008)
  - GKV code is extended for poloidally-global model for application to the zonal-flow response analysis in case with E_r. (Watanabe et al., oral presentation@ICPP2008)
  - Enhanced zonal-flow response is found in a single-helicity case. (Watanabe, et al., 22nd IAEA FEC)

EARTH SIMULATOR

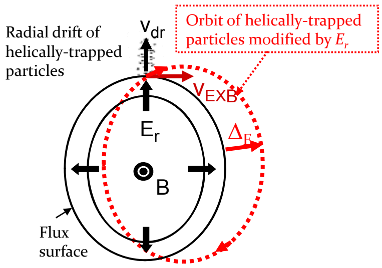


Hierarchy-extended simulation (Core plasma kinetic model group)

- Progresses in gyrokinetic theory and simulations for toroidal plasmas (T.-H.Watanabe, H.Sugama) [continued]



New GKV simulations for zonal-flow enhancement by equilibrium E_r.



$$\mathcal{K}_{Er} = \frac{1}{1+G+\mathcal{E}_{Er}/(k_r a_i)^2} = \left[1+G+\frac{15}{8\pi}(2\epsilon_h)^{1/2}\left(\frac{\epsilon_t v_{ti}}{r\omega_\theta}\right)^2\left(1+\frac{T_e}{T_i}\right)\right]^{-1}$$

Theoretical model for zonal-flow response in case with E_r.

EARTH SIMULATOR

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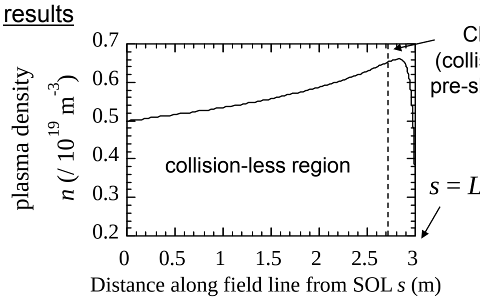
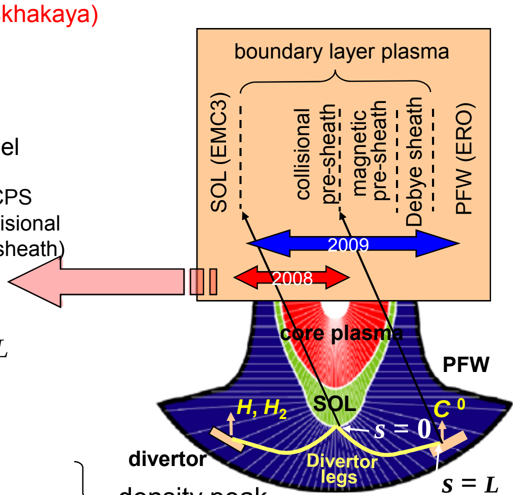
Hierarchy-extended simulation (Peripheral plasma model group)

1D fluid model of plasma profiles in the LHD divertor leg
(G. Kawamura, Y.Tomita, M.Kobayashi, D.Tskhakaya)

objective
- modeling of boundary plasma between SOL and divertor plate and PFW (Plasma-Facing Wall) by fluid model

results





- CPS: collision with neutral → $dn/ds < 0$
- collision-less plasma → $dT_i/ds < 0 \rightarrow dn/ds > 0$

} density peak

⇨ reduction of heat load to divertor plate

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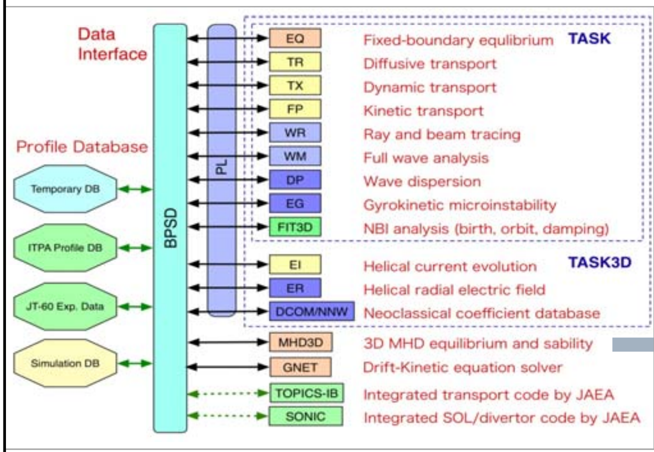
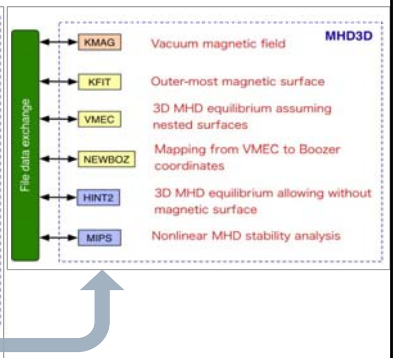
Hierarchy-integrated simulation

• Development of a core transport code in 3D configuration :TASK3D

(A.Fukuyama, Y.Nakamura, M.Sato, S.Murakami, K.-Y.Watanabe, N.Nakajima)





Module structure applicable to 3D configuration

TASK3D:common source for collaborators (in this FY)

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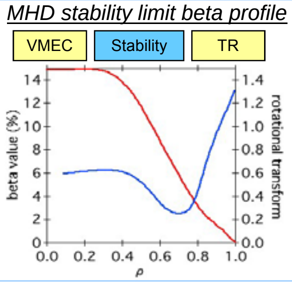
Hierarchy-integrated simulation

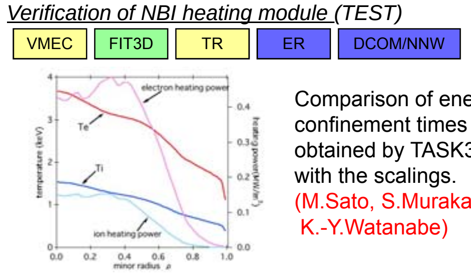
•Analysis of LHD plasmas by TASK3D

MHD stability limit beta profile



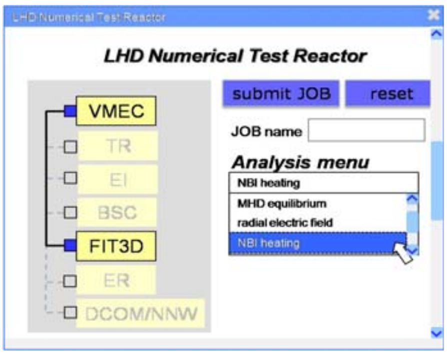
The achievable beta value is expected beyond 6% under the assumption that the ideal interchange modes with m ≤ 4 limit the pressure gradient.
(M.Sato, K.-Y.Watanabe, Y.Nakamura)

Verification of NBI heating module (TEST)



Comparison of energy confinement times obtained by TASK3D with the scalings.
(M.Sato, S.Murakami, K.-Y.Watanabe)

•Development of GUI application



The GUI application is equipped with
・selecting modules,
・setting input parameters and files,
・submitting job,
for easy use of TASK3D.
(M.Sato, K.-Y.Watanabe)
available (in this FY)

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Targets in this mid-term plan

Hierarchy-extended simulation (Core plasma fluid model group)

- to analyze AE-induced excitation of GAM
- to clarify the roles of high wave number pressure-driven modes in LHD
- to clarify the plasmoid motion in LHD
- to clarify interactions between macro-MHD instability and micro-turbulence
- to analyze two-fluid equilibrium and linear stability of LHD plasmas with flows

Hierarchy-extended simulation (Core plasma kinetic model group)

- to analyze influence of macro-scale E_r on zonal flow response in helical systems
- to extend GKV code for more realistic configuration
- to analyze ETG turbulence and zonal flows in toroidal plasmas

Hierarchy-extended simulation (Peripheral plasma group)

- to complete 1D fluid transport model interconnecting SOL and PFW
- to develop a 3D fluid transport model of plasma and neutral in collisional pre-sheath
- to develop a PIC transport model in magnetic pre-sheath and Debye sheath

Hierarchy-integrated simulation

- to intensively check of TASK3D modules by applying TASK3D to experimental data
- to implement impurity module and DD reaction model into TASK3D
- to formulate system of transport equations with plasma flow in 3D configuration

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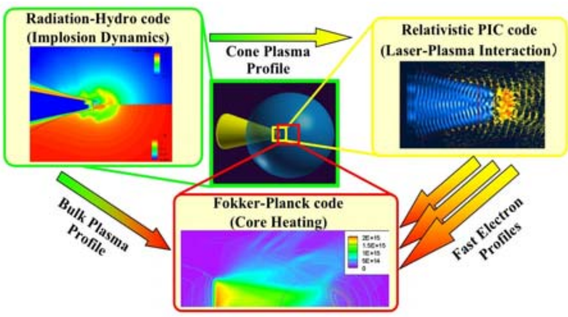
Laser Fusion Simulation Project

Purpose:

To totally clarify physics of the Fast Ignition and to design targets for FIREX (Fast Ignition Realization EXperiment) project at Osaka Univ. by ***FI*³** integrated simulations under tight collaborations among Osaka Univ., Setsunan Univ., Kyusyu Univ., and KPSI JAEA.



Organization of Collaborations

Radiation-hydro code : Osaka Univ.
Relativistic PIC code : NIFS and KPSI JAEA
Fokker-Planck code : Osaka Univ. and Kyusyu Univ.
Level up of ***FI*³** by introducing hybrid code : Setsunan Univ.
To develop collision model : NIFS, Osaka Univ., and Setsunan Univ.

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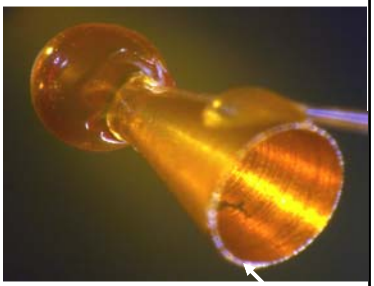
Laser Fusion Simulation Project

*FI*³

(H.Sakagami)

- A pre-pulse of the heating laser generates the preformed plasma and its scale length is also determined by the pre-pulse.
- The preformed plasma with a longer scale length can maintain the bulk electron density n_b at a lower level, so that the core heating is sustained for a longer time. (electron beam intensity $\propto n_b^{-1/2}$)
- However, characteristics of the pre-pulse are not easily controllable.



Au cone

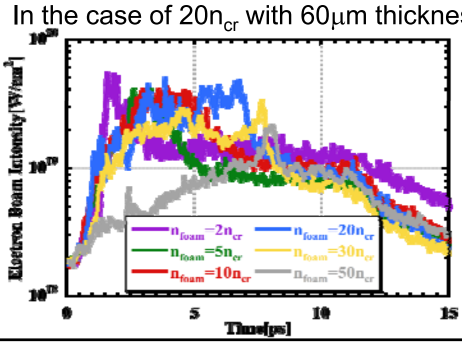
- Thus, we propose to coat the inner surface of Au cone with low density foam, preventing the preformed plasma from being snowplowed to extremely high density at the laser front of the main pulse.

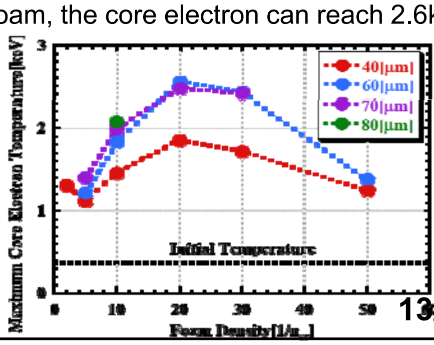
Laser Fusion Simulation Project

*FI*³

(H.Sakagami, T.Johzaki, H.Nagatomo)

- By analyzing the core heating characteristics for various foam parameters with ***FI***³ simulations, it is found that there are an optimum density of the foam and a necessary minimum thickness of the coating.
  - In the case of low density foam, the heating laser can relativistically penetrate into the foam plasma and directly interact with the extreme overdense Au plasma.
  - With high density foam, electrons in the foam plasma are snowplowed to such density that the fast electron beam intensity can be substantially repressed at a low level.
- In the case of $20n_{cr}$ with 60μm thickness foam, the core electron can reach 2.6keV.





Targets in this mid-term plan

FI³

To perform basic evaluation of FIREX target through following steps, under the collaborations with Osaka Univ., Setsunan Univ., Kyusyu Univ. and KPSI JAEA.

1. To develop a Langevin-type collision model based on empirical law, and to introduce it into 1D relativistic particle code
2. To interconnect 2D relativistic particle code into ***FI³***
3. Analysis of fast electron transport by using hybrid code

To realistically analyze FIREX experimental results in Osaka Univ., through following steps

1. To enlarge the scale of ***FI³*** simulations including 2D relativistic particle code
2. To expand the empirical collision model into 2D relativistic particle code
3. Level up of ***FI³*** by introducing the hybrid code

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Plasma Complexity Simulation Project

Purposes

- To clarify the magnetic reconnection phenomena, which are controlled by various physics from micro to macro-scale, in solar and magnetosphere plasma and fusion plasma.
- To clarify the plasma-material interaction in compound physics system.

Method

- To develop and use hierarchy-renormalized simulation model with domain-decomposition method.

Members

- R.Horiuchi, S.Ishiguro, M.Skoric, M.Den, H.Nakamura, H.Ohtani, S.Usami

Collaboration with universities and institutes of NINS

- In solar and magnetosphere plasma; National Astronomical Observatory of Japan (NAOJ), Earth Simulator (ES), Kyusyu univ., Chiba univ.
- In plasma-material interaction; Institute for Molecular Science (IMS), and Shinsyu, Yokohama National, Saitama, Tokyo, Nagoya, and Konan universities.

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Magnetic reconnection phenomena

- Search of magnetic reconnection points in substorm process by MHD model (Fig.1)
- Clarification of generation mechanism of anomalous resistivity due to instabilities by using EM PIC simulation (Fig.2)
- Development and verification of hierarchy-renormalized simulation model based on the domain-decomposition method with MHD model and PIC (Fig.3)

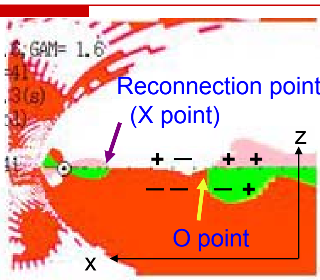
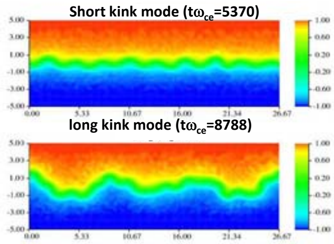
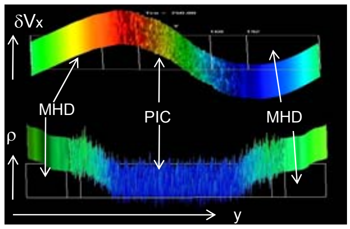


Fig.1 Magnetic topology during the substorm (signs of Bx and Bz) in the noon-midnight meridian of magnetosphere

(M.Den, T.Tanaka)



(T.Moritaka, R.Horiuchi)



(S.Usami, H.Ohtani, R.Horiuchi, M.Den)

Fig.2 Generation of anomalous resistivity by two kink instabilities with different wave numbers.

Fig.3 Numerical verification of hierarchy-normalized model by using 1D Alfven wave propagation (top), and plasma inflow from MHD domain to PIC domain (bottom).

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Plasma-material interaction

- Generation mechanism of C_2H_2 from the chemical spattering on a graphite surface is clarified by using MD simulation (Fig.1)
- Blob simulation by 3D PIC code (Fig.2)
- Development and verification of multi-hierarchy simulation model based on the course projection method (Fig.3)

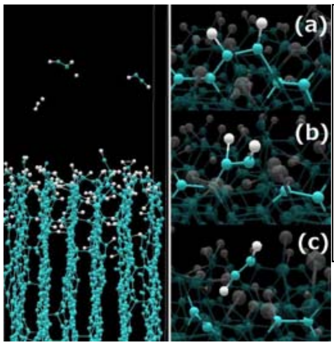


Fig.1 snapshot of C_2H_2 generation with the incident energy of 5eV (left). The C_2H_2 is mainly produced from graphite armchair (1 1 -2 0) surfaces (right (a),(b),(c)).

(A.Ito, H.Nakamura)

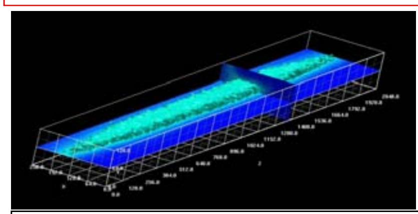
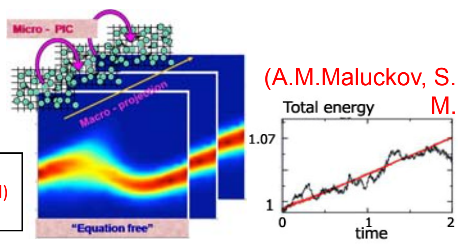


Fig.2 Isosurface and contour plot of ion density.

(S.Ishiguro)



(A.M.Maluckov, S.Ishiguro, M.M.Skoric)

Fig.3 Schematic picture of course projection method (left) and time evolution of total energy by PIC code (red) and course projection method (black) (right)

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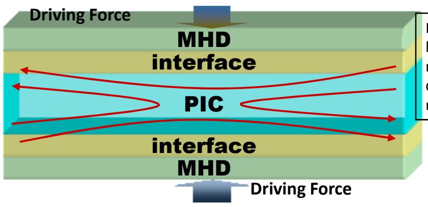
Targets in this mid-term plan

Magnetic reconnection phenomena

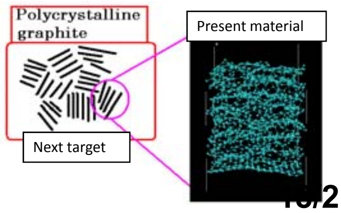
- Verification and improvement of hierarchy-renormalized simulation model, and check of the applicability to magnetic reconnection (left fig.)
- Consideration of method interconnecting micro model with macro model in geo-tail
- Application to fusion plasma (reconnection with strong longitudinal magnetic field)

Plasma-material interaction phenomena

- Expansion of MD of chemical sputtering to large scale (100^3 nm^3) material in hierarchic graphite structures by comparison with Monte Carlo ACAT simulation (right fig.).
- Introduction of Coulomb collision into blob transport simulation and clarification of blob transport phenomena.
- Improvement of the multi-hierarchy simulation model based on the course projection method



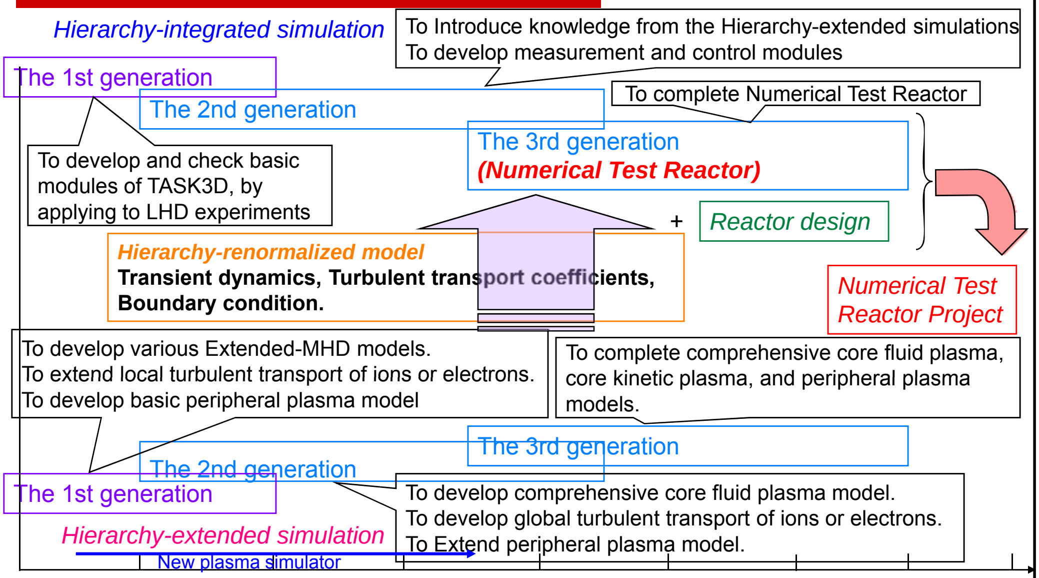
Left: application of hierarchy-renormalized model based on the domain-decomposition method



Right: polycrystalline graphite as next target of MD simulation.

/21

Future plan : Road map of LHD and magnetic confinement simulation project



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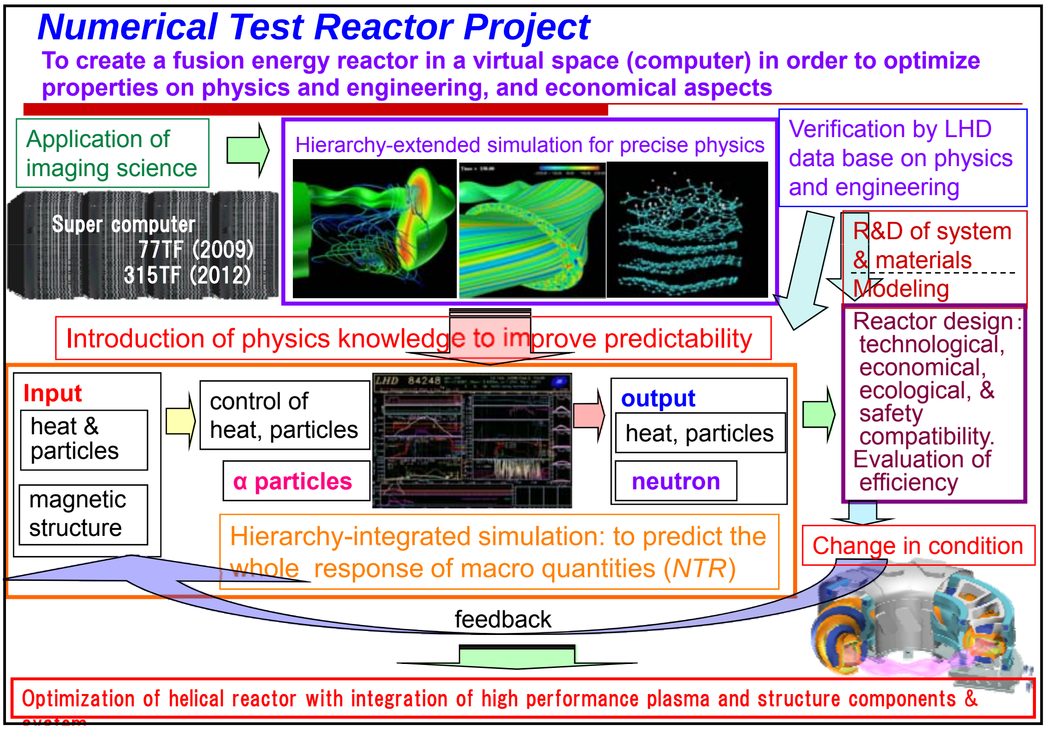

Summary

- Simulation researches based on collaborations are being functionally promoted by constructing 3 projects and working groups.
- By performing large-scale simulations highly enlarged by using full system of the new plasma simulator, we will try to obtain new knowledge of cross-hierarchy interactions and to improve predictability of hierarchy-renormalized simulations.
- In the 2nd mid-term plan, we will proceed to clarify and systematize the confinement physics of fusion plasmas under project researches based on collaborations with road map, and aim at constructing Numerical Test Reactor with predictability (Numerical Test Reactor Project), and also promote the basic science based on the simulations under the coordination researches among various fields.
- Above plan will finally lead to establishing simulation science, in the center of which fusion research sets.

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Activities of The Research Coordination Center (RCC)

1/42

The Research Coordination Center (RCC)

- **Establishment:** in April, 2004.
- **Philosophy:**

  The researchers would serve for the cooperation work on the bases of the big devices such as LHD and it's related science and technologies by holding their own high research capabilities.

  The cooperation would return to NIFS with innovation, we call it "the Boomerang Effect".

  It distinguishes the NIFS's RCC to the cooperation systems in the other universities.

2 /42

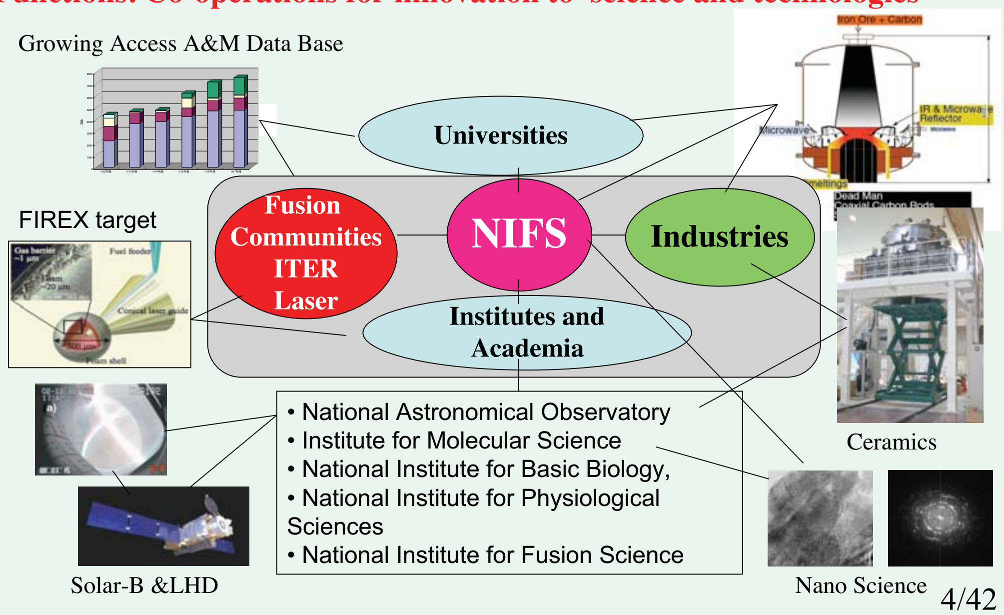
Modified Organizations of RCC

Up to 2007	From 2008
Division of Academic Research Coordination	Division of Academic Research Coordination
International Research Collaboration G.	International Research Collaboration Group
ITER Research Coordination Group	ITER Research Coordination Group
Laser Research Coordination Group	Laser Research Coordination Group
Inter–Institutional Research Coordination G	Inter–Institutional Research Coordination G.
Atomic & Molecular Data Research Center	**Atomic & Molecular and Edge Plasma Data Group**
Division of Industrial–Academic Research C.	Division of Industrial–Academic Research C. Industry Cooperation Group Basic Innovation Science &Technology G.
	Division of Science Communication Fusion Kid's Energy Museum

3/42

Activities of Research Coordination Center

Functions: Co-operations for innovation to science and technologies



4/42

Topics in the Two Years

- Activities of **Atomic & Molecular and Edge Plasma Data Department**
  Y.Hirooka, I Murakami, H.Sakaue, D.Kato
- Division of Industrial-Academic Research C.
  Industry Cooperation Group
  Basic Innovation Science &Technology G.
  M.Sato, S.Takayama, M. Tanaka
- **Division of Science Communication**
  Fusion Kid's Energy Museum
  N. Inoue,

5/42

The New Atomic / Molecular and Edge Plasma Data Group (division)

•The physics on core plasma has given the very promising experimental results for the fusion world. The fusion technology has been accumulated the knowledge of materials for the fusion.

•Many basic ideas has been proposed for the rector design including diverters and first wall etc.

•So to say,it is identical to the ages in 1950~70 in proposing many ideas for plasma confinements, such as such mirrors, Z-pinches, Tokomak and Heliotron,etc.

•Now, we are helming to the research to serve more idea and data for develop the reactor systems. It will be difficult to treat walls as an obstacles affecting to plasma or to see the plasma as the the enemy of materials.

•We are going to investigate the plasma from the view point of walls to accept the radiation of neutrons, protons, alpha particles and high heat flux.

•We are now knocking the next door to the fusion world.

6 /42

Roadmap to resolve PWI-issues in fusion reactors

By Y. Hirooka

Boundary control concepts development

Revaluation of existing core-to-edge plasma data

Enhancement of PWI+A&M research

↓

Applied materials to boundary control

Optimization of hydrogen and helium retention characteristics

Fluid dynamics modeling of liquid metals and molten salts

↓

Proof-of-principle exps. on boundary control concepts

PoP exps. in a divertor simulator

PoP exps. in long-pulse confinement devices (LHD, QUEST)

Extrapolated simulation to numerical fusion reactors

7/42

PWI-issues in steady state fusion reactors

Tokamaks

- High heat/particle fluxes to PFCs
- Erosion and core contamination
- Disruptions
- Giant ELMs
- H-mode (High-T mode)in tokamaks
  - power threshold transition
  - led by passive wall pumping
- S-mode in TFTR
  - led by passive wall pumping

Stellarators/Heliotrons

- High heat/particle fluxes to PFCs
- Erosion and core contamination
- No disruption
- No giant ELMs observed so far
- H-mode in W-AS7
- Superdense mode in LHD
  - led by reduced edge density by LID
- Large SOL surface area for the same plasma volume
  - more PWI-susceptive

↓

A need for the control over PWIs in both tokamak and stellarator/heliotron reactors to sustain high-confinement operations at “steady state”.

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PWIs in magnetic fusion devices

1. **Materials erosion**: $C \Rightarrow W$ $\quad \Gamma \propto n_e C_s$, $E \propto kT_e$, where $C_s = \sqrt{\frac{k(T_i + T_e)}{m}}$

   Erosion depth of 10cm/yr. estimated for the C-divertor in ITER

2. **Tritium inventory**: $C \Rightarrow W$ $\quad \Gamma \propto n_e C_s(T_e)$, $E \propto kT_e$

   Tritium inventory of a few kg/yr. estimated for the C-divertor in ITER

3. **High-heat flux removal**: W, C on Cu $\quad \Gamma \propto n_e C_s(T_e)$, $E \propto kT_e$

   Heat fluxes of ~20MW/m^2 estimated for ITER

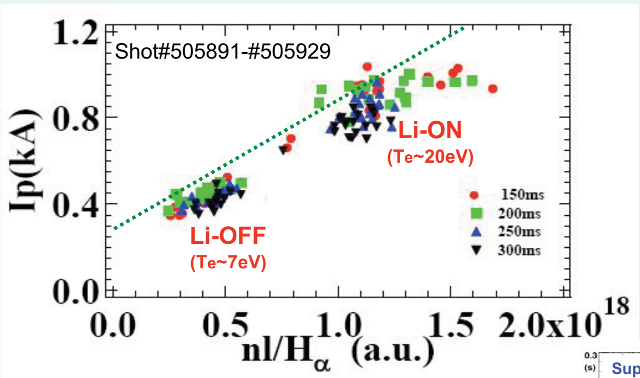
Suppression of PWIs by materials choice

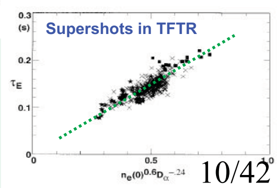
Further suppression of PWIs by edge-plasma control⇒Boundary control

Choice is either the reduction of n_e or T_e?

9/42

Application of Li-MS-PFC to a spherical tokamak





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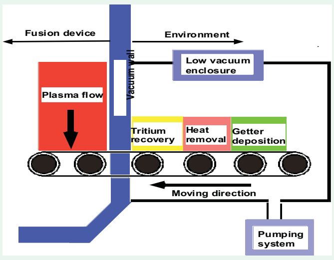
Moving-surface plasma-facing components (MS-PFC concepts)

Moving-solid surface



After Y. Hirooka et al. 17th SOFE(1997)

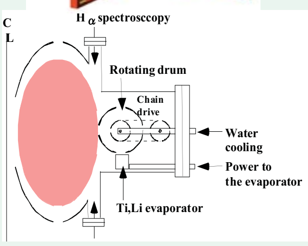
Moving-liquid surface

After M. Abdou et al., Fusion Eng. Des. 54(2001)181.

.

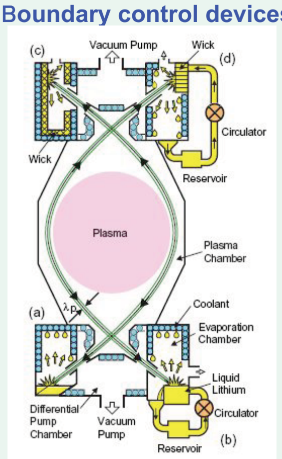
11/42

Application to a spherical tokamak & LHD



R=0.3m, a=0.2m, B=0.25T
50kW RF current drive
(8.2GHz kylstron)

◎Boundary control devices:



After Y. Nagayama SOFT2008

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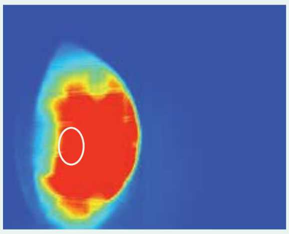
Application of MS-PFC to a spherical tokamak

Li-gettering ON

#505908 w/Ha filter

Li-gettering OFF



#505910 w/Ha filter

13/42

Plasma diagnostics by using impurity ions

By Izumi Murakami

Light Ions to Heavy Ions

- **It is important to understand behavior of impurity ions in peripheral region for plasma transport and plasma control problems. Atomic processes in plasma play an important role to understand these problems and plasma diagnostics. We study atomic processes in plasma and plasma spectroscopy.**
- We have developed collisional-radiative (CR) models for impurity ions, such as Fe ions, Ne ions, O ions, and C ions and used these CR model to obtain electron temperature and density dependences of spectral line intensities. Many kinds of atomic collision processes are included in CR models. By comparing spectral line intensity ratios measured spectroscopically and ratios obtained from CR models, we can estimate plasma parameters.
- We include recombination processes and inner-shell ionization process in the CR model. These processes were not included previously.

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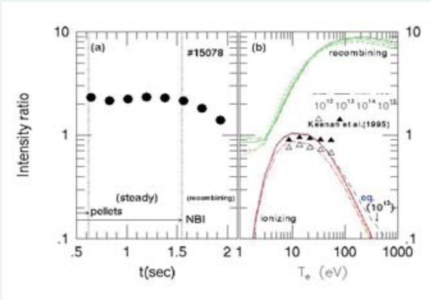
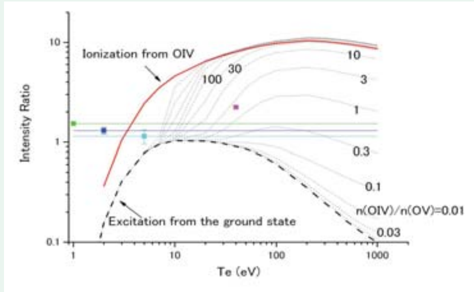
Plasma diagnostics by using OV and OIV lines





(a) Line intensity ratio I(OV 76nm/OV 63nm) for NBI-heated LHD plasma is about 2.23.(#15078)
(b) Theoretical intensity ratio for ionizing plasma (red) and recombinig plasma (green) or equilibrium plasma (blue) cannot explain the measured ratio.

We estimate contribution of innner-shell ionization from OIV ion (red) and this can explain the measured ratio, with assuming electron temperature Te ~ 30-50eV and the ion density ratio n(OIV)/n(OV)~2-5, which is larger than the equilibrium plasma ratio 0.22-0.042.
This indicates NBI-heated LHD plasma is not in ionizing equilibrium.

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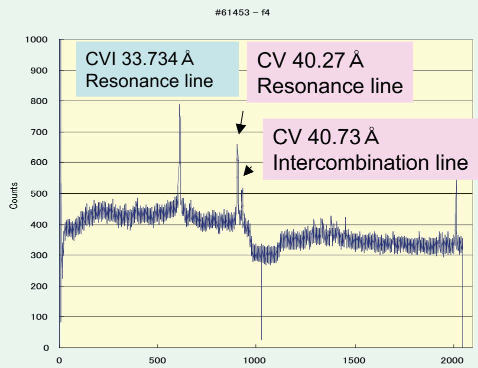
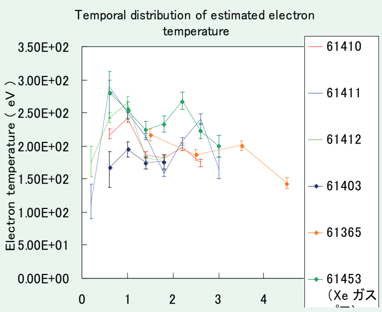
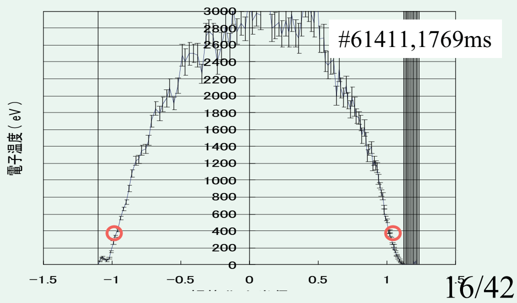
Plasma diagnostics by C V

The collisional-radiative model for CV ion gives electron temperature dependence of each spectral line intenstiy.
Electron temperature is estimated by using intensity ratio of the CV intercombination line to the CV resonance line for NBI-heated LHD plasmas.
Comparing with the electron temperature distribution measured by Thompson scattering, location of CV emitting region can be estimated at around ρ~1. This means He-like Carbon exist in peripheral region.







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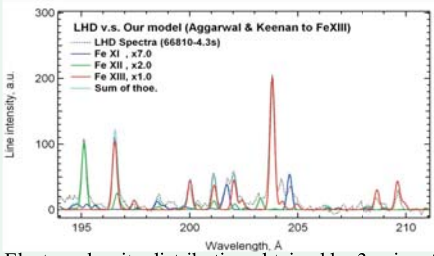
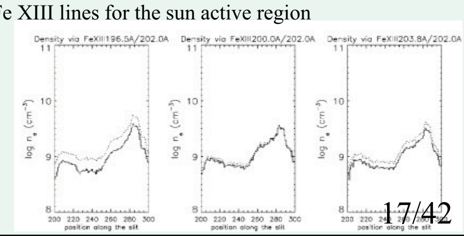
Research on non equilibrium plasma by using LHD and the Solar obserbing satellite "HINODE"

- Collaboration with National Astronomical Observatory and Univ. of Electro-communications.
- To examine non-equilibrium plasmas by spectroscopy, we have developed a collisional-radiative (CR) model for Fe ions, evaluated atomic data for Fe ions, observed the solar plasma by HINODE EIS, measured LHD plasma, atomic collision experiments with compact EBIT.
- We examined Fe ion spectra from LHD plasmas and analysed with using the CR model.
- Using density dependence of Fe XIII line intensity ratios obtained by the CR model, we estimated the electron density distribution of the sun active region.
- We are going to develop a time-dependent CR model and combine with a solar flare model code to examine the mechanism of coronal heating by using Fe ion spectral lines. This model will be able to use for LHD plasma diagnostics.

EUV spectrum of LHD plasma and our model



Electron density distribution obtained by 3 pairs of Fe XIII lines for the sun active region



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Tritium for Fusion

Scientific Research in Priority Areas (2007-2011)

by Daiji Kato

- Tritium inventory and recycling in reactors are important issues of study in **safety** and **economic** aspects of fusion reactors.
- Material and plasma behaviors (physics) under **tritium-rich condition** are little understood.
- Theoretical models and integrated simulation code for global T inventory and recycling are being developed through collaboration of **plasma, material and atomic/molecular physicists**.

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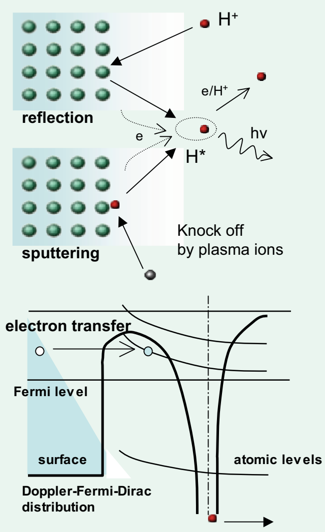
TOPICS 1: Excited atomic hydrogen at metal surfaces

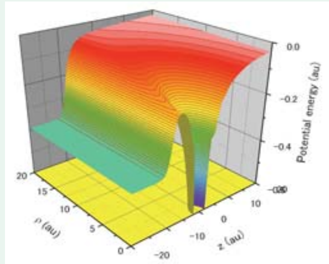
Excited hydrogen plays characteristic roles (larger probabilities of photon emission, ionization and charge exchange) in edge plasmas. *Highly polarized level population* via electron capture at metals surfaces was predicted in this study. This finding is a useful knowledge for *precise spectroscopic measurements of hydrogen-recycling in plasma-wall interaction*.

D. Kato, T. Kenmotsu, K. Ohya and T. Tanabe, 18th PSI (Toledo), J. Nucl. Mater. accepted.



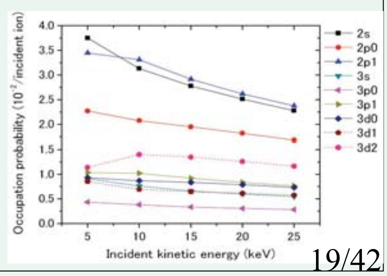
Development of theoretical method to study electronic interaction of hydrogen isotopes and metal surfaces.

Upper figure: Electrostatic potential energy surface of electron near Mo surface. Hydrogen nucleus is located at the origin, 10 a.u. above from Mo surface. Cylindrical coordinates are used.
1 au length = 1 Bohr radius.
1 au energy = 27.21 eV.



Development of first principle method to study excited level population of reflected hydrogen atoms at metals surfaces.

Lower figure: Highly polarized occupation probabilities of excited levels of deuterium atoms reflected at a Mo surface with incident energies of 5 - 25 keV.

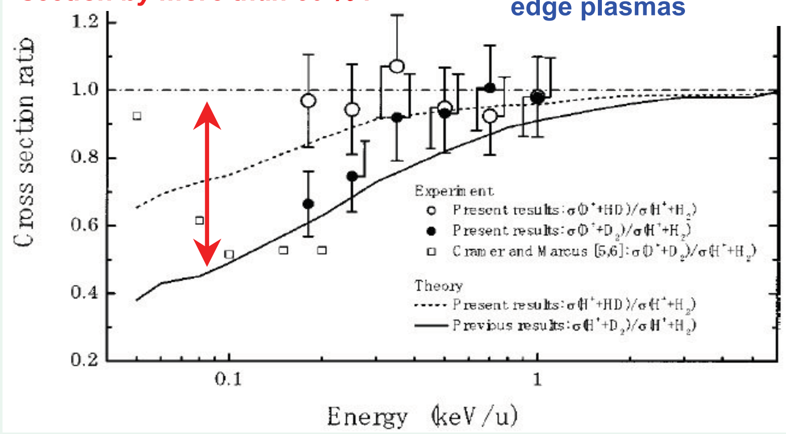


Isotopic effects of atomic collisions

Electron transfer in D^+ + HD and D_2 / H^+ + H_2

Isotopic effects reduce cross section by more than 50 % !

Change molecular assisted recombination (MAR) rates of edge plasmas

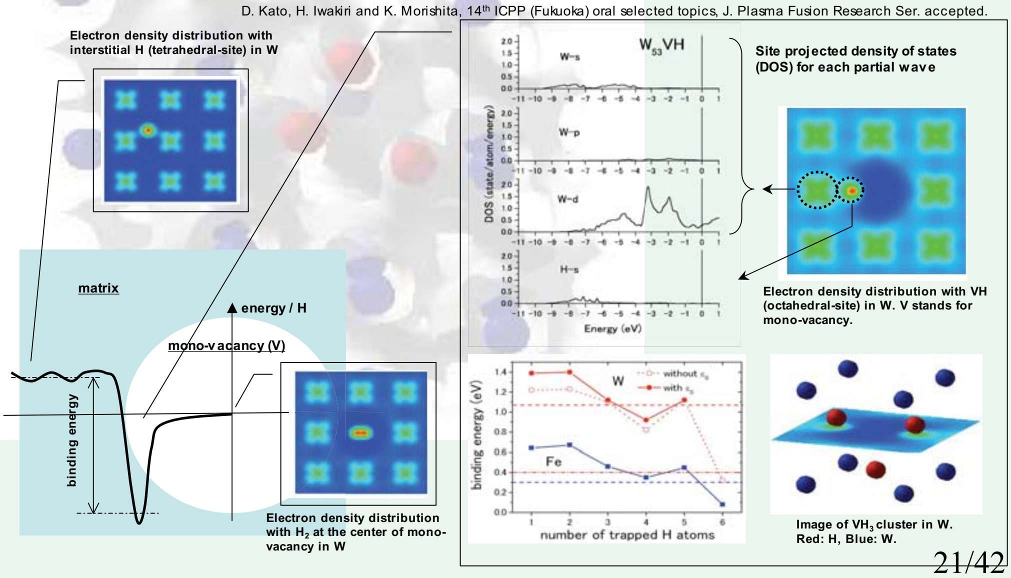


Kusakabe et al., Phys. Rev. A 70, 052710 (2004).

TOPICS 2: Hydrogen trapping in bulk tungsten

Electronic interaction of hydrogen with vacancies are studied by means of the first principle molecular dynamics. *Multiple-hydrogen trapping* by vacancies and *super-abundant vacancy creation* under hydrogen-rich condition were predicted in this study.

D. Kato, H. Iwakiri and K. Morishita, 14th ICPP (Fukuoka) oral selected topics, J. Plasma Fusion Research Ser. accepted.



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EUV spectroscopy of highly charged iron ions with a low energy compact EBIT by Hiroyuki Sakaue

The spectroscopic investigation of highly charged ions attract attention not only in atomic physics but also in the diagnostics of nuclear fusion and astrophysical plasmas.

We measured extreme ultraviolet (EUV) spectra of highly charged iron ions (Fe IX - Fe XXIV) in the range of wavelength 100-300 Å by a new compact electron beam ion trap (EBIT) which was developed for low electron energy operation. The electron energy of this compact EBIT is controllable from 100 eV to few keV, therefore it is appropriate for spectroscopic investigation of the moderately charged ions. A slitless flat-field EUV spectrometer developed exclusively for this compact EBIT is mounted with it and high sensitivity and high resolution spectroscopic analysis of highly charged iron ions become possible. A schematic drawing of the EBIT and the EUV spectrometer are shown in Figure 1

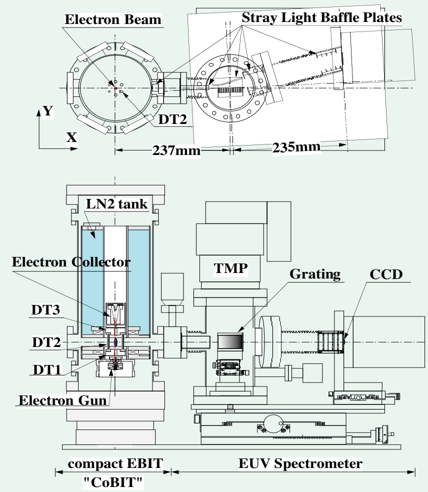

Fig.1 **Cross sectional view of compact EBIT and EUV spectrometer**

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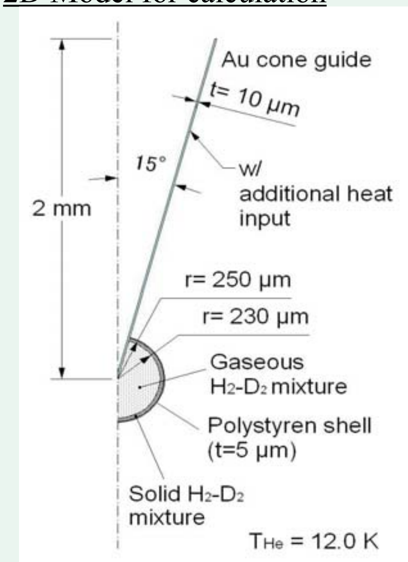
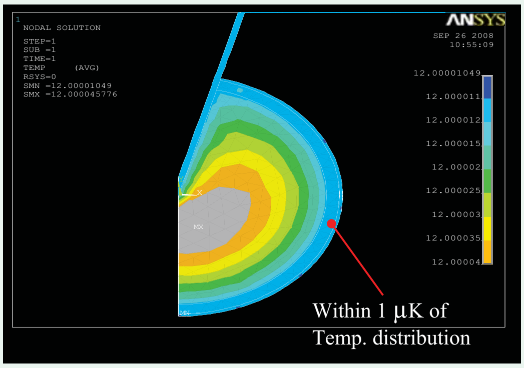
Laser Coop.; Temperature control of FIREX target

2D Model for calculation

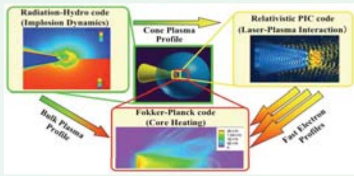


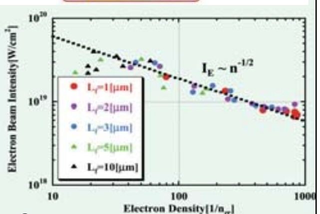
- Heat input to the cone of 0.25nW can minimize the temperature distribution in the solid fuel layer.
- The layer uniformity of the FIREX target would be achieved with the temperature control.

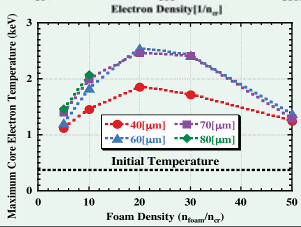


Integrated Fast Ignition Simulations

- FI^3(Fast Ignition Integrated Interconnecting code) project
  - collaboration with Osaka Univ., Setsunan Univ. and Kyushu Univ.
- We found that the fast electron beam intensity has well scaled as the inverse square root of the electron density at the LPI region independent of another parameters.
- We proposed a cone target, of which an inner surface is coated with a low-density foam, to maintain the fast electron beam. FI^3 integrated simulations are performed to estimate core temperatures, and the foam density and the thickness are optimized.







Division of Industrial–Academic Research C.

Industry Cooperation Group
&
Inter–Institutional Research Coordination G.

Sintering of Zero expansion Pore Free Ceramics for Extremely Large Telescope

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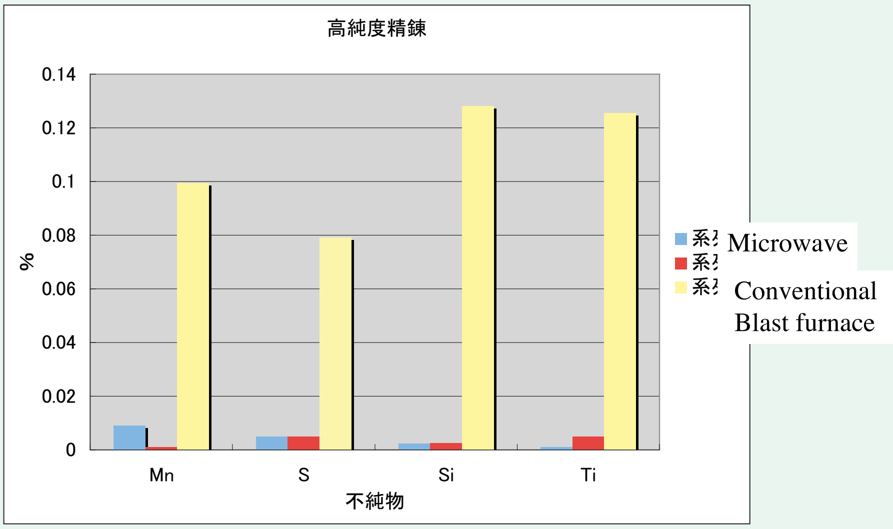
Very High pure steel will contribute to make first wall for fusion



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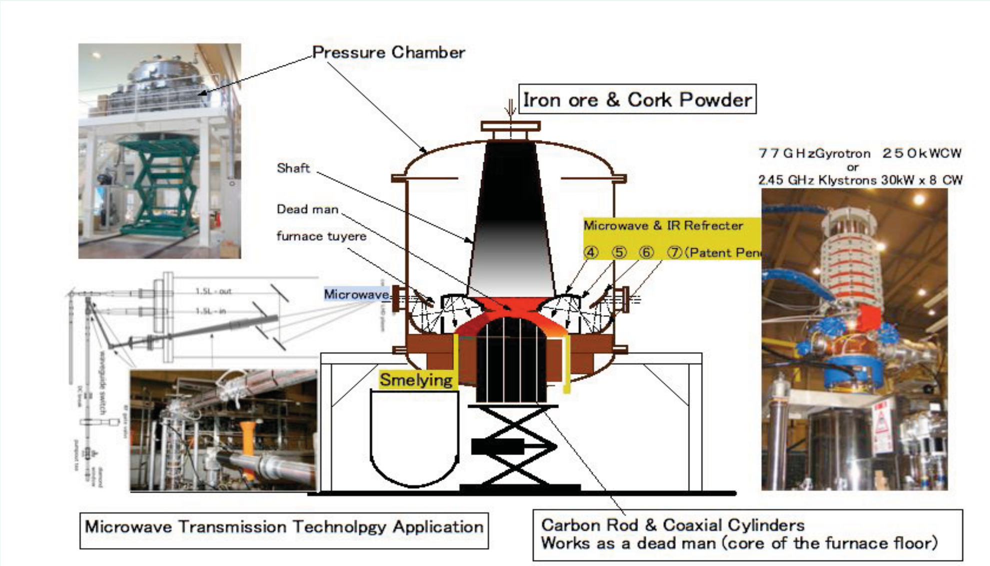
Microwave Steel Making by Motoyasu Sato



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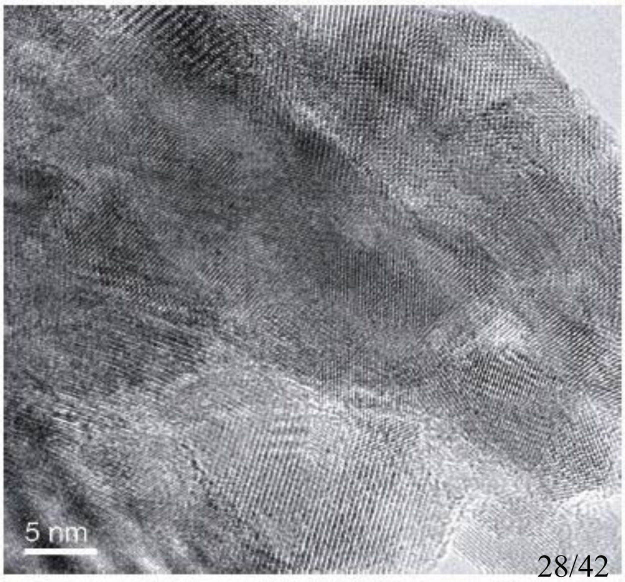
Formation of Nano-Domains by Microscopic Thermal Non-Equilibrium Generated in High Frequency Microwave H-Field

M. Sato1),
S. Takayama1),
A.Matsubara1),
M. Tanaka1),
Maxim Ignatenko1),
Jun Fukusima1)
Nobuyuki Nishi2),
Hideoki Fukushima3),
Rustum Roy4),
Dinesh Agrawal4), ,

1) NIFS
2) Institute of Molecular Science,
3) Toyota Central R&D Laboratory, Japan,
4) Pennsylvania State University, USA



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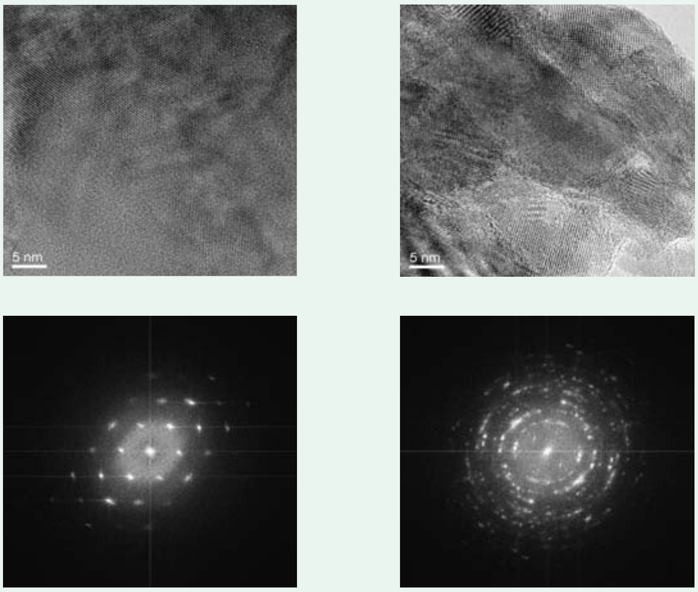
TEM

Starting Fe_3O_4

E field　　　　H field



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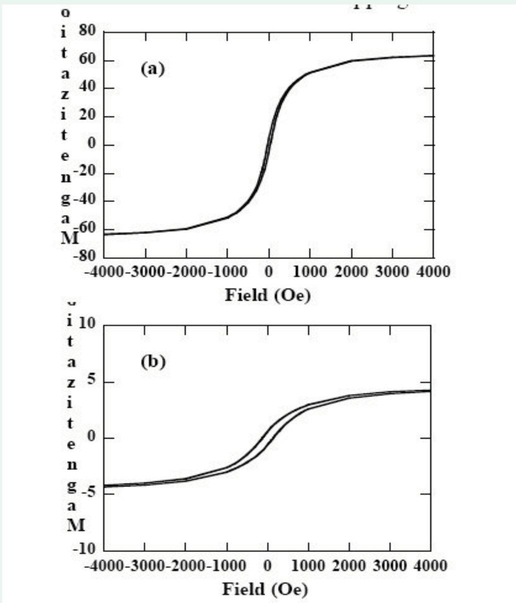

Fig.4 Magnetization curve of samples heated by magnetic field at (a) 1000 degree Celsius and (b) 1200 degree Celsius.

by SQUID magnetic properties measurement system

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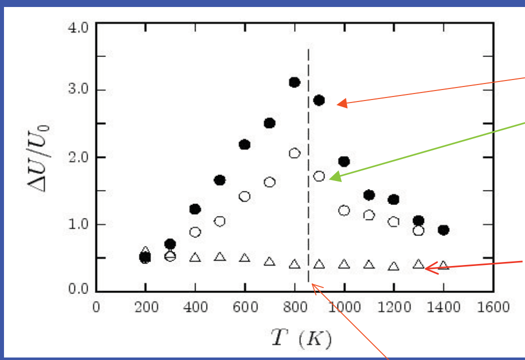
Electromagnetic Field and material Interactions

Energy released by magnetic field changes

by Motohiko Tanaka

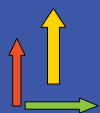


Magnetite

B_{mw} // c-axis

B_{mw} // a-axis

c-axis



Hematite

$\mathbf{B}_{mw}$

Curie temperature

Magnetite (with spontaneous magnetization) is heated

… through the response of spins in unfilled 3d shell,
which continues above the Curie temperature.

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Results of Monte Carlo Simulation

$$U = -\sum_{i,j} J_{ij}\mathbf{s}_i\cdot\mathbf{s}_j + \sum_i g\mu_B \mathbf{s}_i\cdot\mathbf{B}_w$$

For magnetic field reversal: $\mathbf{B}_w \to -\mathbf{B}_w$

1) Energy change arises mainly from the exchange term

Small microwave field spins reorient ⇒ Amplified by exchange interactions !

2) Spontaneous magnetization (second term) vanishes above the Curie temperature, but energy change (first term) remains finite.

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An Analogy of Microwave Heating to the Classic reciprocal cycles
Condition for 2nd law of thermodynamics

Time Scale (Sec)

10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7}

Energy Supply by EM wave
(Couple to Electrons)
Speed of Light

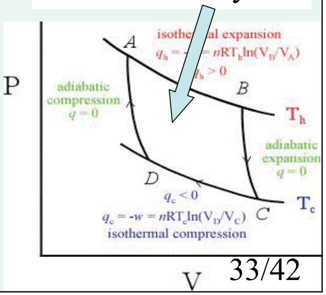
Carnot Cycle
can not work
at the frequency
of Microwave

Classic Cycle
Archimedes Law
must be satisfied

Collision frequency
>> Cycles

Quantum Relaxation
will play a roll to collision frequency in the analogy to classic cycles

Collision frequency
<< Cycles



New cycle theory will establish including
Quantum relaxation and classic collision

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Inter-Institutional Research Coordination
Microwave Sintering of ZPF ceramics

- The latest results are reported for the sintering of zero-expansion Pore-free Stiffness ceramics, called "ZPF". http://www.ceratech.co.jp/english/product_e/01_01_05.html
- ZPF is a very unique composite ceramics. It consisted of SiC powder (about 80 mol %) and Li-Al2O3-SiO (~20%) powder.
- It is not clear, if it is the pure liquid or pure solid sintering, as it is sintered slightly under the melting point of Li-Al2O3-SiO powders.
- Small test pieces (122 x 122 x 20 mm stacking on three layers) sintered successfully in the isothermal insulator box by microwave.
- Larger disks can be sintered in the large kiln at NIFS.

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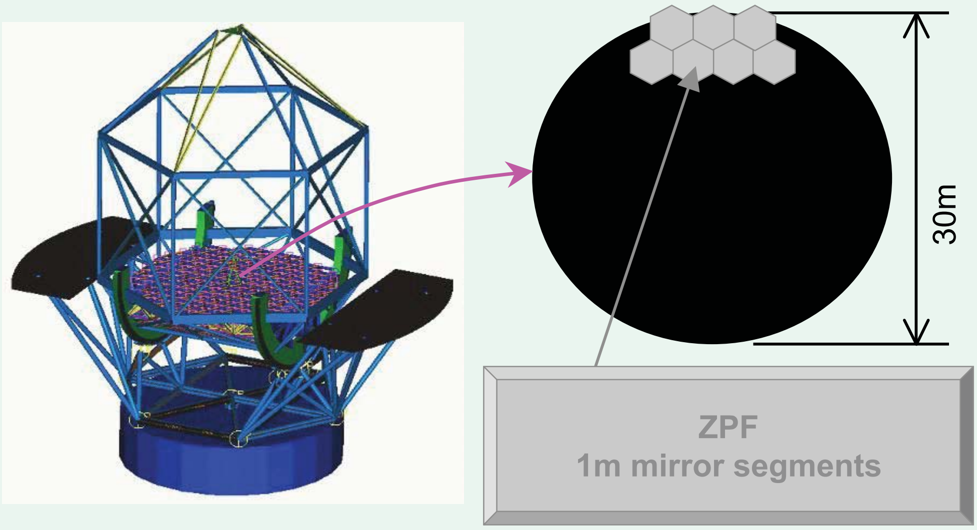
Next Generation ELT



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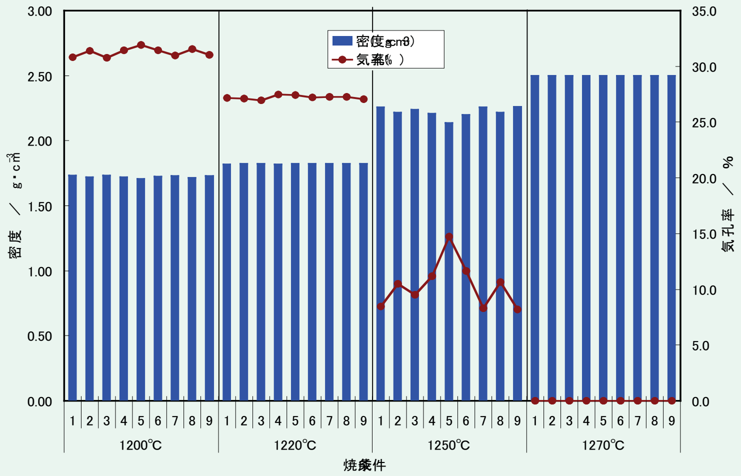
Density distribution 2 (Graph)



◇The densities are all most uniform except for 1250 Deg C
◇ Finish sintering at 1270℃ Completely

2008/02/18

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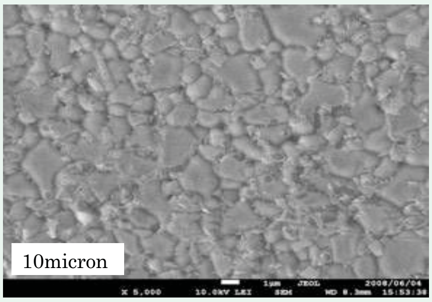
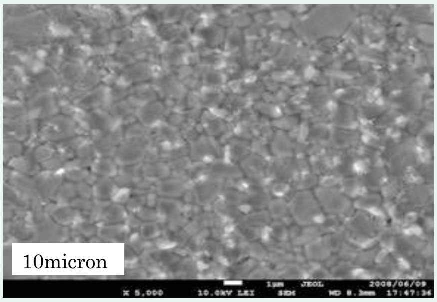
SEM 5000X





SEM Conventional 9bar SEM Microwave 1bar

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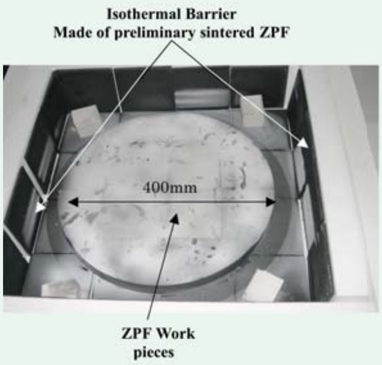
Larger size Disk and Large Kiln



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ITER Collaboration Activities in 2007~2008

By Y. Nakamura

ITER

Check & Review
- Contribution to ITER Design Review (Heating Device, SC Magnet)

Academic Research
- Contribution to ITPA activities (~10 persons/year participate in ITPA meetings)
- Annual meeting on ITPA report and discussion in NIFS

Fusion Technology
- Workshop on ITER pellet injector (Contribution from LHD pellet injector)
- Information exchange on development of negative-ion based NBI device

BA

Device Components
- Qualifying test of SC conductors for JT60-SA

Academic Research
- Cooperation of building-up the computer simulation center (Selection of supercomputer, Physic issues of fusion simulation etc)

Fusion Technology
- Contribution to IFMIF-EVEDA (Development of TBM, R&D for DEMO)

Fostering of Advanced Researchers
- Communication meeting with ITER JADA member for young students in NIFS
- Support for participation to 2nd ITER International Summer School in Japan (Report meeting on ITER ISS)

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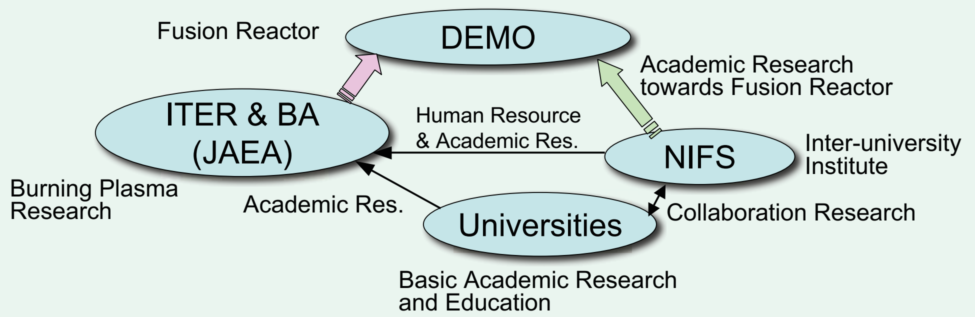
Future Prospects



- Establishment of ITER organization in 2007 and then beginning of device construction phase
- Definite and practical contributions (human resource, review & check, qualifying test of device components etc.) will be requested.
- Academic research using reactor-grade fusion facilities (ITER & BA)
  - α heating physics, burning plasma control, qualifying test of blanket etc.
- Fusion technology towards building a fusion reactor (DEMO)
  - Material research, breeding blanket, power plant system studies etc.
- Fostering of advanced researchers for contributing to ITER & BA and DEMO

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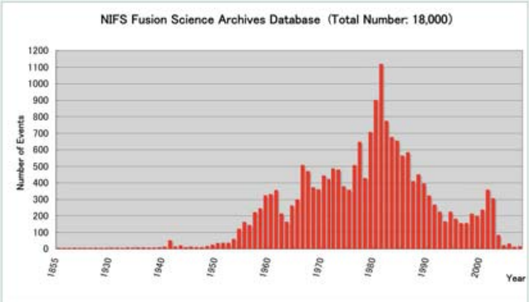
New Achievement in Fusion Science Archives (FSA) by Keisuke Matsuoka

1) Documents:

The number registered amounts to 18,000 as is shown in the figure. Main effort has been focused on making FSA public.



2) Making Electronic Finding Aids Public:

A part of finding aids of NIFS FSA has been made public on the basis of EAD (Encoded Archival Description Intensive) under collaboration with Sokendai (The Graduate University for Advanced Studies), NIJL (National Institute of Japanese Literature) , KEK (High Energy Accelerator Research Organization) and IMS (Institute for Molecular science).

3) Lecture Meeting on Importance of Archives was held by inviting a specialist from National Archives of Japan as a speaker.

4) Presentation of Achievements:

"Special Issue on History of Fusion Research in Japan" of The Japan Society of Plasma Science and Nuclear Fusion Research was issued with the great contribution of NIFS FSA. Flow chart of 50-year fusion research and historic documents e.g., Nobel prize-winner Yukawa's note on fusion, were exhibited at the annual meeting.

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NIFS
Kids Fusion Science Museum

Meet cutting-edge science and technology ! Meet scientist !

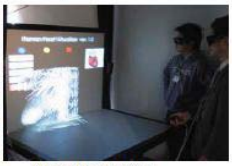
Opening ceremony on Oct. 25, 2008

The Earth Environment and Fusion Energy

Inreach program
Exhibitions: parabola wall, virtual reality system, measurement of universal gravitation, etc.
Events: demonstration, experiment, etc.
Tour: LHD tour, Simulation center tour

Outreach program
Museum: Cooperation with science museums
School: Visiting program for elementary school, Junior high school and high school

Exhibition room (Parabola and diagnostics)



Virtual reality

High school interpreter (Open campus 2008)

Museum cooperation (with Miraikan)

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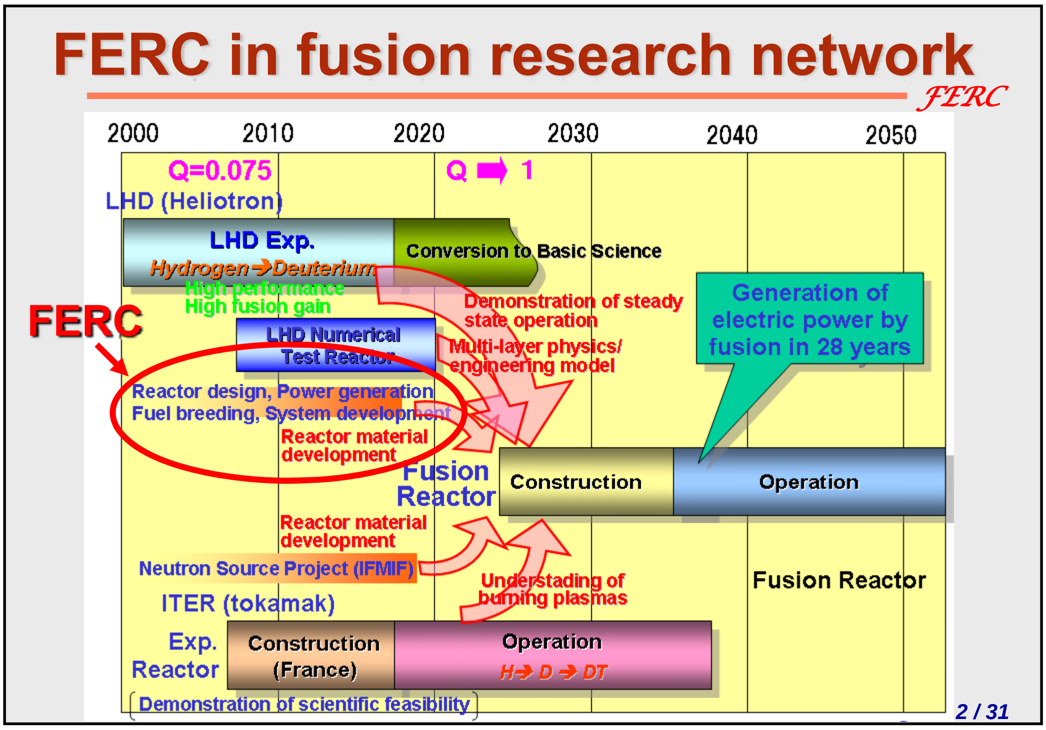
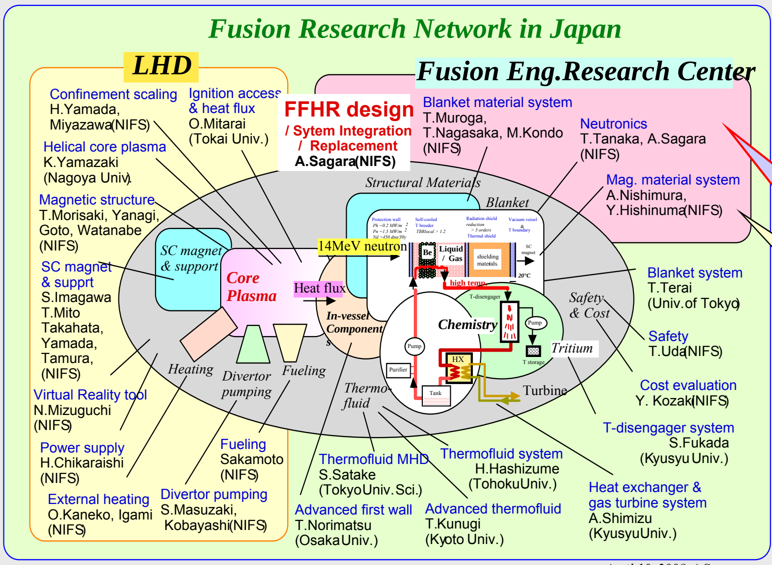
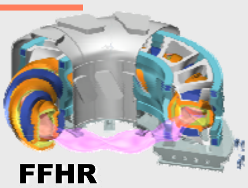
3-5 Highlights for long-life blanket and SC magnet materials



7 staffs in FERC produced world impacts with broad collaborations in fusion research network

FERC





Long-life > 10y
- Welding
- Corrosion
- Irradiation

Int. Collaboration

TITAN : USA (ORNL, INL, UCLA, UCSD)

CUP : China (SWIP, ASIPP)

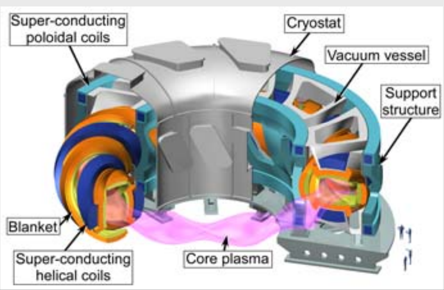
Int. Network Program : EU (IPP), Russia, Ukraine, Korea (KAERI)

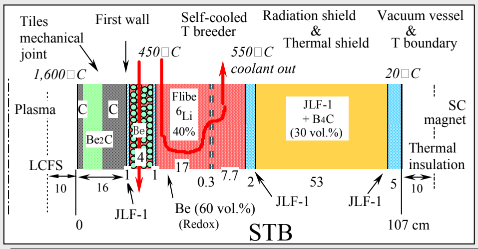
April 10, 2008, A.Sagara

Two sets of optimization have been studied on LHD-type Energy Reactor FFHR towards Demo

FERC

1. To expand the blanket space by adjustment of the coil pitch parameter γ of the continuous helical winding, while reducing the magnetic hoop force to open wide maintenance ports,
2. To solve the replacement difficulty by proposing a long-life blanket concept STB (Spectral-shifter and Tritium Breeder blanket) using carbon tiles to soften the neutron energy spectrum on the self-cooled Flibe-RAF blanket.





- R_p=16m, a_p=2.35m, V_p=1744m^3, B_0= 4.8T,
- 3GWth, 30,000 ton

Replacement-free STB blanket (metal wall < 100dpa / 30y), where C tiles should be replaced in a few years

Present activities in FERC on liquid breeder blanket

FERC

		F.E.Reserch Center		collaboration
Issues	Requirements	Flibe ($LiF+BeF_2$)	Li	Pb-Li
corrosion & safety	Compatibility with structure materials is high ?	No by F & FT -> redox and/or coating	No with N, Yes for V	No with metal Yes for SiC
	Chemical reactivity is low ?	Yes	No ->	Yes
	Activation is low ?	Yes	Yes	No by ^{210}Po
Self-cooling	Thermal conductivity is high ?	No -> turbulence	Yes	Moderate
	Viscosity is low ?		Yes	Yes
	MHD pressure loss is low ?	Yes	No -> coating	No -> coating
	MHD effects to heat transfer is low ?	?	Yes	Yes
Tritium breeding & recovery	Tritium breeding is high ?	Yes with Be -> neutronics	Yes	Yes
	Tritium recovery is easy ?	Yes	No -> hot trap	Moderate
	Tritium confinement is high ?	No -> coating	Yes	No -> coating
operation	Vapor pressure is low ?	Moderate	No	Moderate
	Weight density is low ?	Yes	Yes	No
	Melting point is low ?	No(732K)	Yes(453K)	Moderate(508K)
Data base	Enough for Fusion?	Partly from MSRE(US)	Moderate in US & Japan	Moderate in EU, US

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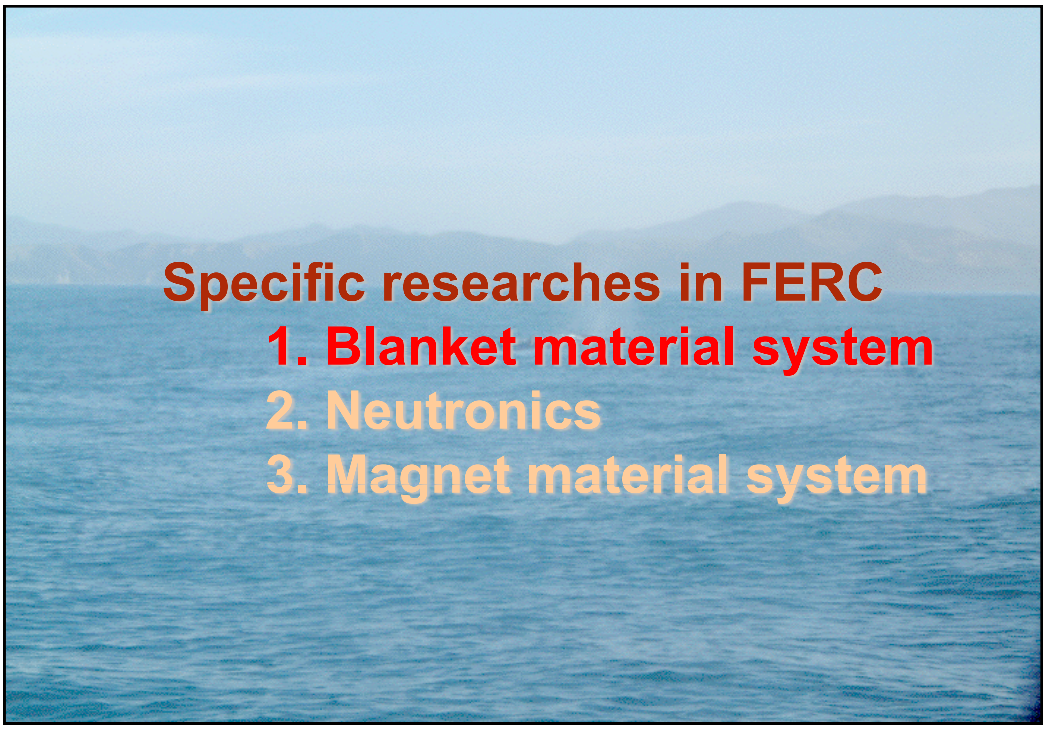
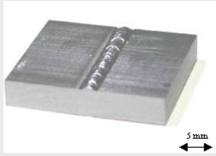


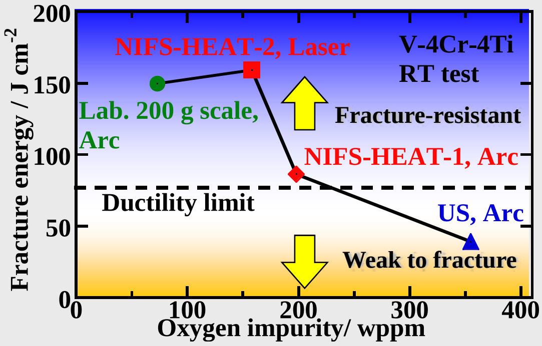
Welding for vanadium alloy became possible

FERC

166-kg ingot of NIFS-HEAT-2 low activation vanadium alloy



Laser weld

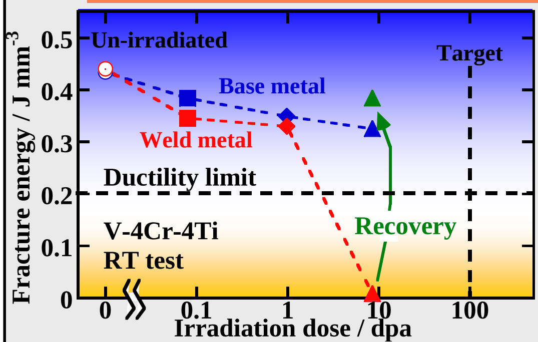


Fracture energy of weld joint at room temperature

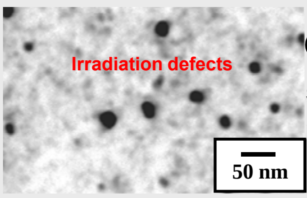
- ✓ High purity large scale V-4Cr-4Ti alloy ingots, NIFS-HEAT-1 and -2, were fabricated and distributed to world research institute.
- ✓ Before NIFS-HEATs, welding of US vanadium alloy was impossible because of low fracture energy at impact load.
- ✓ **Oxygen impurity reduction in NIFS-HEATs made welding possible for vanadium alloy.**

Vanadium alloy weld resisted 1 dpa irradiation

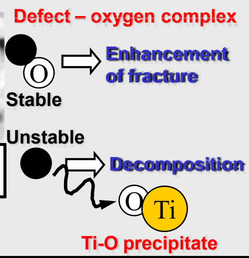
FERC



Fracture energy of weld joint after irradiation



Electron microscope image



- ✓ **Weld metal maintained high fracture energy until 1 dpa, while it degraded at 8.5 dpa.**
- ✓ One of causes for the degradation is nano-size irradiation defects
- ✓ **Annealing at 600°C for 1 hr decomposed them mostly, and recovered fracture energy.**
- ✓ The defects are stabilized by impurity oxygen in weld metal
- ✓ **It is believed that appropriate post-weld heat treatment (PWHT) forms Ti-O precipitates, and promotes decomposition of the defects**
- ✓ Investigation of PWHT effect is undergoing

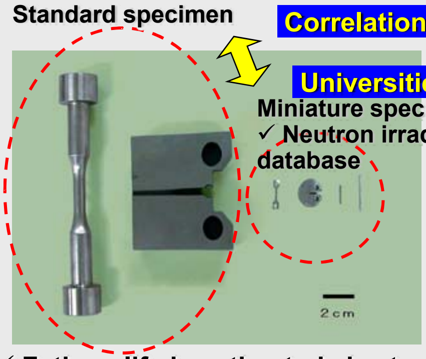
Bridge between standard and miniature test database

FERC

NIFS-FERC
Standard specimen

Correlation

Universities
Miniature specimen
✓ Neutron irradiation database

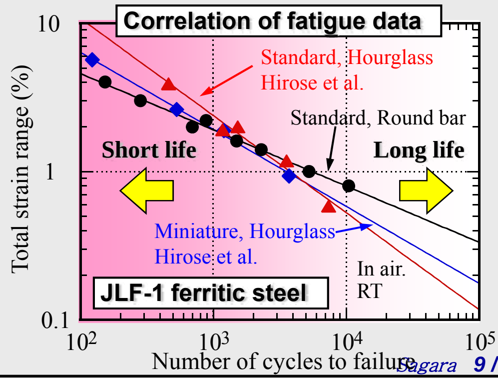


✓ Fatigue life is estimated shorter in small strain range for hourglass shape specimen than round-bar shape by configuration effect

✓ **Test with round-bar shape miniature specimen is ongoing to reveal the specimen size effect**

✓ Neutron-irradiated material data has been accumulated with miniature specimens by Japanese universities.

✓ **NIFS-FERC accumulates standard test data to clarify the correlation between the standard and miniature test database**



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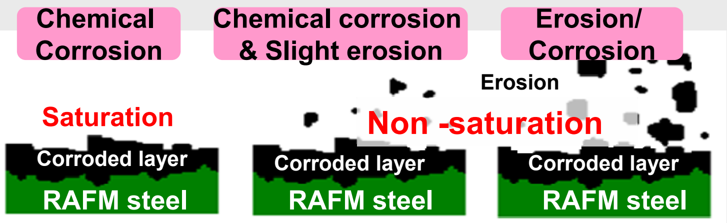
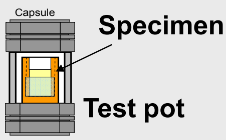
Corrosion characteristics of JLF-1 steel in molten salt Flibe and liquid Li was investigated

FERC

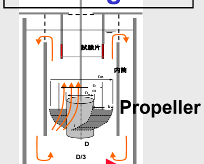


Static



Thermal convection

Flowing test



ΔT Small — ΔT Large

Equilibrium — Real condition

Present work — Future work

✓Corrosion characteristics of JLF-1 steel in Flibe, Flinak and Li were investigated by means of **static test and thermal convection tests.**

✓We are trying to do **forced convection test** based on our skill and technique for the corrosion test at high purity conditions.

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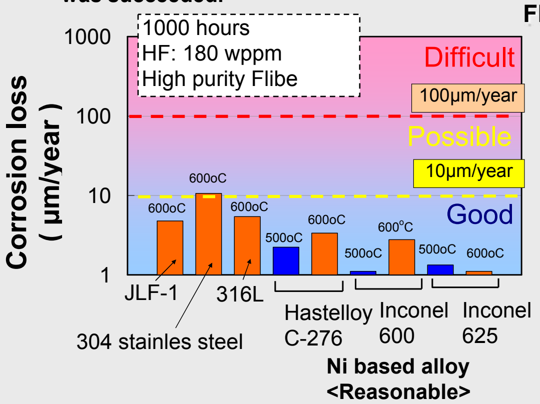
Low corrosion rate of JLF-1 steel in high purity Flibe at static condition was confirmed

FERC

Purification of Flibe was succeeded.

First Flinak



✓**High purity of Flibe** was successfully produced by NIFS - Tokyo univ. collaboration.

✓**First Flinak** was produced. Chemical characteristics of Flinak was **similar** to Flibe. Flinak will be used as simulant of Flibe for **future corrosion** study.

✓Corrosion tests in high purity Flibe were performed. **Corrosion rate** and mechanism **in static condition** was made clear.

Award for young scientist (AESJ)

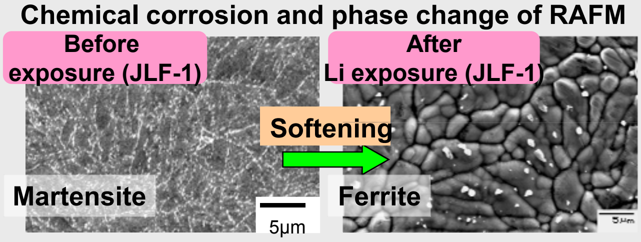
✓It was found that corrosion in Flibe was influenced not only by F but also O and N.

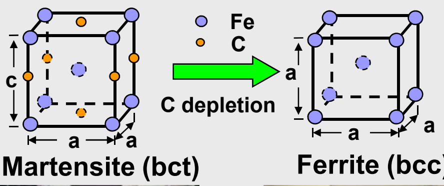
✓**The corrosion in high purity Flibe was low.**

Phenomenon of "Corrosion and Phase change" of JLF-1 in liquid Li was newly found by high purity corrosion test

FERC

Chemical corrosion and phase change of RAFM



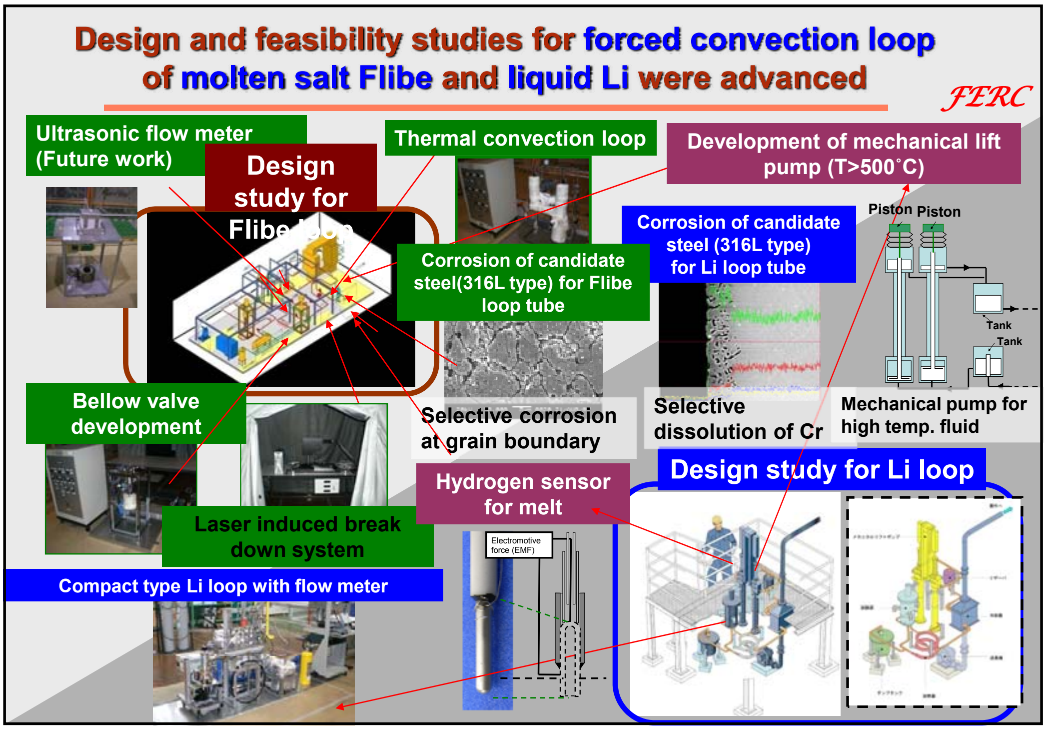


✓**Li convection loop at** high purity condition was successfully operated.

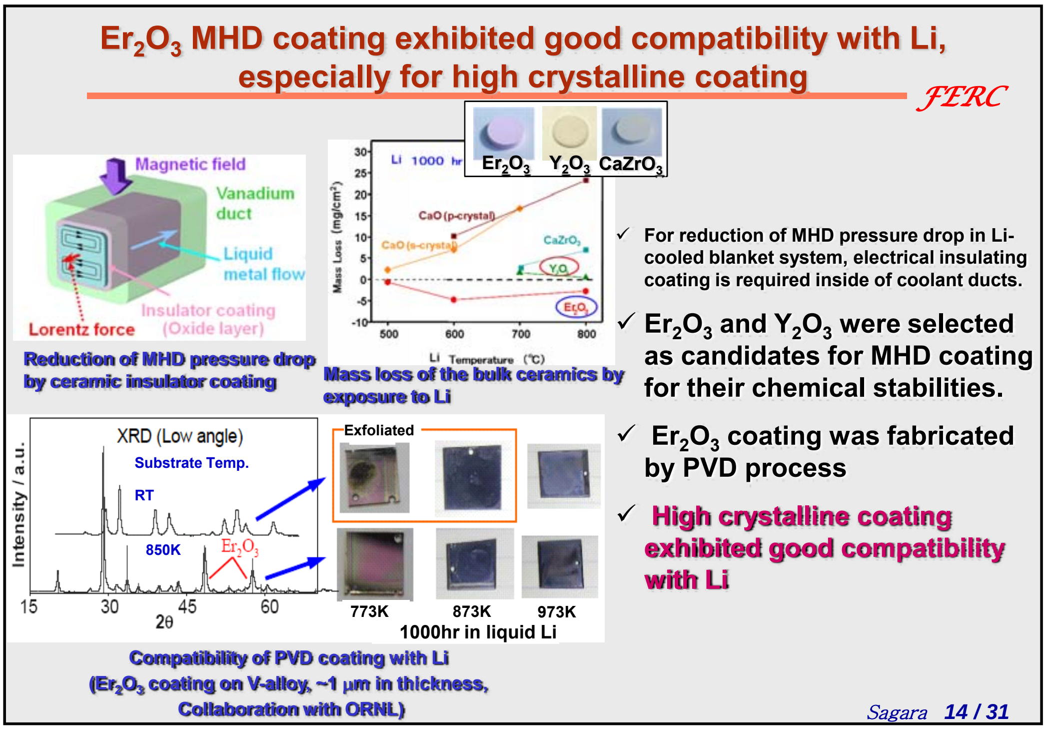
✓**Corrosion** was caused by the formation of Lithium-Chromium-Nitrogen compounds.

✓**The phase change** was caused by C depletion.

Li loop at high purity condition was successfully operated !!



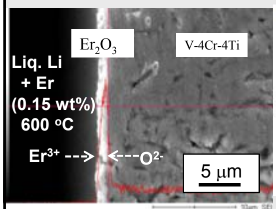
Design and feasibility studies for forced convection loop of molten salt Flibe and liquid Li were advanced
FERC
Ultrasonic flow meter (Future work)
Design study for Flibe loop
Thermal convection loop
Development of mechanical lift pump (T>500°C)
Corrosion of candidate steel (316L type) for Li loop tube
Piston Piston
Tank Tank
Corrosion of candidate steel(316L type) for Flibe loop tube
Bellow valve development
Selective corrosion at grain boundary
Selective dissolution of Cr
Mechanical pump for high temp. fluid
Design study for Li loop
Hydrogen sensor for melt
Laser induced break down system
Compact type Li loop with flow meter
Electromotive force (EMF)



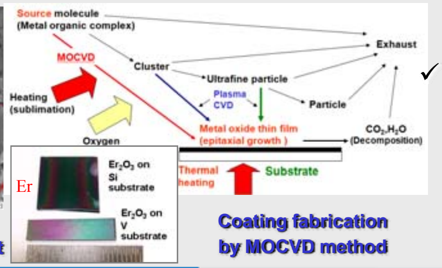
Er2O3 MHD coating exhibited good compatibility with Li, especially for high crystalline coating
FERC
Magnetic field
Vanadium duct
Liquid metal flow
Insulator coating (Oxide layer)
Lorentz force
Reduction of MHD pressure drop by ceramic insulator coating
Li 1000 hr
Er2O3 Y2O3 CaZrO3
CaO (p-crystal)
CaO (s-crystal)
CaZrO3
Y2O3
Er2O3
Mass Loss (mg/cm2)
Li Temperature (°C)
Mass loss of the bulk ceramics by exposure to Li
For reduction of MHD pressure drop in Li-cooled blanket system, electrical insulating coating is required inside of coolant ducts.
Er2O3 and Y2O3 were selected as candidates for MHD coating for their chemical stabilities.
Er2O3 coating was fabricated by PVD process
High crystalline coating exhibited good compatibility with Li
XRD (Low angle)
Substrate Temp.
RT
850K
Er2O3
Intensity / a.u.
2θ
Exfoliated
773K 873K 973K
1000hr in liquid Li
Compatibility of PVD coating with Li (Er2O3 coating on V-alloy, ~1 μm in thickness, Collaboration with ORNL)
Sagara 14 / 31

Advanced coating technologies and function of tritium permeation barrier have been demonstrated

FERC

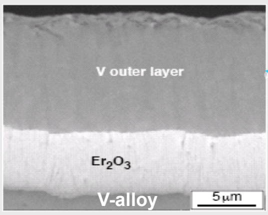


Development of in-situ coating method for Li blanket

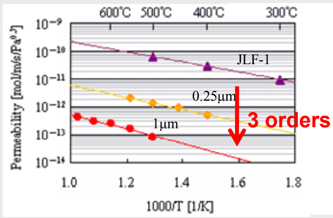


Coating fabrication by MOCVD method

- ✓ Advanced coating by in-situ and MOCVD (*metal organic chemical vapor deposition*) process have been developed for large area coating



Double layer coating by EB-PVD (Collaboration with LLNL)



H permeability of coated JLF-1 Collaboration with U. Tokyo

- ✓ Double layer coating has been also demonstrated for unti-corrosion coating
- ✓ Er_2O_3 coating exhibited 3-order reduction in H permeability

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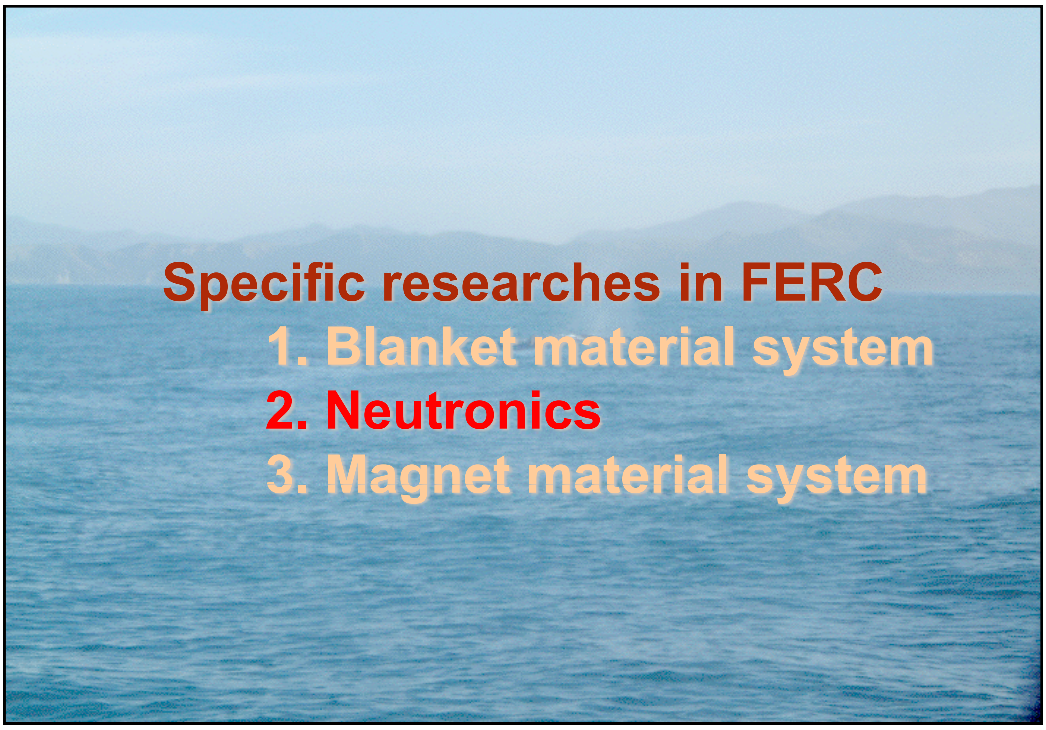
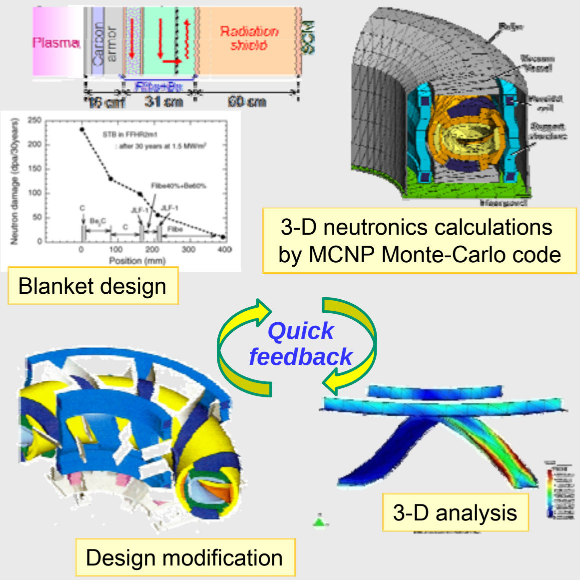


Quick feedback in neutronics design and modification have been conducted and Tritium breeding (TBR>1.1) and sufficient shielding can be achieved

FFRC



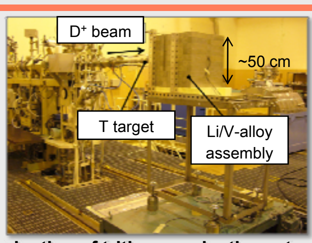
- ✓ Blanket structures and configurations have been investigated by simulations of **neutron transport, tritium production, damage, nuclear heating, radioactivation etc.**
- ✓ New 3-D neutronics calculation system for helical power reactors has been developed.
- ✓ Tritium fuel self-sufficiency could be achieved in helical reactor (Global TBR: >1.1)
- ✓ Semi-closed divertor system has been proposed to avoid neutron streaming

Sagara **17 / 31**

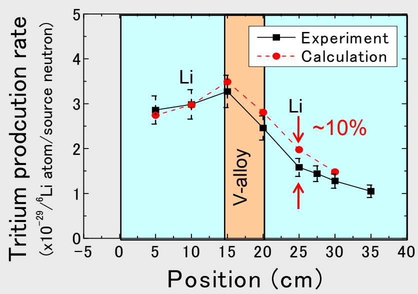
Neutronics designs are being validated by DT neutron irradiations

FFRC

at FNS facility (JAEA)



Evaluation of tritium production rates in Li/V-alloy assembly with small neutron detectors

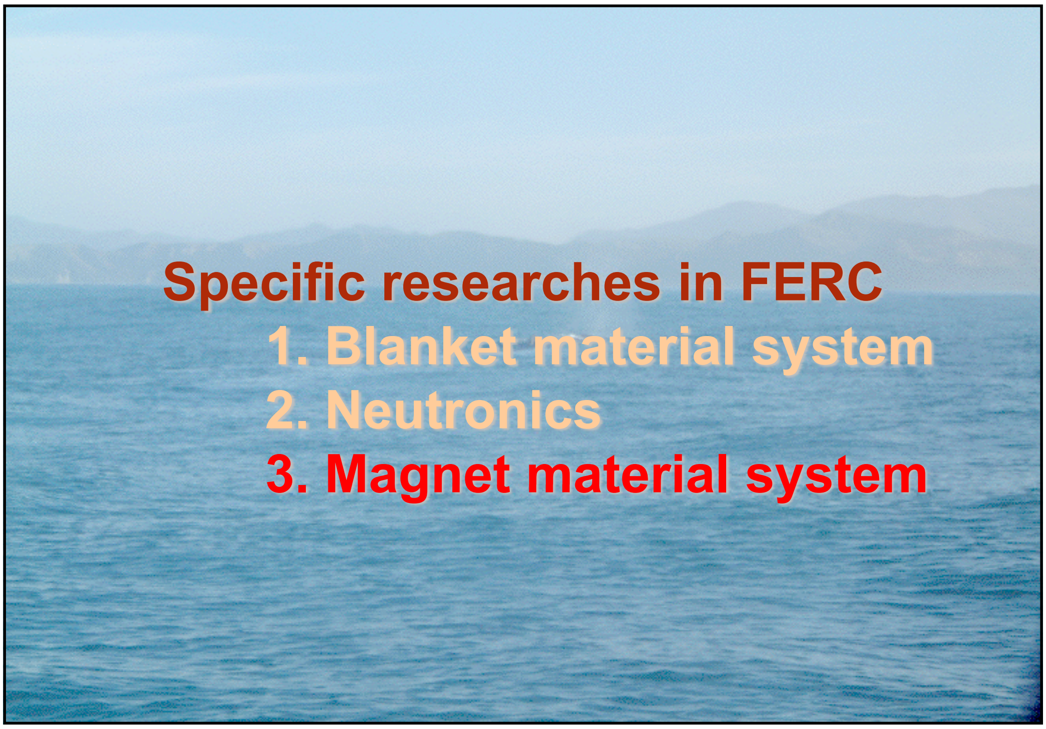


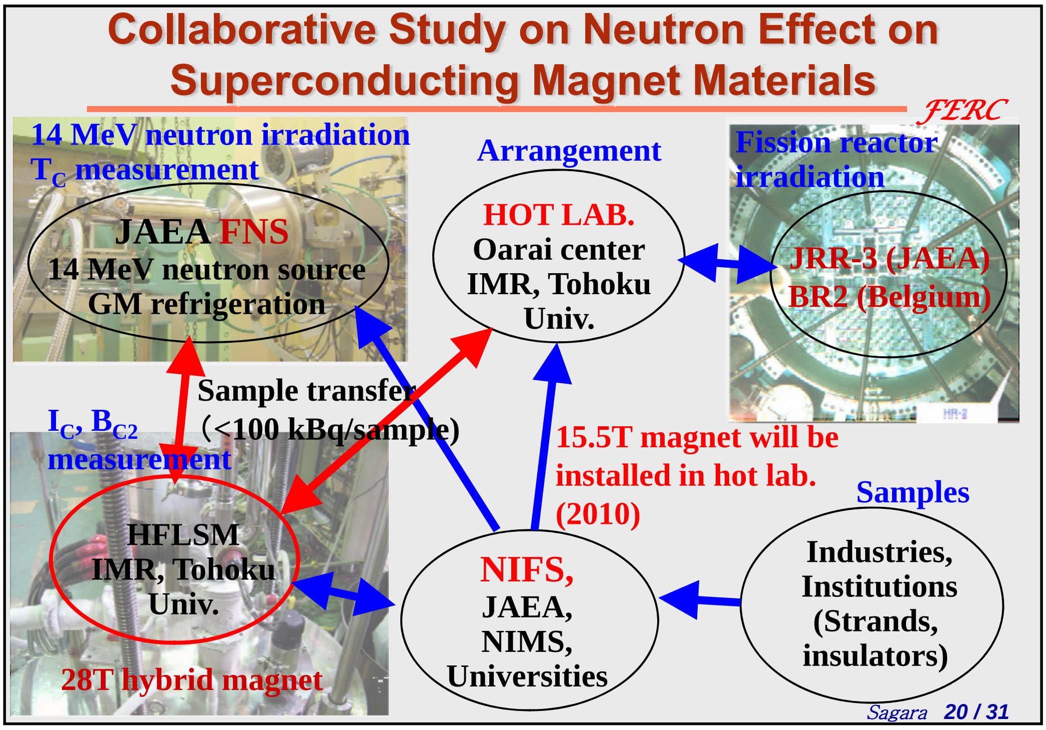
Comparison between calculated and measured tritium production rates in Li/V-alloy assembly

- ✓ DT neutron irradiations on blanket material assemblies are being performed at FNS facility (JAEA)
- ✓ For accuracy evaluations of modeling method, calculation code and nuclear data.
  - ➔ Validation of neutronics performance and information on design margins for TBM and DEMO reactor designs can be obtained.
- ✓ **Accuracy of radioactivity calculation for liquid blanket materials of V-alloy, Er and F was <~20 %**
- ✓ **Accuracy of tritium production rate from Li-6 in Li/V-alloy assembly was <~10 %**

(Tentative analysis)

Sagara **18 / 31**


Specific researches in FERC
1. Blanket material system
2. Neutronics
3. Magnet material system


Collaborative Study on Neutron Effect on Superconducting Magnet Materials
FERC
14 MeV neutron irradiation
T_C measurement
JAEA FNS
14 MeV neutron source
GM refrigeration
Arrangement
HOT LAB.
Oarai center
IMR, Tohoku Univ.
Fission reactor irradiation
JRR-3 (JAEA)
BR2 (Belgium)
Sample transfer
(<100 kBq/sample)
I_C, B_{C2} measurement
HFLSM
IMR, Tohoku Univ.
28T hybrid magnet
15.5T magnet will be installed in hot lab. (2010)
NIFS,
JAEA,
NIMS,
Universities
Samples
Industries,
Institutions
(Strands,
insulators)
Sagara 20 / 31

Critical Current of NbTi, Nb_3Sn, Nb_3Al after 14 MeV Neutron Irradiation

FERC

> I_C of Nb_3Sn increased.

Dependence of change in I_C on magnetic field was clarified.

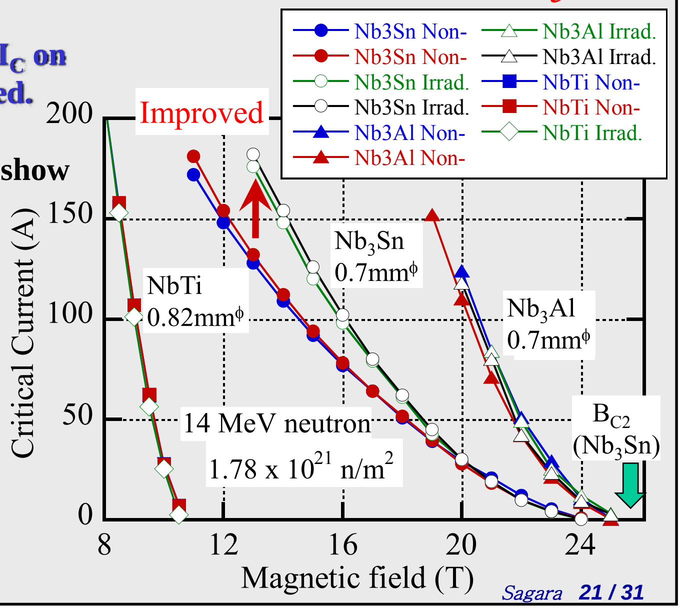
The World-first Data.

> NbTi and Nb_3Al do not show I_C increase.

> **B_{C2} of Nb_3Sn does not change after neutron irradiation. (~25.5 T)**

The World-first Data.

*Pinning force might be strengthened and/or number of pinning sites be increased by **Knock-on Effect** of neutron.*



Sagara **21 / 31**

J_e of V_3Ga wire was enhanced by new PIT process (R&D of Low activation superconducting wires)

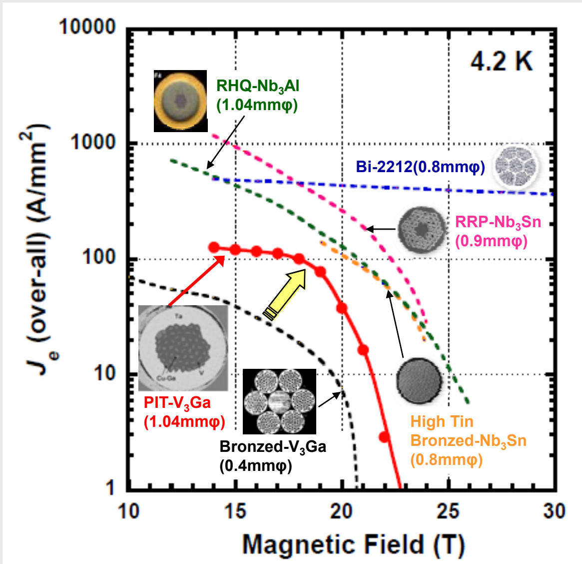
FERC

✓ B_{c2} was increased by the new PIT (powder in tube) process using "high Ga cont. compound". (21T → 23T)

✓ **Engineering J_c of PIT processed V_3Ga wire showed 100 A/mm² around 18 T.**

✓ **The optimum cross-section configuration was required to improve J_c-B property.**

✓ **The strain effect (high strength) and multifilament deformation will be investigated.**



Sagara **22 / 31**

Selected Publications in FY2006 to FY2008

FERC

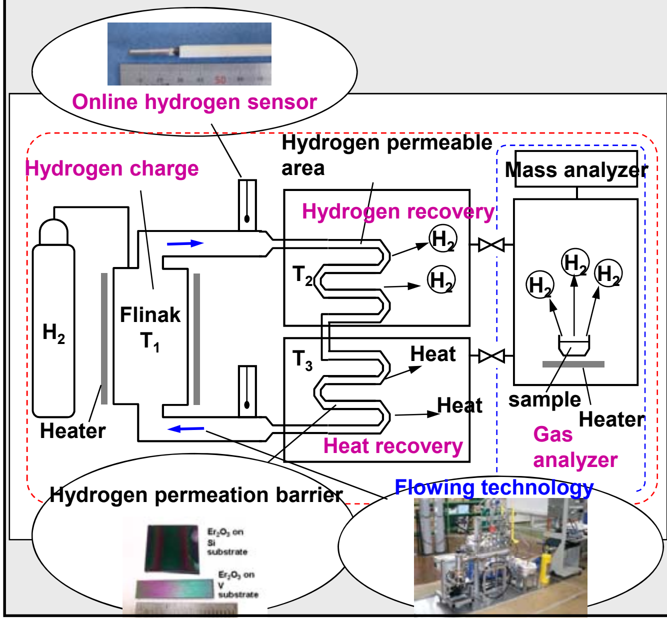
	Titles	Authors	Journals	Total Number of Papers: First Author	Stu-dents	Collaboration: Domestic	Within NIFS	Int'l
Reactor Design Studies	Optimization activities on design studies of LHD-type reactor FFHR	A. Sagara, T.Tanaka, T. Muroga et al.	Fusion Engineering and Design (accepted)	3		15	6	3
Blanket	Fluoridation and oxidation characteristics of JLF-1 and NIFS-HEAT-2 low-activation structural materials Metallurgical study on corrosion of austenitic steels in molten salt LiF-BeF2 (Flibe)	T. Nagasaka, M. Kondo, T. Muroga, N. Noda, A. Sagara et al. M. Kondo, T. Nagasaka, A. Sagara, N. Noda, T. Muroga, et.al	Journal of Nuclear Materials (accepted) Journal of Nuclear Materials (accepted)	8	3	5		1
Materials	Microstructure of Creep-deformed V-4Cr-4Ti Strengthened by Precipitation and Cold Rolling	T. Muroga, T. Nagasaka, J.M. Chen, Y.F. Li and H. Watanabe	Journal of Nuclear Materials (accepted)	6	5	13		8
Neutronics	Neutronics investigation of advanced self-cooled liquid blanket systems in the helical reactor	T. Tanaka, A. Sagara, T. Muroga and M.Z. Youssef	Nuclear Fusion,Vol 48,035005 (7pp) (2008)	4	3			
Super-conducting Magnet	Change in Properties of Superconducting Magnet Materials by Fusion Neutron Irradiation The new route process of V3Ga mono-cored and multifilamentary wires using high Ga content Cu-Ga compound and V matrix precursor	A. Nishimura, S. Nishijima, T. Takeuchi, T. Nishitani Y. Hishinuma	Fusion Engineering and Design, Vol. 82, pp. 1555-1560 (2007) Journal of Physics: Conference Series vol.97 no. pp.012131 (2008)	16		7	2	
			Total	37	11	40	8	12

Future plan of FERC

1. Blanket material system
2. Neutronics
3. Magnet material system

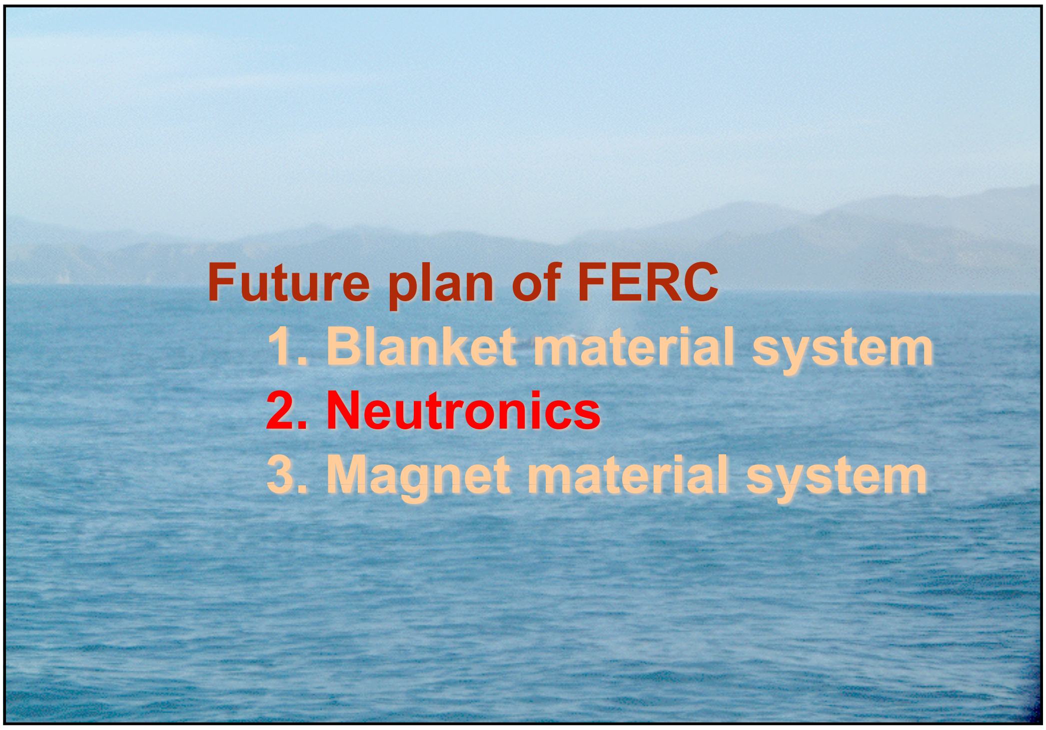
System integration for fuel and heat recovery in blanket

FERC



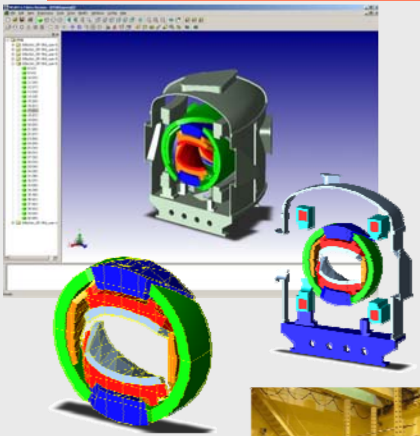
System integration for the feasibility studies on compatibility of **hydrogen recovery and heat exchange** in the flowing system is planed with the use of **Flinak** towards the Demo reactor.

Sagara **25 / 31**



Future plan for neutronics

FERC

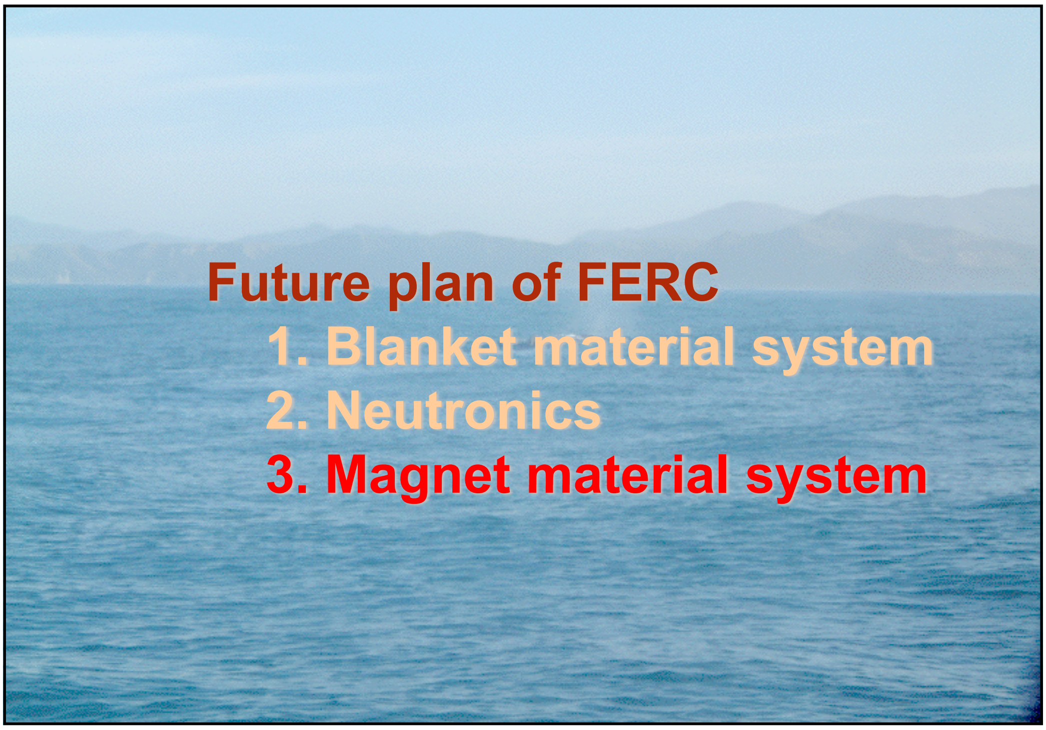


CAD geometry imported
Into conversion system MCAM,
developed by ASIPP, CHINA

Neutronics experiments
on blanket material assembly

- ✓ Each of JA, US, EU and CN groups is making efforts for importing 3-D CAD data into neutronics simulations. But in most cases, using simple surfaces (like plane, sphere, torus, quadratic surfaces etc.) for <u>symmetric geometries.</u>
- ✓ Collaborative studies for importing **CAD data of asymmetric geometries** have been started with ASIPP, China.
  ➔ <u>Treatment of complicated spline surfaces are challenging.</u>
- ✓ Neutronics evaluation and validation by **DT neutron irradiations (at FNS,** JAEA) will be performed on armor, shielding, reflector materials etc.
  ➔ <u>Aiming for mockup test of liquid cooled TBMs in the future</u>

Sagara **27 / 31**



Future plan of FERC

1. Blanket material system
2. Neutronics
3. **Magnet material system**

Future Plan of Superconducting Magnet Technology Research for Fusion

FERC

- Collaborative network for neutron irradiation research will be expanded to different research fields.
  > Next target: In-situ observation during/after neutron irradiation at ~10 K
- Neutron irradiation effect on super-conducting wires, tapes and insulators.
  > Higher radioactive samples will be able to be evaluated at hot lab.
  > All Nb_3Sn strands (11 types) for ITER TF magnet will be tested.
- Development of superconducting conductors and magnet structures for large electro-magnetic force.

Neutron Irradiation system at ~10 K will be installed in JMTR at Oarai.
Conceptual design activity started. (Head; JAEA)

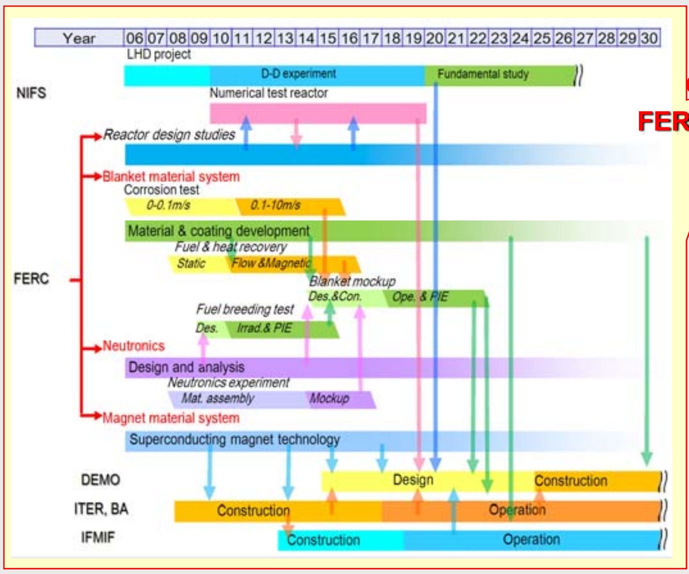
15.5 T superconducting magnet and 500 A current lead will be installed at hot lab in Oarai center of Tohoku Univ.
1.17 M$ was approved by MEXT for 2008, 2009 and 2010. (Head; Tohoku Univ.)

Candidate: Nb_3Al, YBCO, Bi2212, etc. High strength material

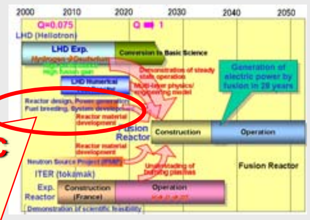
Sagara 29 / 31

Roadmap for FERC to Demo reactor

FERC



FERC



- with applying external resources
- as the COE of collaborations
- with contributing ITER, BA and IFMIF
- and educating Dr. course students.

Sagara 30 / 31

Summary

FERC

1. FERC produced world impacts with broad collaborations in fusion research network
2. On long-life liquid Flibe and Li blanket based on the reactor design, large R&D progress was made on low activation V-alloy and ferritic steel for miniature test, welding, irradiation, corrosion and coating.
3. On neutronics for reactor design, new R&D's have been initiated for a quick-feed back 3D code system and 14MeV irradiation mockup tests.
4. On SC material system, wide R&D progress has been made with collaboration networks on neutron irradiation effects and low activation SC materials.
5. Future plans are addressed for R&D on system integration of liquid breeder blanket, neutronics and SC magnet technology as the COE of collaborations with applying external resources.

Sagara 31 / 31

13 Dec., 2008, Special Review Meeting, Takayama, S. Sakakibara

High-Beta and Related 3D MHD Characteristics

Satoru Sakakibara

National Institute for Fusion Science

Outline

- Motivation
- Subjects of high-beta stellarator/heliotrons
- Results of recent high-beta experiments
  - High beta operation
  - Related physics:
    - MHD equilibrium
    - MHD stability
    - Confinement and transport
- Discussion for realization of reactor
- Summary and the next subject

Motivation

Production of high-β plasma is the common subject in magnetic confinement systems

Production of High-β Plasmas

Transport	MHD Equilibrium	MHD Stability
NC, turbulence etc.	stochastisity etc.	growth of MHD mode etc.

Experimental Verification

↓

Optimization of Configuration

↓

Economical Reactor

Understanding of high-β physics related to β-limit

Tokamak: NTM, RWM, ELM... **Helical**: Stability? Equilibrium? Transport?

Subjects of High-beta Heliotrons

MHD equilibrium, **stability** and **transport** are key issues for production of high-beta plasmas:

MHD Equilibrium:

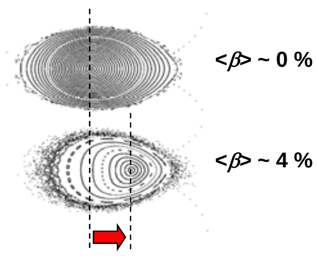
- Change of magnetic topology and relationship with beta-limit
  - Stochastization of peripheral magnetic field lines

MHD Stability:

- Effect of pressure-driven mode (Interchange and Ballooning modes)
  - Magnetic hill in the periphery

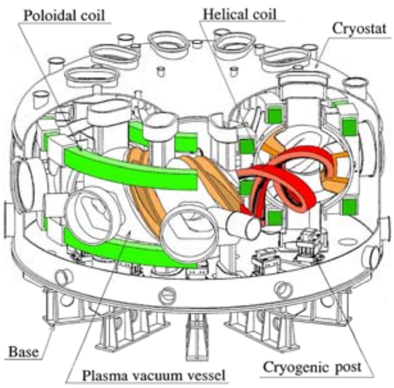
Transport:

- transport related with finite-β effects (magnetic topology, beta and so on)
  - Particle loss due to an increment of helical ripple, turbulence caused by steep ∇p



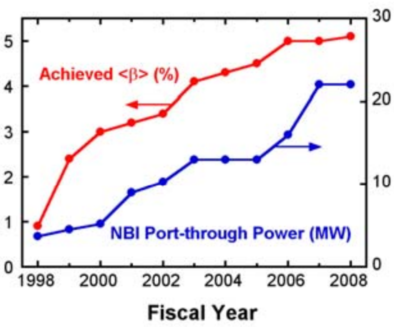
High-β Experiments in LHD

Achieved β has increased year by year, with an increment of heating power and adjustments of magnetic configurations.



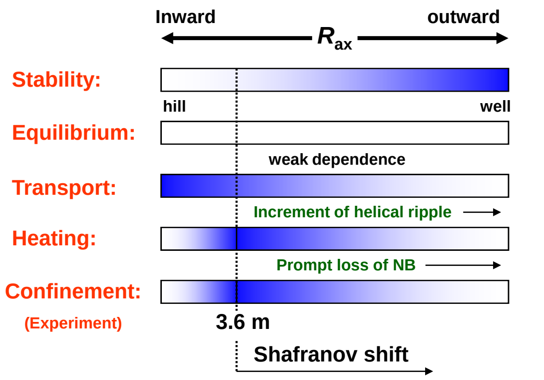
R = 3.9 m, a_{eff} ~ 0.65 m, B_t < 3 T

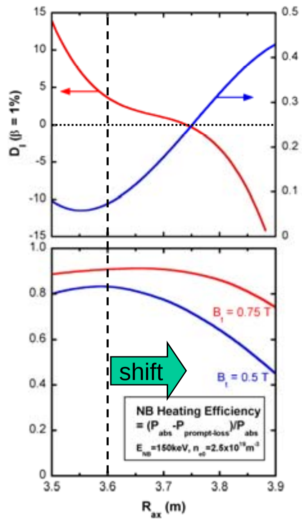
B_t (T)	0.5	0.45	0.425	0.41
A_p	5.8	6.3	6.6	



R_{ax} is a key parameter for high-β

Magnetic axis position is one of configuration parameters characterizing MHD and transport:





Shafranov shift deteriorates transport and heating efficiency, although it is better for stability

→ adjustment of aspect ratio

Plasma Aspect-Ratio

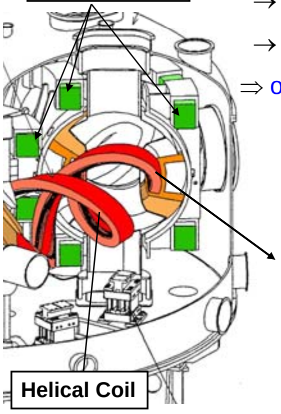
Plasma aspect-ratio can be changed by controlling current center of HC

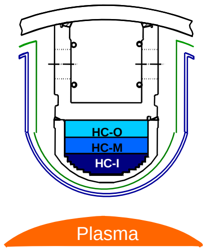
Increment of A_p leads to a reduction of Shafranov shift

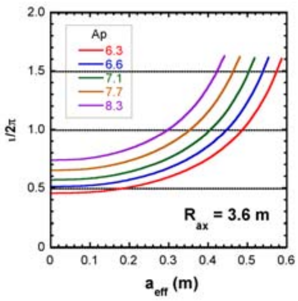
→ favorable for heating efficiency, transport and eq. β-limit

→ enhanced magnetic hill and reduction of magnetic shear

⇒ optimum A_p for high-beta plasma production







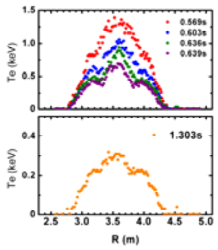
Experiments for A_p Optimization

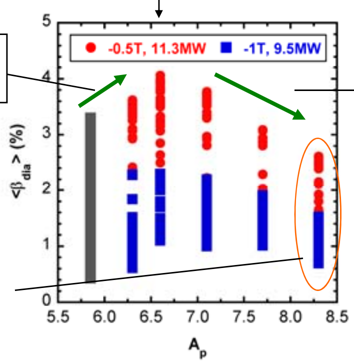
Optimum A_p was found out in the experiments.

Sakakibara S *et al* 2006 *FS&T* **50** 177

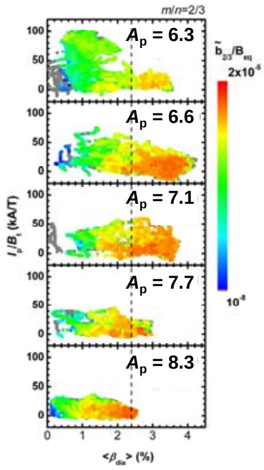
Increment of heating efficiency

Minor collapse caused by m/n = 1/1 mode





Enhanced Edge MHD (m/n = 2/3)



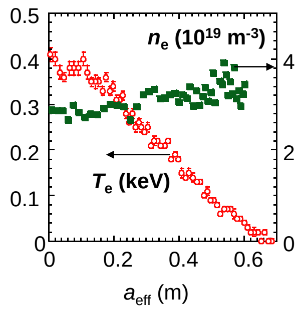
small R_{ax} shift, reduction of ε_{eff}

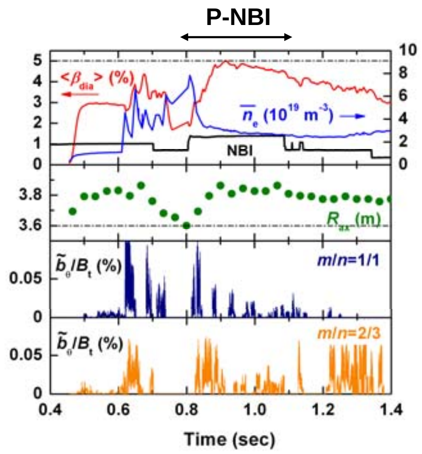
strong shear, weak magnetic hill

High-beta Discharge – Pellet Injection –

- Perpendicular-NBI was applied after several pellets were injected and tangential NBI is turned off which leads to reduction of Shafranov shift.
- MHD activity is not enhanced in high-beta regime with more than 4 %

R_{ax} = 3.6 m, B_t = -0.425 T

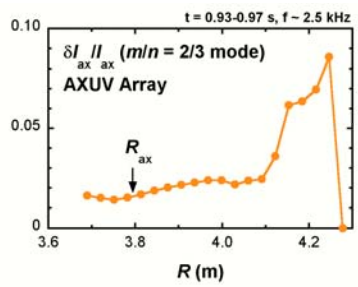


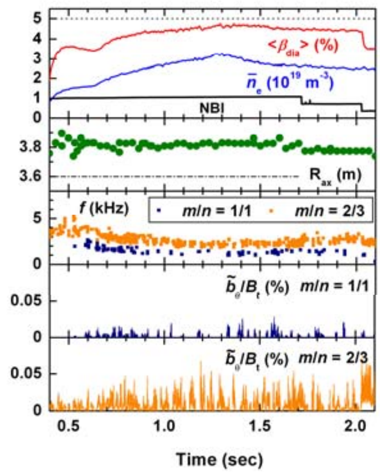


High-beta Steady State Discharge

- $<\beta_{dia}>_{max}$ ~ 4.8 %, β_0 ~ 9.6 %, H_{ISS95} ~ 1.1
- Plasma was maintained for 85τ_E
- Shafranov shift Δ/a_{eff} ~ 0.25
- Peripheral MHD modes are dominantly observed.

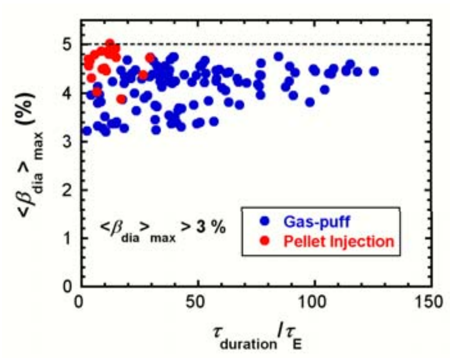
R_{ax} = 3.6 m, B_t = -0.425 T

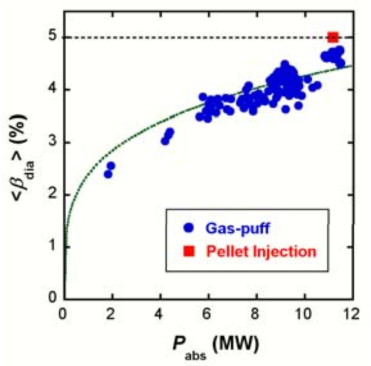




Results of High-β Experiments

- 5.1% plasma was maintained for more than $10\tau_E$, whereas 4.8 % one was for 85 τ_E
- The duration time in gas-puff discharge is limited by NBI
- Beta increases with input power
- No disruptive phenomenon





Sakakibara S *et al* 2008 *Plasma Phys. Control. Fusion* **50** 12 124014

13 Dec., 2008, Special Review Meeting, Takayama, S. Sakakibara

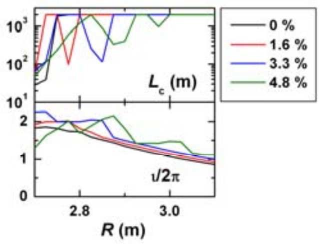
11/32

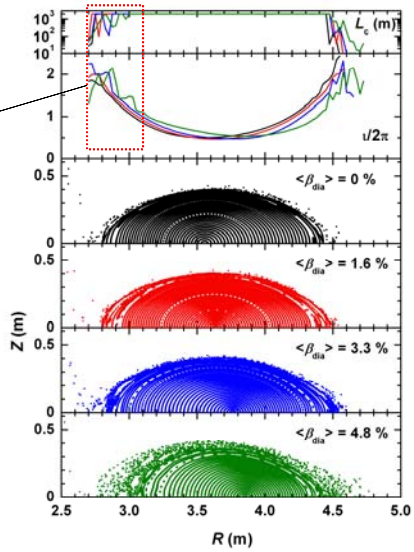
High-β physics related to β-limit

- MHD Equilibrium
- MHD Stability
- Confinement and Transport

How about MHD Equilibrium?

HINT2 Equilibria





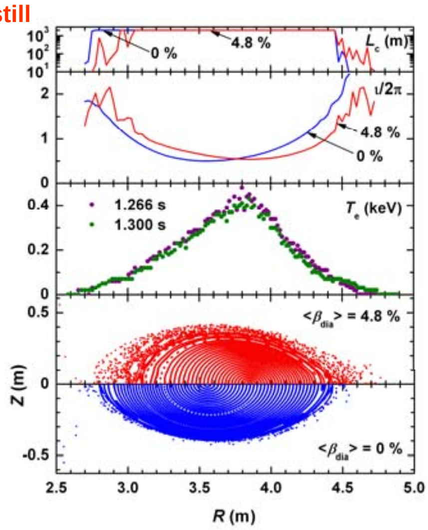
- The connection length in the periphery becomes to be short with the increment of the beta
- The volume inside LCFS is drastically changed at 4.8 %, and the stochasticity erodes from the outer region

Equilibrium in <β>=4.8% Plasma

T_e gradient in the stochastic area is still maintained at 4.8 % plasma

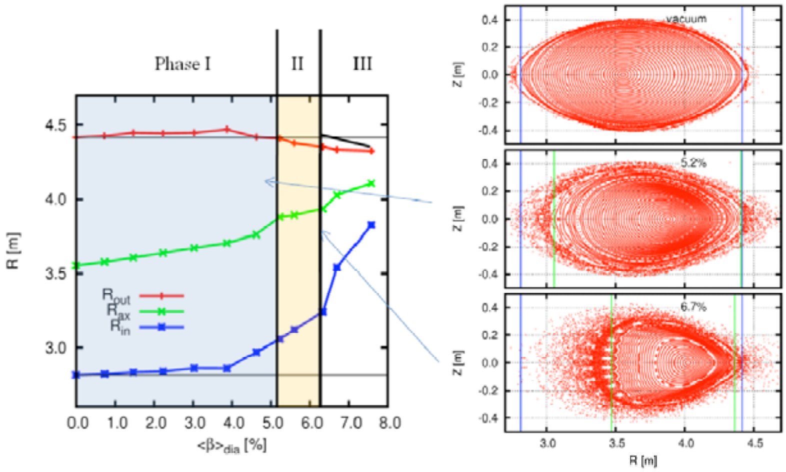
- Inflection points at profile start to appear, corresponding to the LCFS
- The volume inside LCFS is decreased by 32 % compared to the vacuum case

- No degradation of achieved β in the present β range
- It is predicted that the stochastic region is extended further in higher-β range



Prediction of Equilibrium Beta-Limit

Stochastic magnetic field structure penetrates to core?



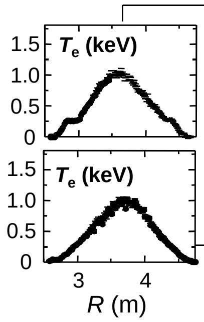
Suzuki Y *et al* 2008 *IAEA FEC2008*

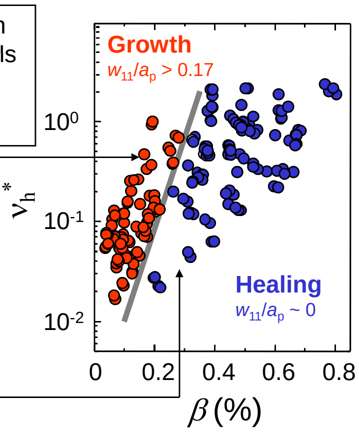
Spontaneous change of Magnetic Islands

- Healing and growth of the magnetic island have been observed in the experiments and are related to collisionality and beta.

External Perturbation given by external coils (m/n = 1/1)

$w_{11}/a_p \sim 0.17$





High-beta (4.8 %)

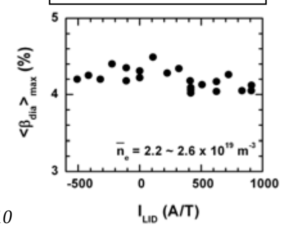
- $\nu_h^* \sim 5$, $\beta \sim 1.8$ %

$\rightarrow$ Healing

$-\tau_R \sim 12$ ms

(T_e = 0.1 keV, L = 0.1 m)

island scan in high-β



Narushima Y *et al* 2008 *NF* ***48*** *7 075010*

Discussion on MHD equilibirum

- **Can pressure and the gradient remain in the stochastic area?**

  → common to ELM-RMP etc.

High-beta plasma

- Perpendicular transport is dominant in high v_h* plasma
- Effects of peripheral MHD activities
- Healing of magnetic island

↑ not included in HINT2 Equilibria! (Bootstrap effect etc.)

- **Avoidance of Equilibrium Beta-limit**

- Real-time Control of Magnetic axis (2008-)

High-β physics related to β-limit

- MHD Equilibrium
- MHD Stability
- Confinement and Transport

How about MHD Stability?

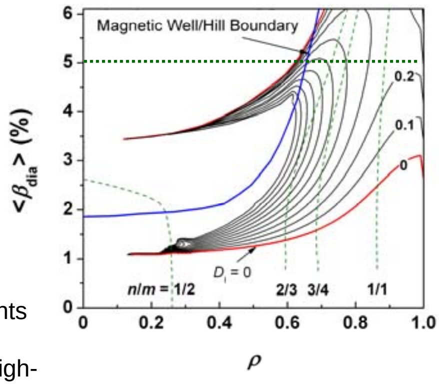
Linear theory

- Mercier criteria are extended to the periphery
- Resistive mode is unstable in the magnetic hill

Experiments

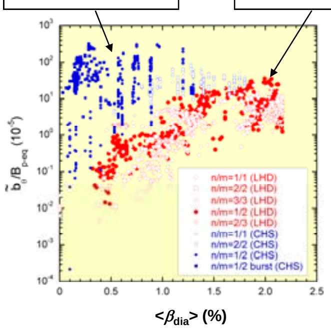
- $\langle \beta_{dia} \rangle$ reached 5.1 %
- Mercier criteria do not limit the operation regime
- Ideal low-*n* mode with less than a certain growth rate is harmless
- Internal and external measurements indicate that dominant low-order modes are excited at $n/m \geq 1$ in high-β regime.

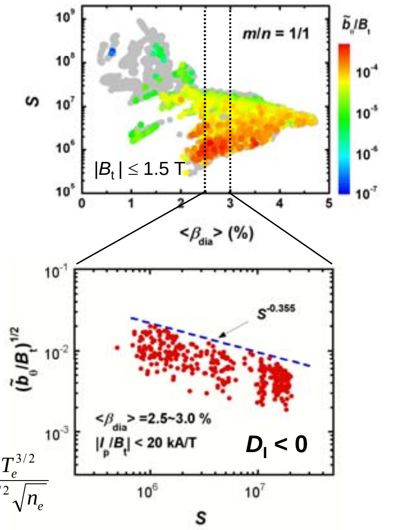
→ characteristics of observed mode



S Dependence of MHD Mode

- Clear *S* dependence of mode amplitude, $w_{MHD} \propto S^{-0.355}$, has been found
- This tendency can be found in the comparison with CHS (low-*S*).





$$S = \frac{\tau_R}{\tau_A} \propto \frac{aBT_e^{3/2}}{ZA^{1/2}\sqrt{n_e}}$$

Sakakibara S *et al* 2001 *NF and* **2006** *FS&T*

Linear Stability Analysis – Resistive mode –

Resistive Interchange Mode (FAR3D)

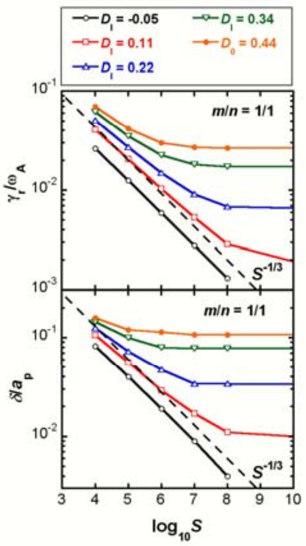
- The growth rate and the mode width is proportional to $S^{-1/3}$ in ideally-stable plasma
- S dependence become to be weak when $D_I > 0$

Experiments:

- $w_{MHD} \propto S^{-0.355}$ at $D_I < 0$
- $D_I \sim 0.1$ at $<\beta_{dia}> = 4.8$ %

→**consistent with experimental results!**

- The observed low-*n* MHD modes are expected to be suppressed in the reactor with high-*S*
- However, ideal mode should be stabilized in order to keep this *S* dependence.



Linear Stability Analysis – Ideal mode –

Mercier Mode

- unstable in the magnetic hill
- $D_{I\text{-max}} \sim 0.25$, $D_I \sim 0.1$ ($\iota/2\pi = 1$)

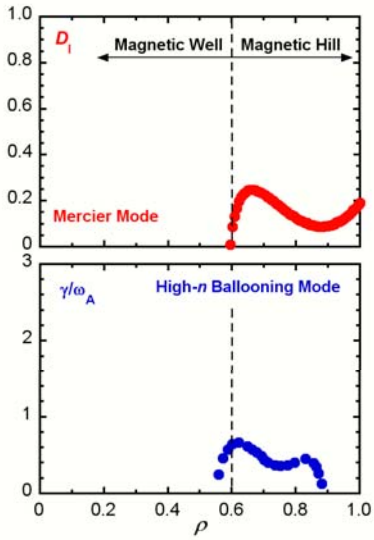
Ideal Low-*n* Interchange Mode (TERPSICHORE[1])

- stable (no mode with $\gamma/\omega_A > 10^{-2}$)
- Threshold $\gamma/\omega_A \sim 10^{-2}$ was obtained through comparison between operational region and calculation

Watanabe K.Y 2005 *Nucl. Fusion* **45** 11 1247

High-*n* Ballooning Mode [2]

- localized in the periphery with magnetic hill and local magnetic shear



[1] Cooper W A 1992 *Plasma Phys. Control. Fusion* **34** 1011

[2] Nakajima N *et al* 2007 *Fusion Sci. Technol.* **51** 79

MHD Database in Stellarator/Heliotrons

Plans for MHD database in stellarator/heliotrons

- Common understanding of characteristics of MHD activity and its effects on profiles and confinement

- Empirical scaling of onset parameters
- Parameter dependence of saturation level of the fluctuation
- Validity of linear stability boundary (D_I, D_R, Low-n alnalysis)

⇒ contribute an extension of free degree of magnetic configurations for reactor design.

- Objects : the **onset parameters** and **fluctuation level** (amplitude)
- Devices: LHD, CHS, Heliotron-J, W7-AS, TJ-II, H-1 etc.
- Kick off : January 2009 ~

Onset and Fluctuation Level of MHD modes

Passive Experiments

- Parameter Dependence

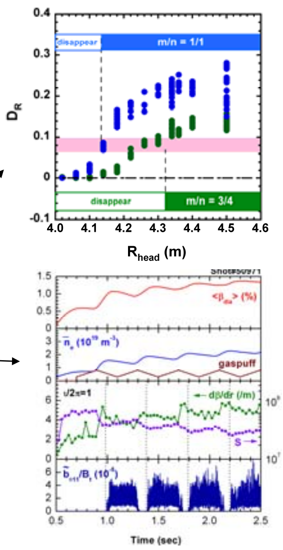
  (S, β, dβ/dr, I_p etc.)
- Configuration Dependence

  (Well/Hill, magnetic shear etc.)

Active Experiments

- ∇p control by movable limiter
- Gas-puff Modulation
- Vertical Field Control by PC (2008-)

  → finding the stability boundary



Sakakibara S *et al* 2006 *Plasma and Fusion Research* **1** 003

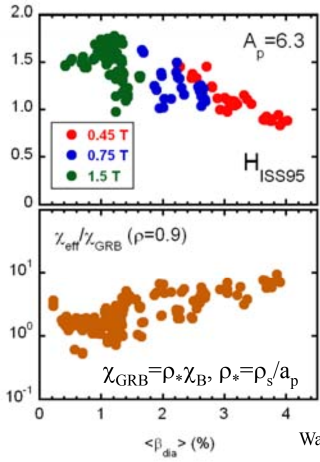
Sakakibara S *et al* 2006 *Plasma and Fusion Research* **1** 049

High-β physics related to β-limit

- MHD Equilibrium
- MHD Stability
- Confinement and Transport

How about confinement and transport?

- Global energy confinement gradually degrades with increasing β
- Reduction of H_{ISS95} is caused by an increment of local transport in the periphery



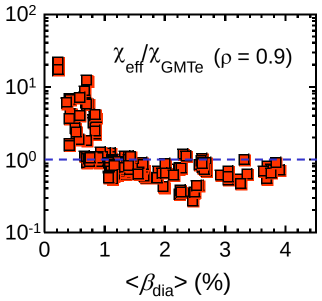
Watanabe K.Y 2005 *Nucl. Fusion* **45** 11 1247

Local Transport and Density Fluctuation

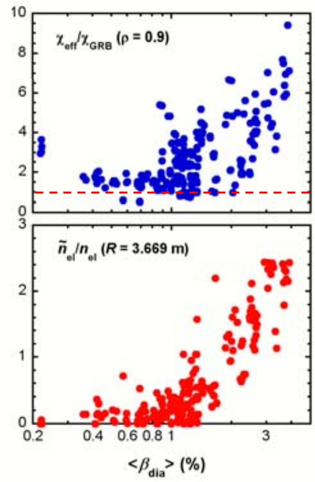
- It is possible to interpret the local transport by using resistive-g mode model

$$\chi_{GMTe} \propto \underbrace{\frac{q}{\hat{s}}(\kappa_n R_0)^{\frac{4}{3}} \frac{a_{eff}}{R_0}}_{\text{geometry}} \underbrace{\left(\frac{\beta R_0}{L_p}\right)^{\frac{4}{3}} S^{-\frac{2}{3}} v_{T_e} a_{eff}}_{\text{plasma}}$$

Carreras B A *et al* 1989 *Phys.Fluids* B1, 1011



- Density fluc. increases with χ



Discussion for Realization of Reactor

From experimental knowledge of LHD...

MHD Equilibrium

- Plasma confinement and achieved β were limited by the stochastization of magnetic field structure in W7-AS (M.C. Zarnstorff, IAEA2002). Erosion of stochastisity from the edge appears in high-β LHD according to HINT calculation.

→ Securing the magnetic surfaces is one of key issues for higher-β.

MHD Stability

- Mercier criteria are not always important for the operation. However, we should know the validity of linear theory on Mercier and ideal low-*n* modes for reactor-design.
- Resistive mode is expected to be suppressed even in the magnetic hill, in reactor-plasma with high-*S* if ideal mode is stable.

Confinement and Transport

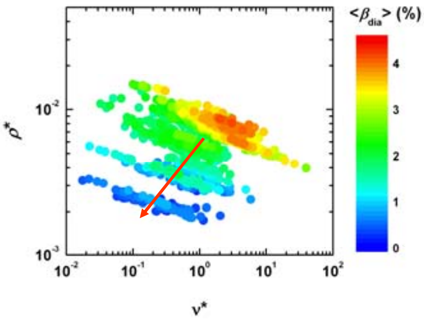
- H_{ISS95} of more than 1 is kept in the β range with ≤ 5 %, whereas reduction of global energy confinement is caused by increasing local transport in the periphery
- If it is caused by the resistive-g mode turbulence, the turbulence is expected to be suppressed by increasing *S* as well as low-*n* mode.
- High-*n* ballooning effect should be clarified.

Summary

- Volume averaged beta value of 5.1 % was successfully obtained in recent experiments and steady-state plasma with 4.8 % was maintained for $85\tau_E$.
- Shafranov shift is smaller than conventional beta-limit. Although it is predicted that an extension of stochastic region due to finite-beta effects, the pressure gradient seems to be still maintained in that area.
- Although low-*n* MHD activities affect local profiles, they do not limit the achieved beta. The saturation of the mode has clear *S* dependence, which is qualitatively consistent with the model of the resistive interchange mode.
- Global energy confinement gradually degrades with beta, which is caused by the increment of local transport in the periphery. The effects of the spontaneous change of the equilibrium, high-*n* ballooning mode and the turbulence on it should be clarified.

Next Subjects related with High-β

- **Production of high-β plasma with more than 5.1 %**
  - Restriction of Shafranov shift are required for maintaining high heating efficiency of NBI and avoiding equilibrium beta limit.
  - Real-time control of R_{ax} by external coils starts in FY2008
  - It is expected to contribute researches related to finite-β effects
- **Search for low-$\rho*$, low-$\nu*$ and high-*S* regime with high-β**
  - Investigation of physics related to high-β in the low-ρ^*, low-ν^* and high-*S* regime is required.



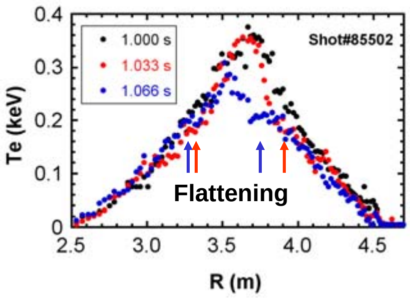
First Trial of R_{ax}-scan experiments

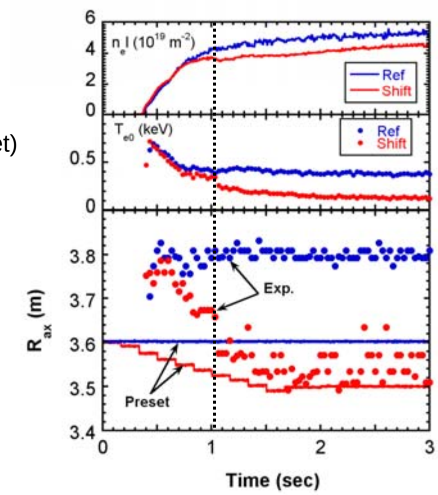
Rapid sweep of R_{ax} induced minor collapse

- Reference:

  R_{ax} = 3.6 m, B_t = -0.425 T, A_p = 6.6

  <β> ~ 4%
- R_{ax} =3.6 m → 3.5 m for 1.4 sec (Preset)
- Collapse : ~ 1.05 sec in core

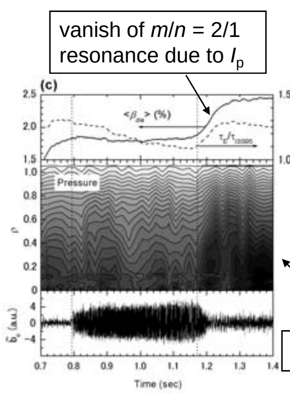


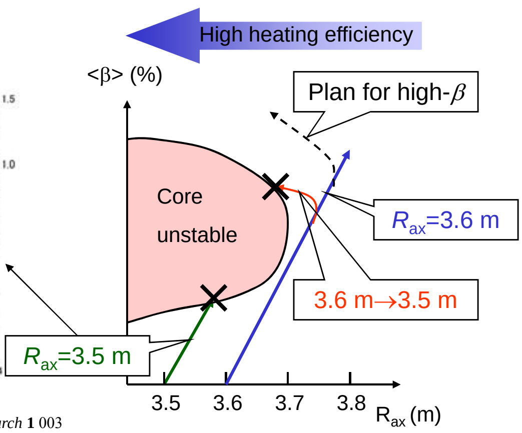


Scenario of High-β operation using R_{ax} control

How to sweep R_{ax} is a key for an access to higher-β regime

- enter the plasma to "second stable" regime → stable and good heating!
- clarify "actual" unstable regime experimentally → understanding of physics!





Sakakibara S *et al* 2006 *Plasma and Fusion Research* **1** 003

3-7 High Density Operation and Its Prospect for Helical Reactor

December 13, 2008
HIDA Earth Wisdom Center, Takayama

NIFS Special Review Meeting by Advisors and Foreign Researchers in FY 2008

High Density Operation and Its Prospect for Helical Reactor

LHD Project, National Institute for Fusion Science

Ryuichi Sakamoto
National Institute for Fusion Science

Contents

❖High density / high performance discharges in LHD
- Internal Diffusion Barrier (IDB) formation in LHD
- Sustainability of pellet fueled high performance plasma

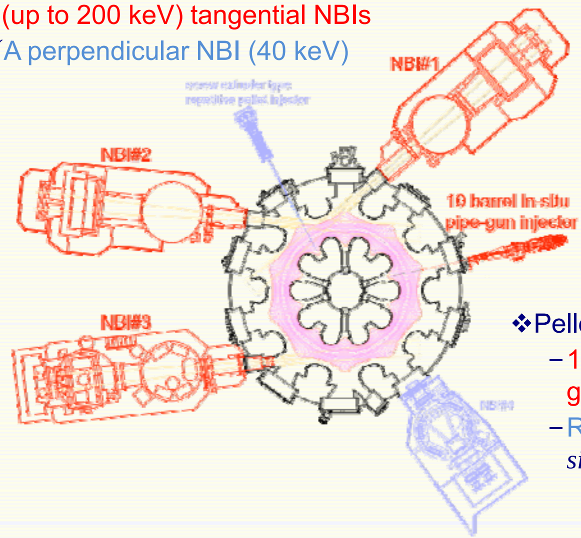
❖Feasibility of IDB scenario for helical reactor
- Power balance calculation with plasma profile effects
- Prospect of pellet refueling for fusion reactor

Particle control in fusion reactor

- ❖Core fueling plays a primary role in a future fusion reactors in which magnetically confined burning plasma is sustained by its own α particle heating.
  - –High priority issue
- ❖Pellet injection is one of the best solution for core fueling at this time.
  - –Direct particle supply capability to the inside of LCFS
  - –Negligibly low energy requirement for core fueling
- ❖Experimental study aiming at high performance plasma that is compatible with core fueling has been performed in LHD.

Large Helical Device (LHD) and pellet injectors

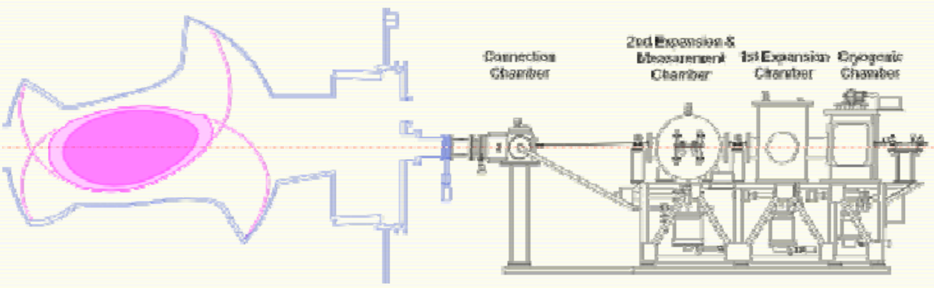
- ❖Neutral beam heating (NBI)
  - ✓Three negative ion based high energy (up to 200 keV) tangential NBIs
  - ✓A perpendicular NBI (40 keV)



- ❖Pellet injectors
  - –10 barrels *in-situ* pipe-gun injector, *since 1998*
  - –Repetitive pellet injector, *since 2002*

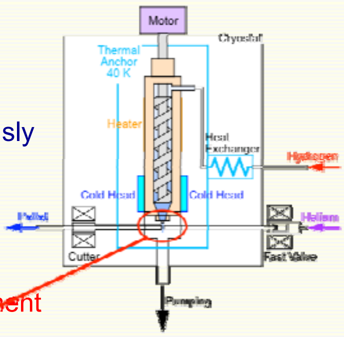
10 barrels *in-situ* pipe-gun injector

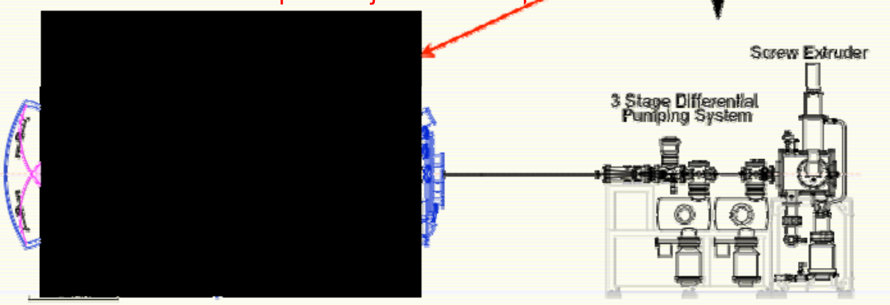
- ❖Number of Barrels: **independent 10 barrels**
- ❖Pellet Size: **3.4 mmϕ×3.4 mmL**, (optional: 1.0 mmϕ – 4.8 mmϕ)
- ❖Pellet velocity: **1200 m/s**, (optional: 100 m/s – 1200 m/s)
- ❖Materials: **Hydrogen**, (optional: Neon, Neon doped hydrogen)
- ❖Pumping of Propellant gas : **3 stage differential pumping system**
- ❖The world's first liquid-He free pellet injector with a pair of cryo-coolers



Repetitive pellet injector with screw extruder

- ❖Pellet Size: **3.0 mmϕ×3.0 mmϕ**
- ❖Injection Frequency: up to **11 Hz**
- ❖Steady state operation
  - –Liquefaction and solidification is simultaneously processed with solid hydrogen extrusion
  - –Continuous production of solid hydrogen rod
  - –55 mm/s extrusion for 3.0 mm rod
  - –liquid-He free with a pair of cryo-coolers
  - –Contribution to ITER pellet injector development





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  - –Internal Diffusion Barrier Formation in LHD
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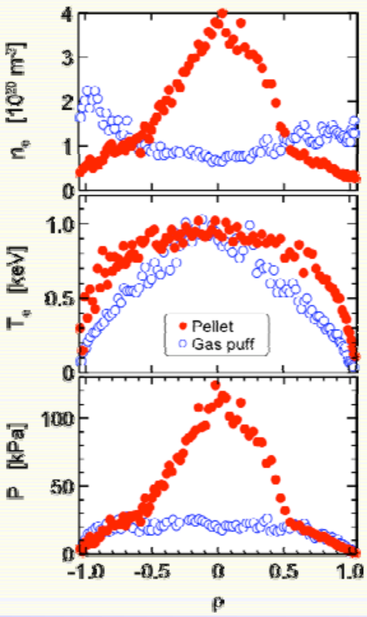
What's Internal Diffusion Barrier?

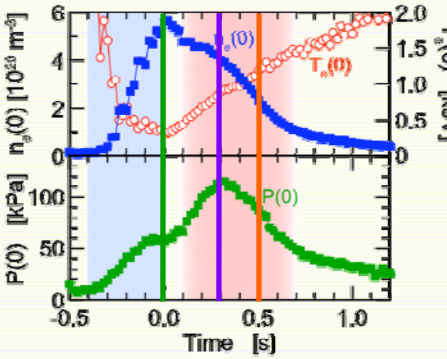
- ❖High-density improvement mode in LHD
  - –Characterized by steep density gradient
  - –Enables core plasma to access a high-density/high-pressure regime
  - –Reproducibly obtained by employing intensive multi-pellet injection
- ❖Characterize particle transport property
- ❖Explore operational limit of the IDB plasmas

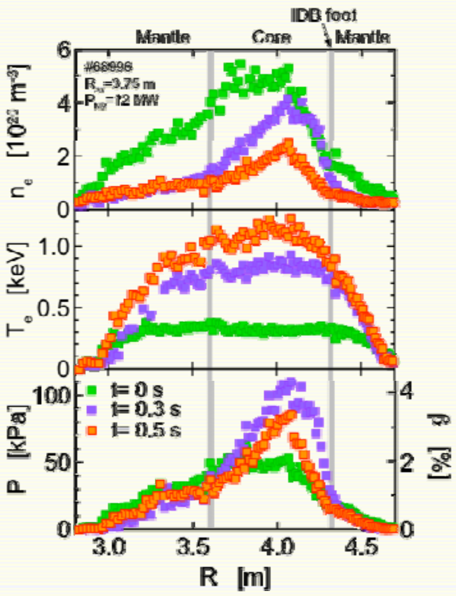


How to make the IDB

- ❖Intensive multi-pellet injection
- ❖IDB formation in Density decay phase

Temperature recovery rate
∨
Core density decay rate





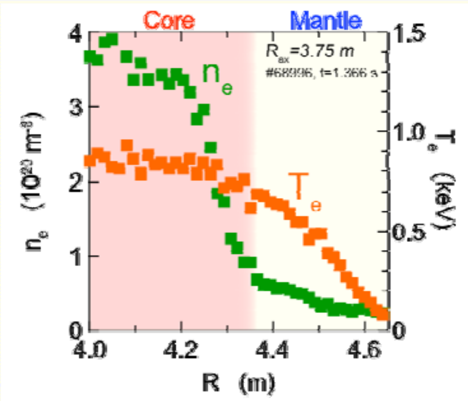
Particle transport property of IDB plasmas

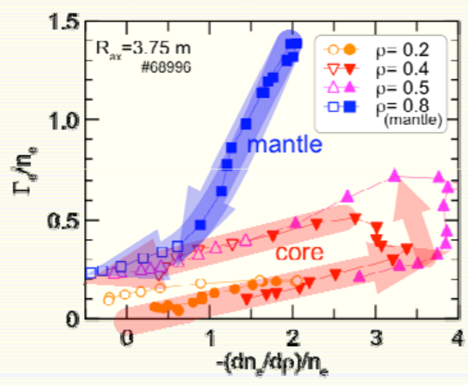
❖Particle transport coefficient of IDB plasma is estimated from relationship between time evolution and gradient of density profiles.

$$\Gamma_e = -D_e \frac{\partial n_e}{\partial \rho} + n_e v_e$$

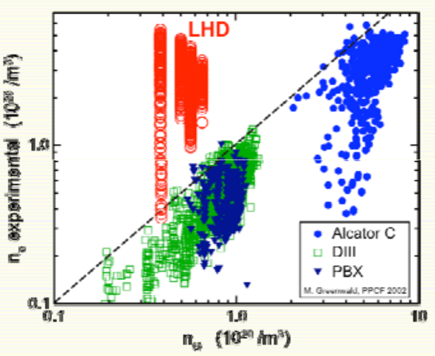
$$Y = D_e X + v_e$$

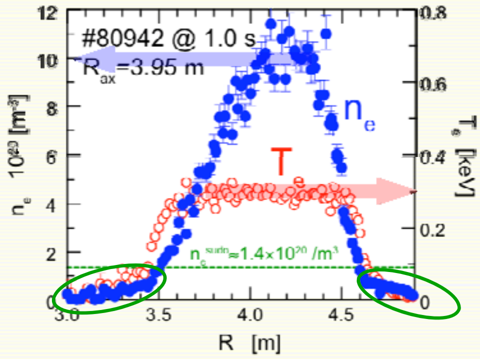
where
$$\begin{cases} X = -\dfrac{1}{n_e}\dfrac{\partial n_e}{\partial \rho} \\ Y = \dfrac{\Gamma_e}{n_e} = \dfrac{\int (S_e - \frac{\partial n_e}{\partial t})dV}{n_e A} \end{cases}$$





High density achievement with pellet fueling





❖The maximum attained central density is >1×10^{21} m^{-3} at B_t = 2.5 T

❖Low density mantle plasma prevent radiation collapse

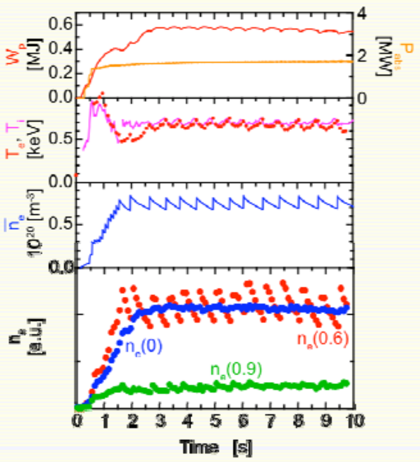
❖Attainable density is restricted by power balance.

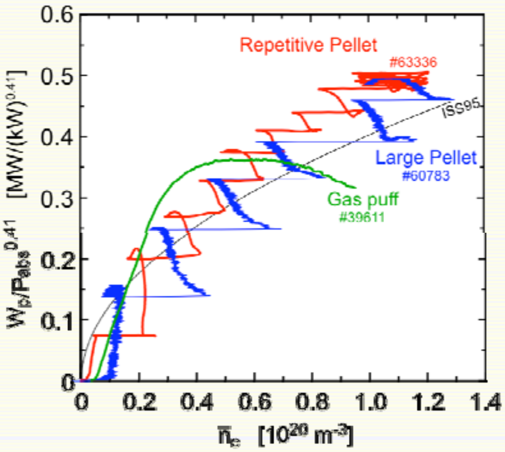
- Lack of central heating power due to high density put a ceiling on attainable density
  - ✓Pellet cannot ablate effectively at low temperature plasma (<300 eV)

Quasi stationary sustainment of pellet refueled plasma

❖Constant central density and temperature are sustained quasi-stationary by using repetitive pellet injection. (<1.2×10^{20} /m^3)

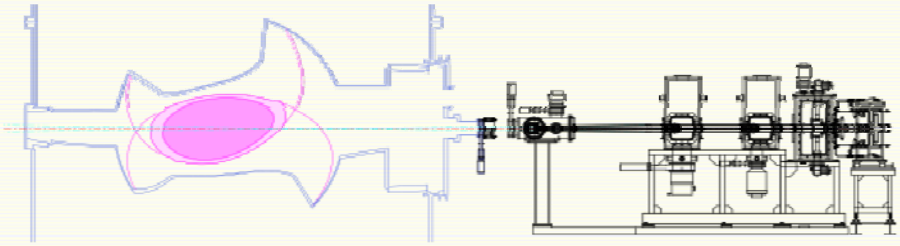
❖Larger mass are required in order to sustain high density IDB plasma. (> 5.0×10^{20} /m^3)





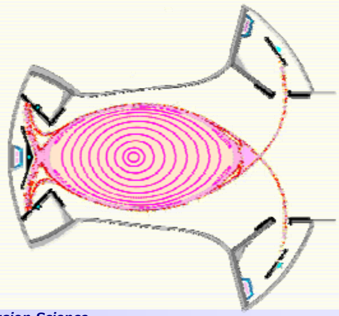
New facilities for high density sustainment experiments

❖20 barrels in-situ pipe-gun pellet injector (under development)



❖Closed helical divertor (under design)

- Active pumping capacity corresponding to throughput of massive pellet fueling
- Steady state heat removal capability



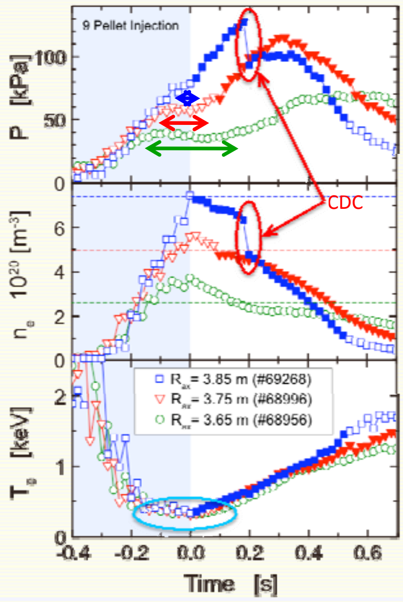
Operational Limit of IDB Plasmas

❖Lack of central power deposition

- High density plasma inhibit NB penetration to the core
  - ✓put a ceiling on attainable density due to ineffective pellet ablation
  - ✓slackened growth state of the pressure rise in high density regime
- Efficient central heating is key to extend operational regime

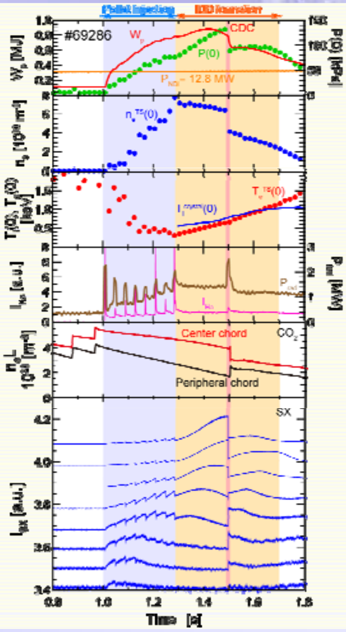
❖Core density collapse (CDC) event

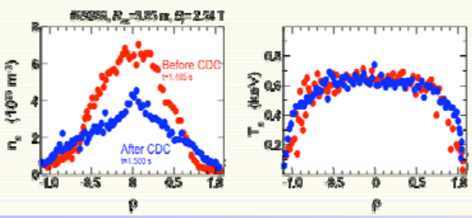
- Core density is abruptly expelled at high pressure regime.



IDB (High-central β) Discharge with CDC

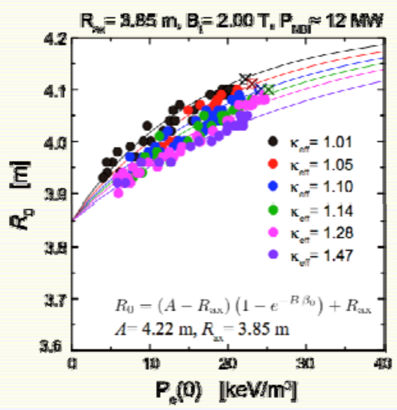
- ❖CDC is an abrupt event where the core density is collapsed within 1 ms.
  - –much faster than other MHD relaxation events in LHD
- ❖Mechanism of the CDC has not been clarified.
- ❖Potential solution: Suppression of Shafranov shift
  - –Vertical field control (inward shift)
  - –P-S currents suppression
    - ✓Aspect ratio (reduce minor radius)
    - ✓Ellipticity (vertical elongation)

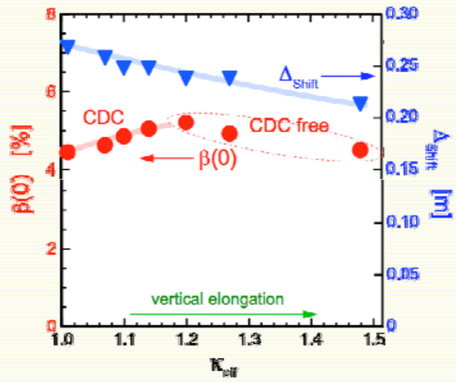




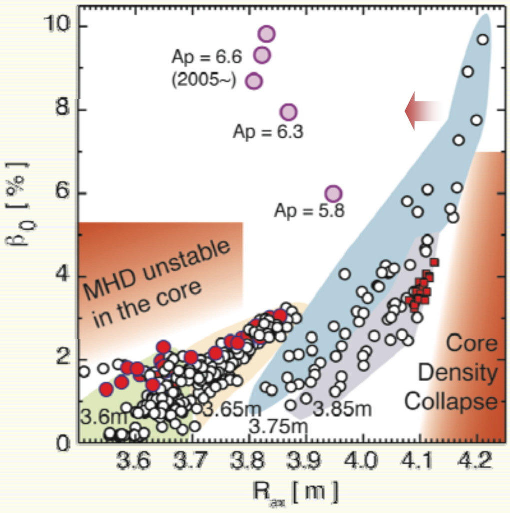
Suppression of Shafranov Shift by Vertical Elongation

- ❖Vertical elongation is effective to suppress the Shafranov shift
  - –CDC limits central pressure for κ< 1.2
  - –CDC disappears when κ> 1.2
  - –Higher central beta has been achieved under CDC free condition





Operation Regime of high-beta plasmas



❖MHD activity and CDC event should be avoided in order to form a high-central-beta plasmas

– Inward R_{ax}: core-localized MHD
– Outward R_{ax}: CDC

❖The control of the magnetic axis is the key

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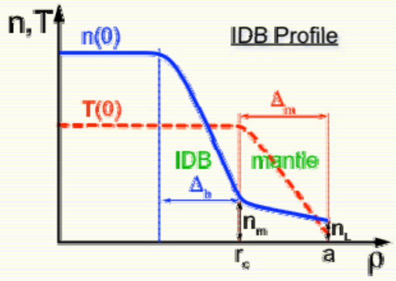
Model Calculation with Plasma Profile Effect

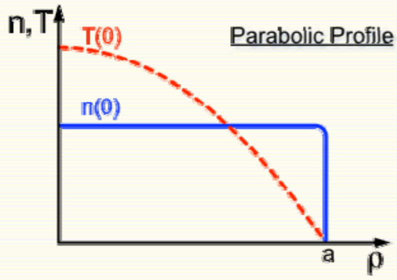
❖General parameters

- Major / Minor radius: 15 m / 2.3 m
- Magnetic field: 8 T
- Z_{eff}: 1.5
- Improvement factor: 1.2



❖Model Profiles

- IDB Profile (Core fueling):
  - ✓ Δm=0.4, Δb=0.3, $n_m=1\times10^{20}$ m^{-3}
- Parabolic profile (Peripheral fueling):
  - ✓ n=n(0), T=T(0)(1-ρ^2)



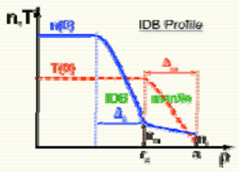
Power Balance and Ignition Condition

❖Alpha heating: $P_\alpha = \int \frac{n^2}{4}\langle\sigma v\rangle Q_\alpha dv$

❖Bremsstrahlung loss: $P_b = 1.5\times10^{-38}\int Z_{eff}^2 n^2\sqrt{T}dv$

❖Confinement loss: $P_L = \frac{3\int Tndv}{F_H\tau_E^{ISS95}}$ (for Parabolic profile)

$$P_L = (n_m\chi_m\frac{dT}{dr} + 5T(0)D_b\frac{dn}{dr})S$$



$$n_m\chi_m\frac{dT}{dr} \gg 5T(0)D_b\frac{dn}{dr}$$

$$\frac{D_b}{\chi_m} \ll \frac{n_m\Delta_b}{5(n(0)-n_m)\Delta_m} = 0.03$$

(IDB condition)
D_b< 0.15 m^2s^{-1}
χ_m< 5 m^2s^{-1}

$$P_L = n_m\chi_m\frac{dT}{dr}S$$ (for IDB profile)

❖Ignition Condition: $P_\alpha - P_b - P_L \geq 0$

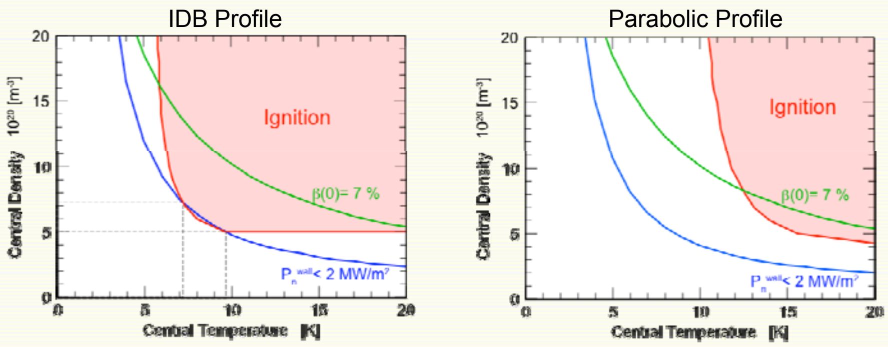
Operational Regime

❖Ignition regime: $P_\alpha - P_b - P_L \geq 0$

❖IDB profile allow access to ignition condition with lower temperature.

– Bremsstrahlung loss is suppressed

– T(0)= 7 ~ 10 keV, n(0)= 5 ~ 7 × 10^{20} m^{-3}



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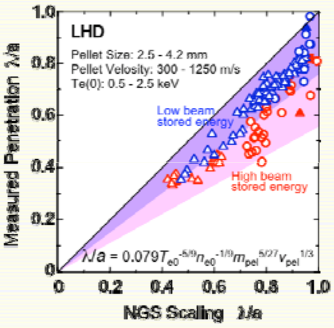
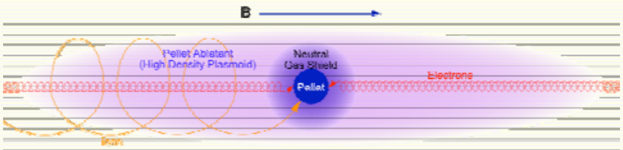
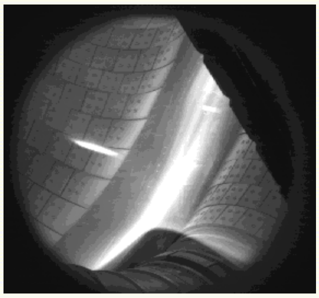
Validity of NGS pellet Ablation Model

- ❖Neutral Gas Shielding (NGS) Models
  - Ablated materials (pellet ablatant) shield the pellet from a background plasma
  - Electron heat flux dominate the pellet ablation
    - ✓energy flux to the ablatant
    - ✓cross section in the ablatant
  - □ particles have less impact on the pellet ablation.



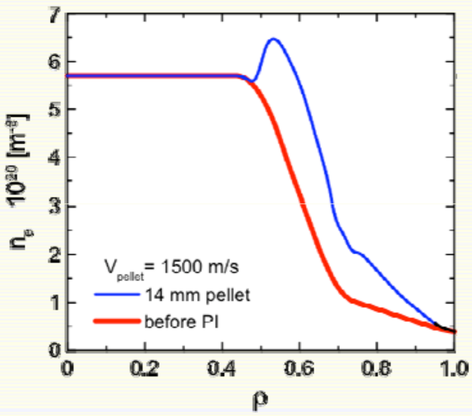
- ❖The NGS models can explain the pellet penetration in LHD.





Pellet refueling to fusion plasma

- ❖Pellet penetration to large scale IDB plasma is estimated by using NGS pellet ablation code.
  - Major / Minor radius: 15 m / 2.3 m
  - $T_e(0)$= 7.0 keV, $n_e(0)\approx 6\times 10^{20}$ /m^3, IDB profile
  - Fueling rate $N_{pellet}/N_{plasma}\approx 0.2$ (same fueling rate as LHD experiment)
- ❖Pellet penetrate to ρ≈ 0.5 under feasible pellet velocity.
  - Relatively low temperature operation allow the pellet penetration
  - High density operation allow the large pellet injection and it compensates for reduction of penetration depth due to high temperature.
  - Compatibility with core fueling



Summary

- ❖Internal Diffusion Barrier (IDB) has been reproducibly obtained by using intensive multi-pellet injection.
  - Enables core plasma to access very high-density/high-pressure regime
  - Core diffusivity is kept at low level even high-density regime
- ❖Quasi stationary sustainment of high-density/high-performance plasma has been demonstrated by using repetitive pellet injection.
  - In order to extend operational regime to higher density, active divertor pumping is required in addition to higher throughput pellet injection.
- ❖LHD experiment suggest the high density operation is suitable for helical system.
  - High density scenario enables a realistic reactor design which is compatible with core fueling.

Turbulent Transport and Zonal Flows

T.-H. Watanabe
National Institute for Fusion Science /
The Graduate University for Advanced Studies (Sokendai)
Toki, Gifu, JAPAN

Thanks to: H. Sugama, S. Ferrando-Margalet, M. Nakata, O. Yamagishi, S. Satake, K. Tanaka, H. Yamada, and W. Horton

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Outline

- Introduction
  - Zonal flows, ITG instability, GKV code
- Zonal flow response in tokamak and helical plasmas
- GKV simulations of ITG turbulence in tokamak and helical plasmas
- Recent results of gyrokinetic theory and simulation studies at NIFS
- Summary and future directions

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Introduction

Zonal flows, ITG instability, GKV code

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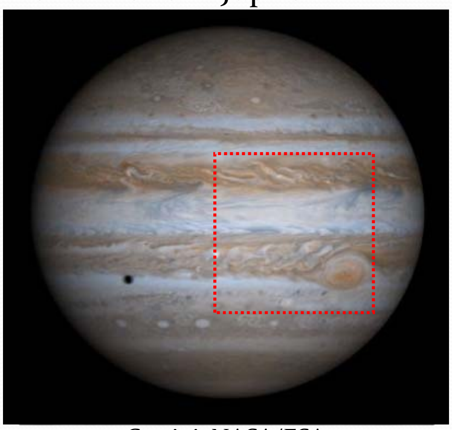
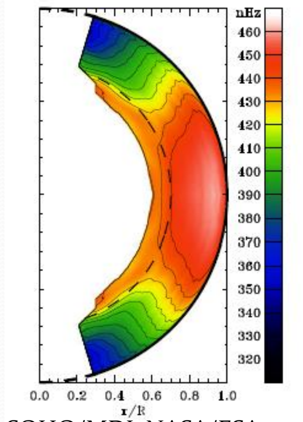
Zonal Flows in Nature

Zonal Flows in Jupiter



Cassini, NASA/ESA

Differential Rotation in Sun



SOHO/MDI, NASA/ESA

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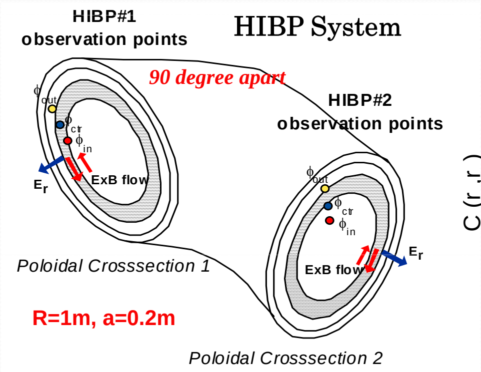
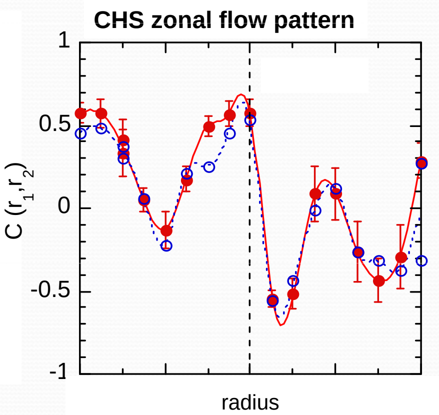
Identification of Zonal Flow in Fusion Plasma





A. Fujisawa et al., PRL **93** 165002 (2004)

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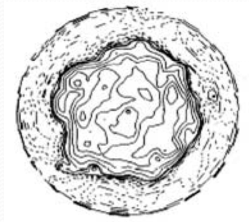
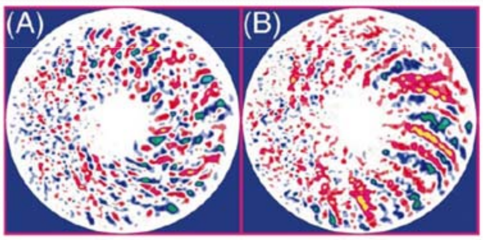
Zonal Flows and Turbulence in Fusion Plasma Simulations

- Zonal flows have been found in various types of plasma turbulence simulations.
  - A pioneering work by Hasegawa & Wakatani for zonal-flow generation in turbulence (upper)
  - Gyrokinetic simulation of toroidal ITG turbulence by Lin et al. (lower)



Hasegawa & Wakatani, PRL **59**, 1581 (1987).



Lin et al., Science **281**, 1835 (1998).

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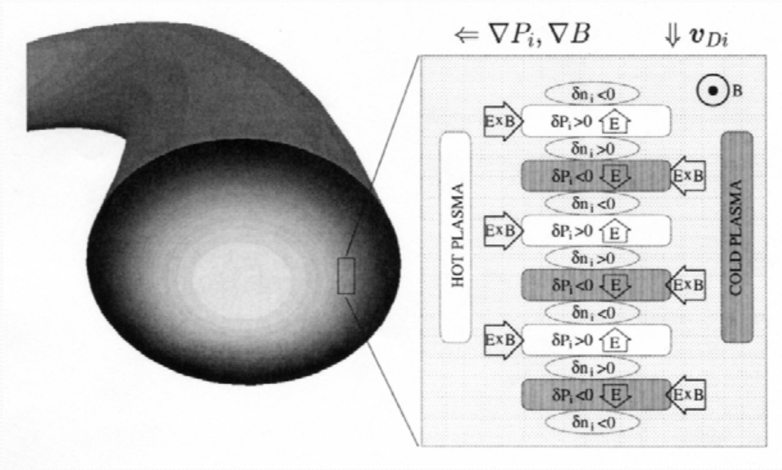
Mechanism of Toroidal ITG Mode



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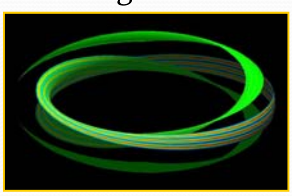
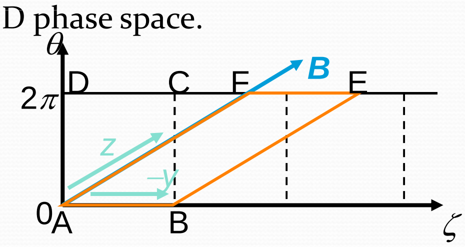
Gyrokinetic Simulation Code, GKV

- Nonlinear gyrokinetic equation for perturbed ion gyrocenter distribution δf is numerically solved in the five-dimensional phase space, $(x, y, z, v_{||}, \mu)$

$$\left[\frac{\partial}{\partial t}+v_\parallel \hat{\mathbf{b}}\cdot\nabla+\mathbf{v}_d\cdot\nabla-\mu(\hat{\mathbf{b}}\cdot\nabla\Omega)\frac{\partial}{\partial v_\parallel}\right]\delta f+\frac{c}{B_0}\{\psi,\delta f\}=(\mathbf{v}_*-\mathbf{v}_d-v_\parallel\hat{\mathbf{b}})\cdot\frac{e\nabla\psi}{T_i}F_M+C(\delta f)$$

  - Adiabatic electron response, flux tube geometry.
  - Electrostatic potential is given by the quasi-neutrality
  - High resolution of 5-D phase space.





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Zonal-flow response in tokamak and helical plasmas

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Zonal Flow Response in Tokamak

- Rosenbluth and Hinton (1998) derived a response function (kernel) of zonal flow in a tokamak.
- A residual zonal flow remains after the Landau-damping of geodesic acoustic mode (GAM).

$$K = \frac{\left\langle \phi_{k_x}(t=\infty) \right\rangle}{\left\langle \phi_{k_x}(t=0) \right\rangle} \approx \frac{1}{1+1.6q^2/\varepsilon^{1/2}}$$

- The response function describes how strongly the zonal flow is generated by a given source term
- Standard benchmark test of gyrokinetic codes

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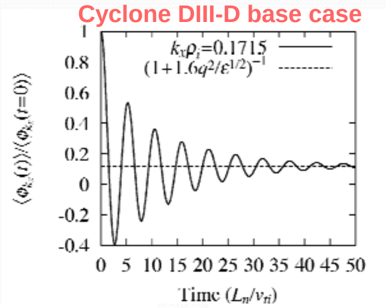
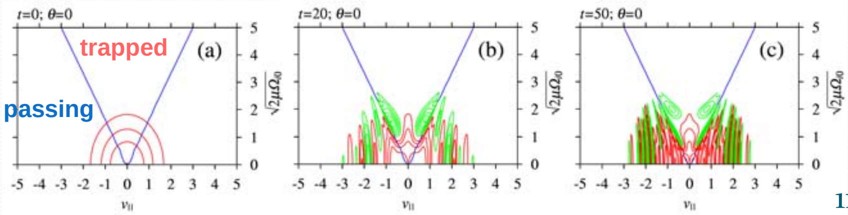
GKV Simulation of Zonal-Flow Response in Tokamak

- Zonal flow potential asymptotically approaches the residual level after the Landau damping of GAM.
- The damping rate agrees with theory with finite k_r

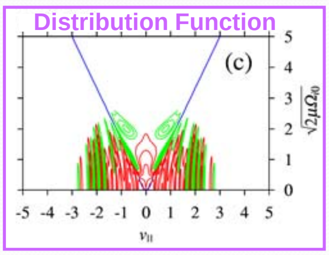
[Sugama & Watanabe, JPP 2006].

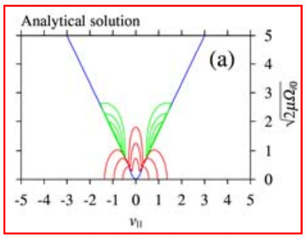


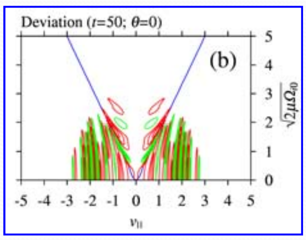


Velocity-Space Structures of δf in Response to Zonal Flow

- We have found that distribution function consists of two parts, (a) coherent and (b) ballistic components.





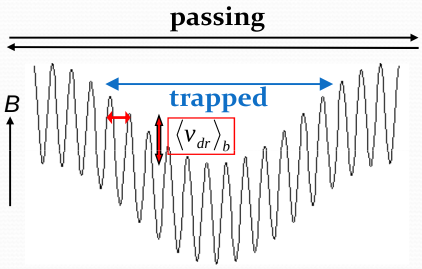


- The coherent part sustains the residual zonal flow.

[Sugama & Watanabe, NF 2006]

Effect of Helical field on Zonal Flow

- Radial drift motion of helical-ripple-trapped particles leads to additional shielding effect of zonal flow.
- Gyrokinetic theory and simulation suggest increase of zonal flow response in the neoclassically-optimized helical systems.
  - Sugama & Wataanbe, PRL 2005
  - Ferrando, Sugama & Watanabe, PoP 2007



Classification of particle orbits in helical system

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GK Theory of Zonal-Flow Response in Helical Systems

- Theoretical analysis of zonal-flow response by R.-H. has been extended to helical systems.

Long-time Response Function

$$\mathcal{K}_L(t) \equiv \frac{1 - (2/\pi)\langle(2\epsilon_H)^{1/2}\{1 - g_{i1}(t,\theta)\}\rangle}{1 + G + \mathcal{E}(t)/\left(n_0\langle k_\perp^2 a_i^2\rangle\right)}$$

- Reduction of helical-ripple-trapped particle's drift improving the neoclassical transport also enhances the zonal-flow response !

Sugama & Watanabe, PRL 2005, PoP 2006

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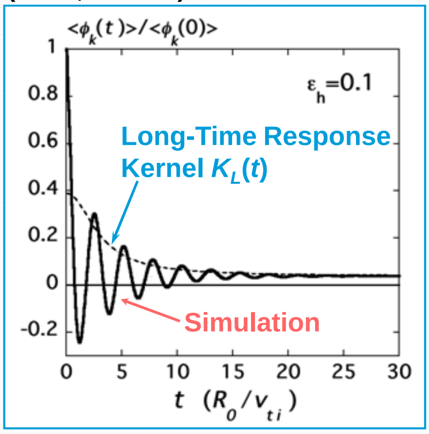
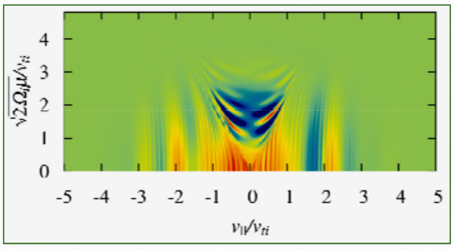
GKV Simulation of Zonal-Flow Response in Helical Systems

(L = 2, M = 10)



(q = 1.5, ε_t = 0.1, $k_r a_i$ =0.131)

- Radial drift of helical-ripple-trapped particles makes mean negative part of δf.



Velocity distribution function for θ=8π/13 at t = 6.23 R_0/v_{ti}.

Sugama & Watanabe, PRL 2005, PoP 2006

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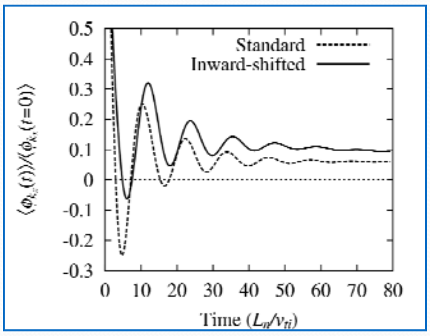
Higher Zonal-Flow Response in Inward-Shifted LHD Plasma

- Parameters are taken from LHD experimental results.
- Higher zonal-flow response is obtained for the inward-shifted LHD plasma which has lower neoclassical ripple transport.
    - A possible scenario of turbulent transport reduction in the I.-S. case.



Watanabe, Sugama & Ferrando, PRL 2008
Ferrando, Sugama & Watanabe, PoP 2007

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GKV simulations of ITG turbulence in tokamak and helical plasmas

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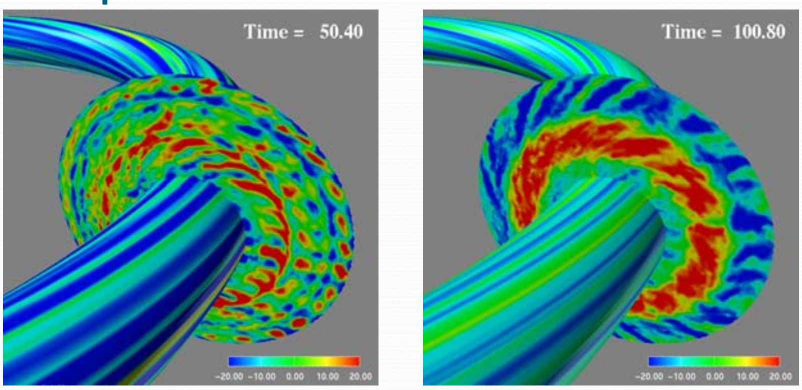
GKV Simulation of ITG Turbulent Transport in Tokamak



- ITG turbulence and zonal flows with broad spectrum in a statistically steady turbulent state

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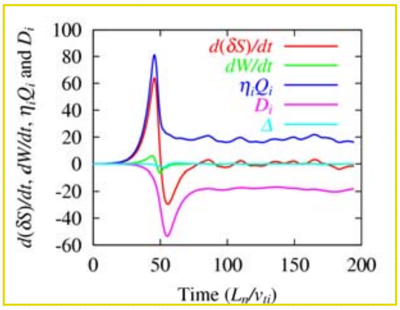
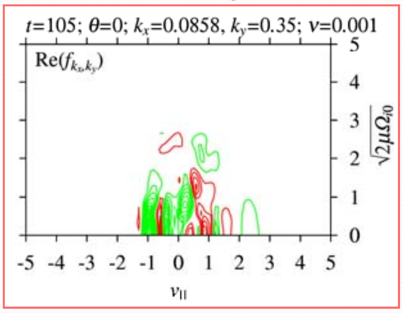
Confirmation of Entropy Balance in Toroidal ITG Turbulent Transport





- Steady transport flux is obtained with the entropy balance satisfied.
- Fine velocity-space structures of δf are generated in the toroidal ITG turbulence.

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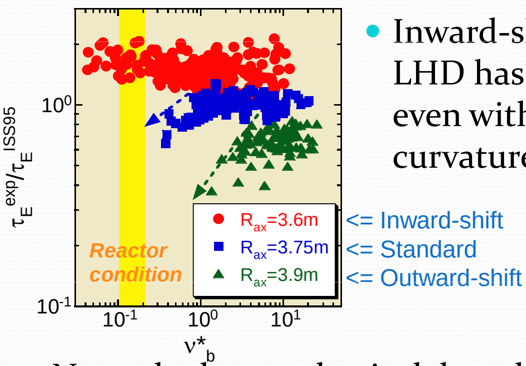
Better Confinement found in Inward-Shifted LHD Plasma



- Inward-shifted configuration of LHD has better confinement even with unfavorable field-line curvature (Yamada et al.).

- Not only the neoclassical, but also the anomalous transport is improved in the inward-shifted LHD configuration.

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Possible Scenario of Transport Reduction for Helical Plasmas

- Inward-Shifted LHD plasma is optimized for reducing the neoclassical ripple transport.
- Slower radial drift motions of helical-ripple-trapped particles lead to higher zonal-flow response.

  <= zonal-flow response analysis
- Then, stronger zonal flows can be generated by turbulence in the inward-shifted case.
- Thus, we expect anomalous transport reduction in the inward-shifted LHD Plasma.

  The conjecture needs to be verified by gyrokinetic simulations of turbulent transport.

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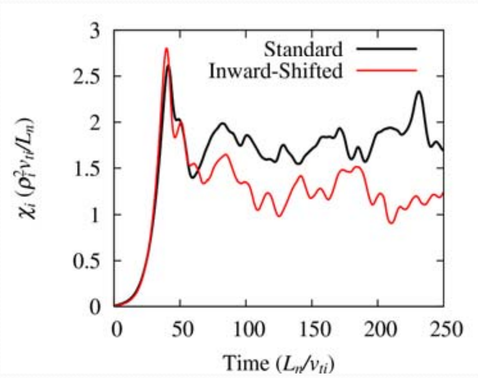
Inward-Shifted Case Shows Lower Ion Heat Transport

- GKV simulation of ITG turbulence for the inward-shifted case shows reduction of the ion heat transport by stronger zonal flows.
- This tendency is consistent with the LHD experiments as expected.



Time-history of χ_i obtained by the GKV simulations of the ITG turbulence in the LHD configurations.
(Watanabe, Sugama & Ferrando., PRL 2008)

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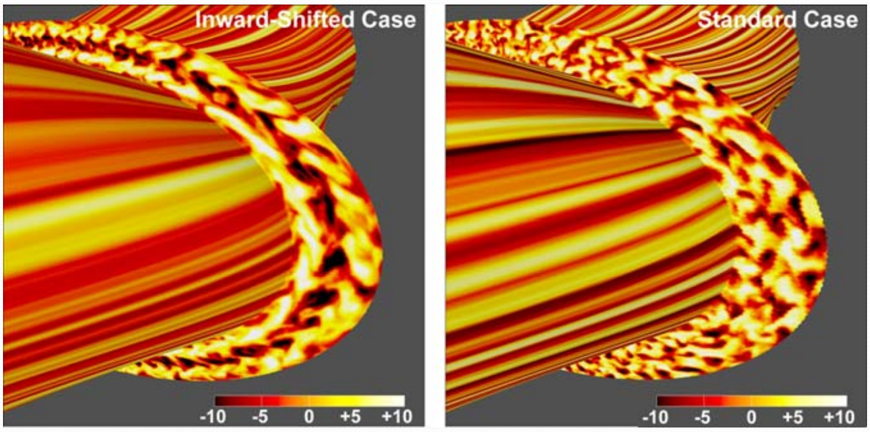
Stronger Zonal flows are Generated in Inward-Shifted Configuration



GKV simulation results of electrostatic potentials at t=120
(Watanabe, Sugama & Ferrando, PRL 2008)

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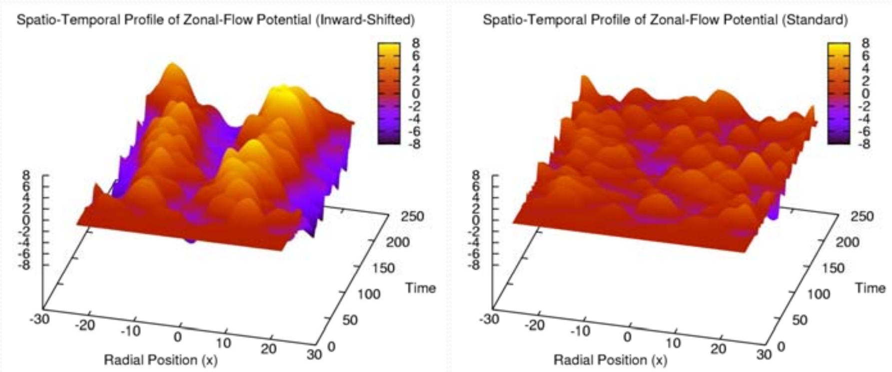
Zonal-Flow Structure is Clearly Found in Inward-Shifted Case



Spatio-Temporal Profiles of the Zonal-Flow Potential

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Recent results of gyrokinetic theory and simulations at NIFS

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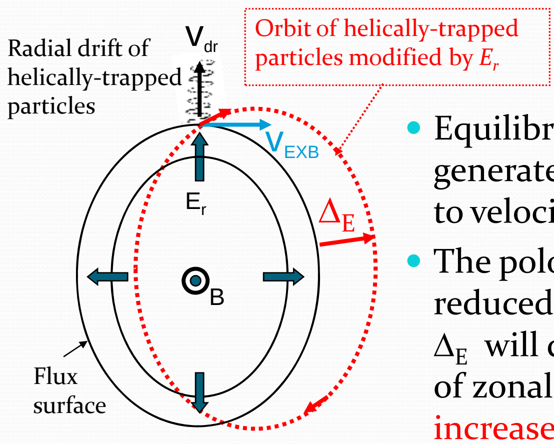
Effects of Equilibrium-Scale E_r on Zonal-Flow Response



- Equilibrium-scale E_r field generates an *ExB* component to velocity.
- The poloidal *ExB* rotation with reduced radial displacement Δ_E will decrease the shielding of zonal-flow potential and increase its response !

(Mynick & Boozer, PoP 2007)

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GK Theory of Zonal-Flow Response with Equilibrium-Scale E_r

- Equilibrium-scale E_r associated with the neoclassical transport in helical systems also enhances zonal flows.
- Shielding of helically-trapped particles with poloidal angular frequency $\omega_\theta = - cE_r/rB$ is given by

$$\mathcal{E}_{Er} = \frac{15}{8\pi}(2\epsilon_h)^{1/2}(k_r a_i)^2 \left(\frac{\epsilon_t v_{ti}}{r\omega_\theta}\right)^2 \left(1+\frac{T_e}{T_i}\right)$$

- Collisionless long-time limit of zonal-flow response kernel:

$$\mathcal{K}_{Er} = \frac{1}{1+G+\mathcal{E}_{Er}/(k_r a_i)^2} = \left[1+G+\frac{15}{8\pi}(2\epsilon_h)^{1/2}\left(\frac{\epsilon_t v_{ti}}{r\omega_\theta}\right)^2\left(1+\frac{T_e}{T_i}\right)\right]^{-1}$$

Sugama, Watanabe & Ferrando, PFR 2008

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Extension of GKV Code to Poloidally Global Model

- GKV code is recently extended to the poloidally global model for studying the E_r effect on zonal flows in helical systems.
- Flux coordinates (Ψ_T, α, ζ) with $\alpha = \theta - \iota\zeta/2\pi$
- Field-line label α dependence of $|B|$

$$B = B_0\left[1-\varepsilon_t(r)\cos(\alpha+\iota\zeta/2\pi)-\varepsilon_l(r)\cos(l\alpha+(\iota l/2\pi - M\zeta))\right]$$

- Gyrokinetic equation for zonal flows with E_r

$$\left[\frac{\partial}{\partial t}+v_\parallel\hat{\mathbf{b}}\cdot\nabla+i\mathbf{k}_r\cdot\mathbf{v}_d-\mu(\hat{\mathbf{b}}\cdot\nabla\Omega)\frac{\partial}{\partial v_\parallel}+\omega_\theta\frac{\partial}{\partial\alpha}\right]\delta f = -i\mathbf{k}_r\cdot\mathbf{v}_d\frac{e\langle\psi\rangle}{T_i}F_M$$

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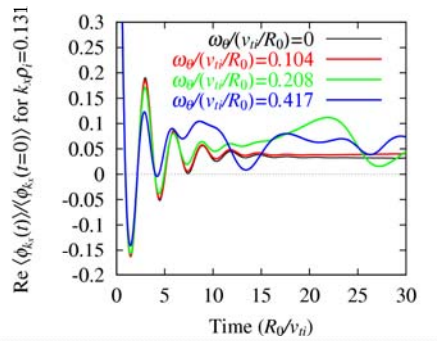
GKV Simulation of Collisionless Zonal-Flow Damping with E_r

- GKV simulation of collisionless zonal-flow damping with E_r has been carried out.
- Equilibrium-scale E_r contributes to enhancement of zonal flow response after the initial GAM damping.



Time-history of zonal flow potential for different E_r.

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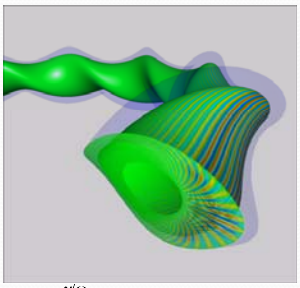
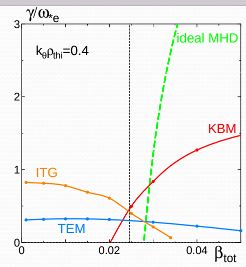
Linear Gyrokinetic Stability Analysis by Using GOBLIN Code



- Linear stability of Electrostatic (drift wave) /electromagnetic (MHD-like) modes can be investigated.
- Electrons/ions (circulating, trapped) can be treated with the same computation load (eigenvalue code).
- Complicated magnetic configuration (helical/shaped tokamak) with various n/T profiles can be treated.



[by O. Yamagishi]

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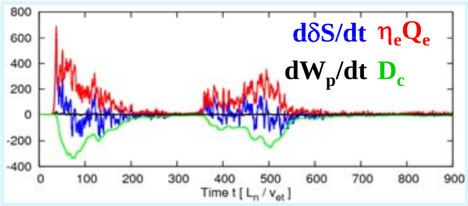
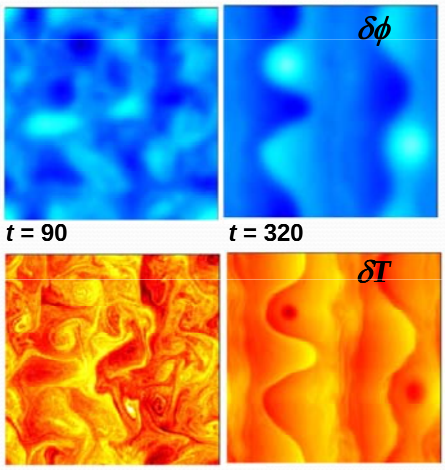
Transition of ETG Vortex Structures and Electron Heat Transport



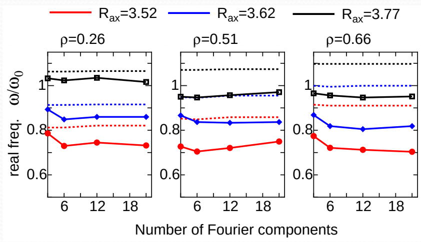


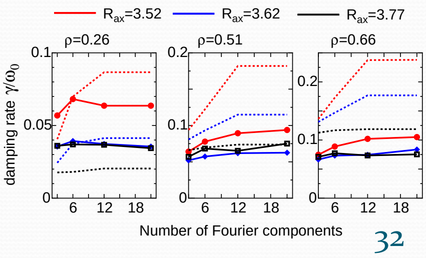
- Reduction of turbulent transport associated with self-organized vortex structures is found in gyrokinetic simulations of slab ETG turbulence.

[Nakata, Watanabe, Sugama & Horton, APS/DPP 2008] 31

Drift Kinetic Simulation of GAM Oscillation in LHD Plasmas

- Dependence of GAM on R_{ax} is compared between drift kinetic transport code (FORTEC-3D) and the analytic formula.
- VMEC equilibrium is used.
- Inward shift ⇒ lower GAM frequency & higher damping rate.
- Higher-(m,n) components of B spectrum, also enhance GAM damping on outer flux surface.





Satake, Sugama &Watanabe, NF 2007

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Summary and future directions

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Summary

- We have investigated ITG turbulent transport and zonal flows in tokamak and helical systems:
  - GK theory of zonal flows and GAM is successfully confirmed by GKV simulations.
  - GKV simulations fully resolving df in 5-D phase space made the first step in simulation studies of turbulent transport in LHD plasmas.
- Coupling of the neoclassical and anomalous transport through zonal flows appears in helical systems.
- The synergetic studies of theory and simulation should be further promoted.

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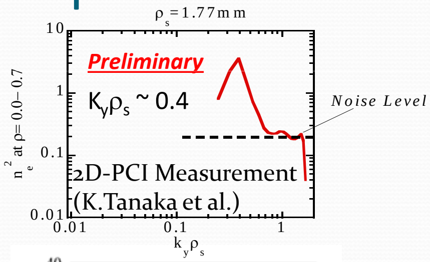
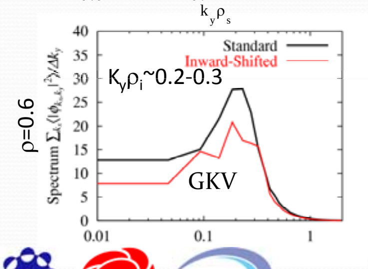
Collaborations with LHD Experiments and other GK groups





- Preliminary comparison with experiments
- Collaborations with LHD experimental group will be further promoted.
- International collaborations for benchmarking helical gyrokinetic codes are in progress.

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Future Extensions of GKV Code

- Introduction of geometry and equilibrium parameters that are more relevant to LHD experiments
- ITG turbulence simulation with equilibrium radial electric field => Isotope effect
- Electron dynamics
  - ITG/TEM turbulence with non-adiabatic electron response
  - Effects of finite-collisionality
  - ETG turbulence in helical plasmas
- Development of global gyrokinetic simulation code

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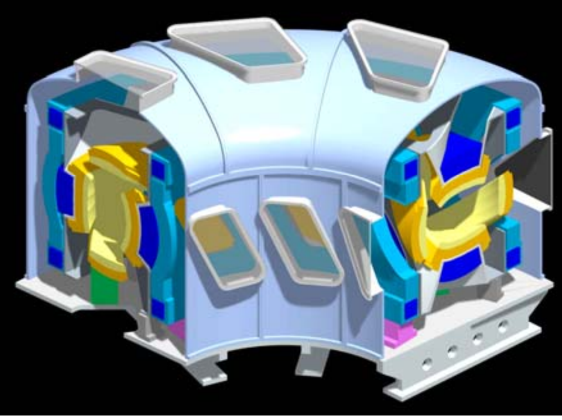
Development of long-life liquid blanket

Takuya Nagasaka

NIFS-FERC staff: Akio Sagara, Takeo Muroga, Arata Nishimura, Yosimitsu Hishinuma, Teruya Tanaka, Masatoshi Kondo



1. Introduction: NIFS and Japanese universities focus on liquid breeder blanket

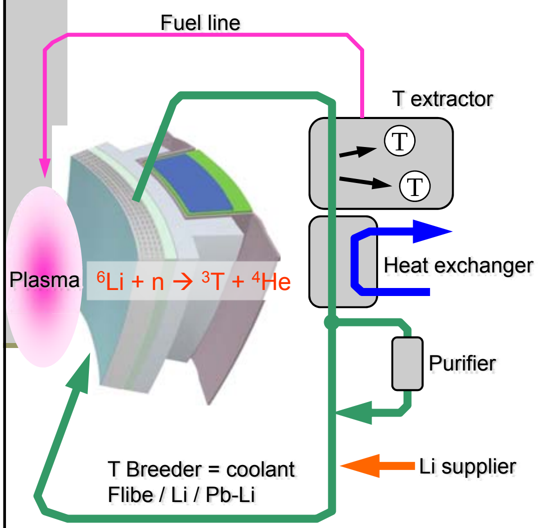
Type	T breeder	Coolant	Structure	ITER-Day-1st TBM	DEMO design
Solid breeder blanket	Li_2TiO_3 etc.	H_2O	RAF steel	WCSB (JP)	A-SSTR (JP)
	Li_2TiO_3 etc.	He	RAF steel	HCSB (JP, EU, KO)	I-HCPB (EU)
	Li_2TiO_3 etc.	He	SiC ceramic		DREAM (JP) A-HCPB (EU) ARIES-I (US)
Liquid breeder blanket	Flibe	Flibe	RAF steel		FFHR (JP)
	Flibe	Flibe	V alloy		FFHR-FV (JP)
	Li	Li	RAF steel	HCML (KO)	HCML (KO)
	Li	Li	V alloy		FFHR-LV (JP) ARIES-RS (US)
	Li-Pb	H_2O	RAF steel		WCLL (EU)
	Li-Pb	He	RAF steel	HCLL (EU) DFLL (CH)	DCLL (EU)
	Li-Pb	Li-Pb	RAF steel		ARIES-ST (US)
	Li-Pb	Li-Pb	SiC ceramic		TAURO (EU) ARIES-AT (US)

Organization in Japan

- JAEA (solid breeder blanket)
- Universities – Collaboration – NIFS (liquid breeder blanket)

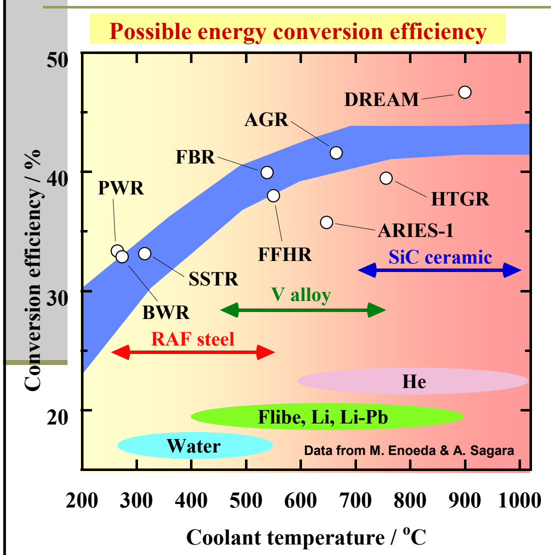
- Water-cooled solid breeder (WCSB) blanket is recognized to be the most feasible with the current technology
- The other blankets are more attractive for power plant, but require more database and challenging technologies

Liquid breeder blanket can be simple, and provide thermal efficiency and operation efficiency



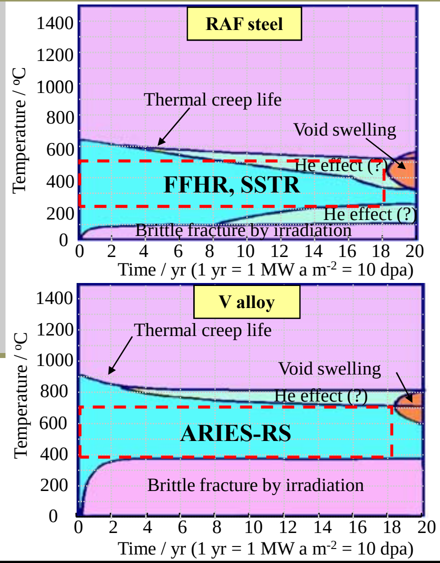
- Simple structure
  - T breeder itself can be coolant in liquid breeder blanket
- On-time control of breeder
  - Purity and composition of breeder is controlled outside the blanket
  - Li is continuously supplied outside blanket during operation
- High thermal efficiency and operation efficiency are possible
- Key technology
  - Consistency of T extraction with heat exchange
  - Purification
  - Materials

Energy conversion efficiency is determined by material operation temperature



- Possible energy conversion efficiency of blanket is increased with coolant temperature
- Liquid breeder blanket can obtain higher efficiency than water-cooled blanket
- Coolant temperature is limited by operation temperature for structural materials
- RAF steel is the 1st candidate because of its industrial maturity
- V alloy and SiC ceramics are recognized as advanced materials for higher efficiency blanket

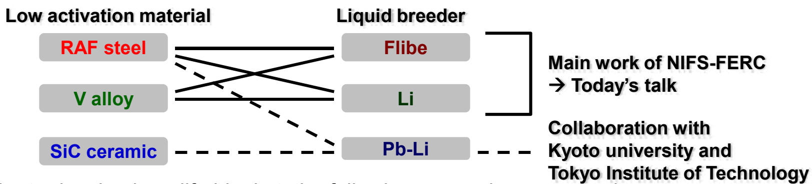
Material design window defines the operation temperature and lifetime of blanket



- Design window shows possible operation temperature and lifetime for low activation materials
- The possible operation condition is enclosed by the following material properties
- Higher limit temperature
  - Thermal creep
  - He effect
  - Void swelling
- Lower limit temperature
  - Brittle fracture by irradiation
- Followings are potential limitation, but not included in the current design window
  - Brittle fracture at welds
  - Material corrosion by coolant

2. Purpose and contents

- NIFS-FERC have been focusing on the liquid breeder blanket



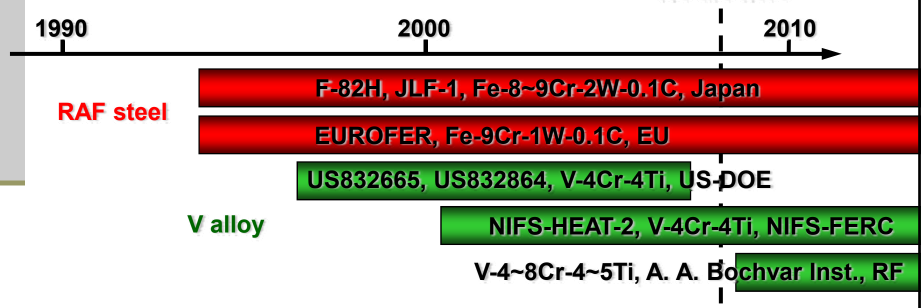
- In order to develop long-life blanket, the following researches are ongoing

Limitation for operation temperature and lifetime	RAF steel	V alloy
Thermal creep	Ongoing	Ongoing
He effect	IFMIF	IFMIF
Void swelling	Universities	Universities
Ductility loss by irradiation in weld metal	JAEA	Ongoing
Corrosion by Flibe / Li	Ongoing	Ongoing

- Purpose of the present study
  - To evaluate material property
  - To clarify mechanism for property degradation and improvement
  - To obtain guiding principle for long-life material

3. Welding: Large-heat projects of RAF steels and V alloys lead to welding study

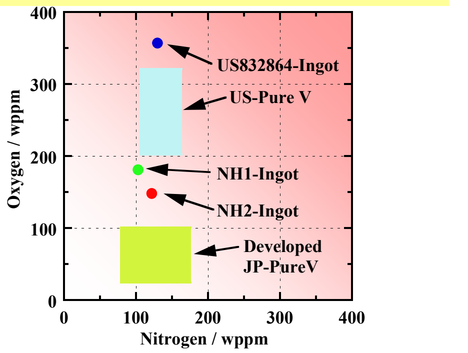
- Blanket construction requires various shape product fabrication (plate, tube and rod) and welding technology for low activation materials
- Large-heat projects provided these products to world institutes for Round Robin tests including welding study
- Large heat more than 100 kg in the world



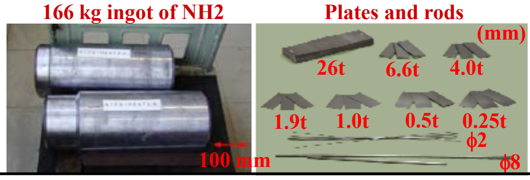
- NIFS-FERC have been taking part in the Round Robin tests for RAF steels
- NIFS-FERC promoted an initiative for large-heat project of V alloy

High purity metal vanadium was developed for V alloy large heats

Oxygen and nitrogen impurity in V alloy large heats

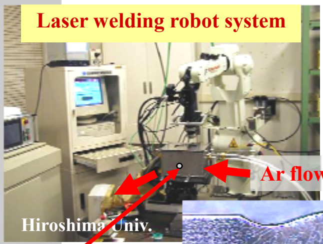


166 kg ingot of NH2 — Plates and rods

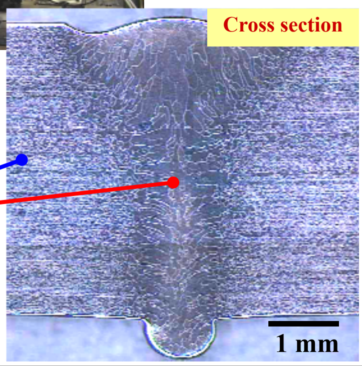


- Carbon, nitrogen and oxygen were well known to degrade various properties of vanadium and its alloys
- NIFS-FERC developed metal vanadium with low oxygen level in industrial scale melting size
- NIFS-HEAT-1 (NH1) and NIFS-HEAT-2 (NH2) ingots were fabricated from the developed vanadium
- Various products, such as plates, rods and tubes, have been distributed to world institutes for Round Robin tests
- NIFS-FERC initiated welding studies with the NIFS-HEATs

NIFS-HEAT-2 was welded in high purity Ar flow to avoid impurity contamination



Welding box

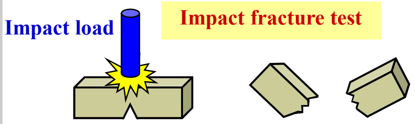


Impurity (wppm)

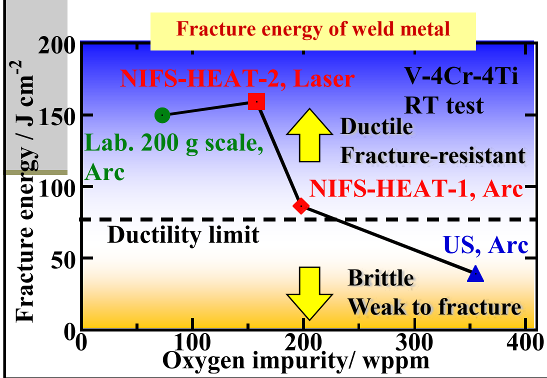
	BM	WM
C	51	49
N	123	129
O	139	158

- Welding box with 6N-grade (99.9999%) Ar flow was developed for welding of V alloy to avoid impurity contamination from the air
- Base metal (BM) and weld metal (WM) was chemically analyzed on C, N and O
- It was confirmed that no remarkable contamination occurred during welding
- Tensile strength, bending ductility and fracture energy of WM were comparable to BM
- In order to estimate irradiation property and material lifetime, fracture energy is important

Fracture energy of weld metal was much improved by oxygen reduction



Fracture energy: absorbed energy for fracture



- Absorbed energy for fracture is measured in impact fracture tests
- Brittle fracture with low fracture energy is induced below the ductility limit

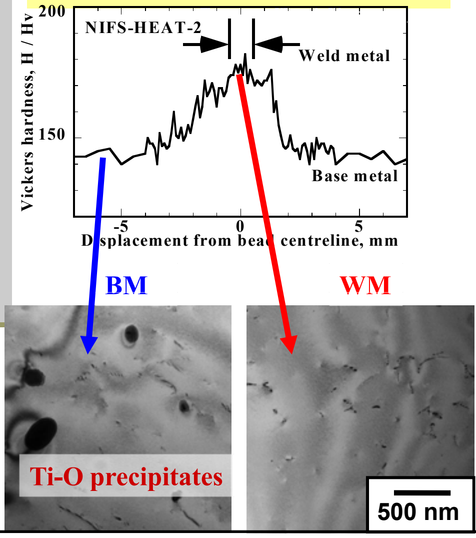
Brittle
Low fracture energy

Ductile
High fracture energy

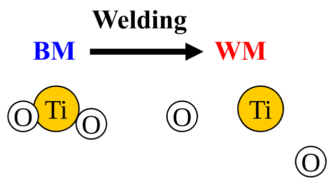
- Welding of US alloy was impossible, because of low fracture energy
- Oxygen impurity reduction in NIFS-HEATs made welding possible

Oxygen is released into weld metal by decomposition of Ti-O precipitates

Hardness distribution around weld bead

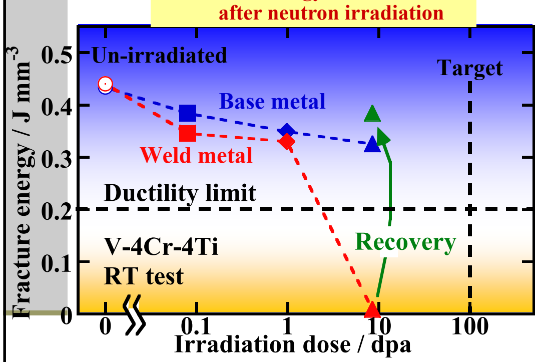


- It is well known that solid solution hardening by impurity O induces brittle fracture in V alloys
- In base metal, the impurities are stabilized as Ti-O precipitates
- During welding, the Ti-O precipitates are decomposed, and went into solution in weld metal
- The released oxygen, induces hardening and brittle fracture in weld metal of US alloy



Degradation of fracture energy was enhanced in weld metal, and was recovered by post-irradiation annealing

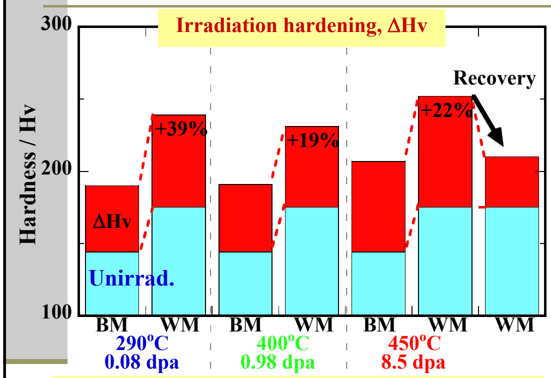
Fracture energy of weld metal after neutron irradiation



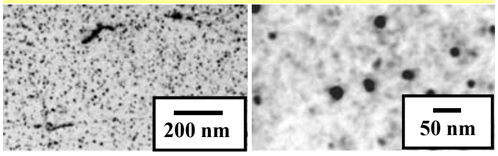
Irradiation temperature: 290 ~ 450 °C
Irradiation facility: JMTR, JOYO (JP), HFIR (US)
1 dpa ~ 5 x 10^{24} neutrons m^{-2}

- Resistance to 100 dpa irradiation was expected for low activation materials
- 100 dpa is roughly 10 yr lifetime (net operation year under 1 MW m^{-2}) for blanket materials
- Base metal maintained high fracture energy up to 8.5 dpa
  - Excellent resistance to neutron irradiation
- Weld metal maintained high fracture energy after 0.98 dpa irradiation
  - This is big progress in welding of V alloy
- However, it became brittle at 8.5 dpa
  - Brittle fracture was enhanced in weld metal
- Ductility of weld metal was recovered by post-irradiation annealing at 600°C for 1 hr

Degradation of fracture energy was induced by accelerated irradiation hardening in weld metal



Irradiation defects in weld metal (290oC, 0.08 dpa)



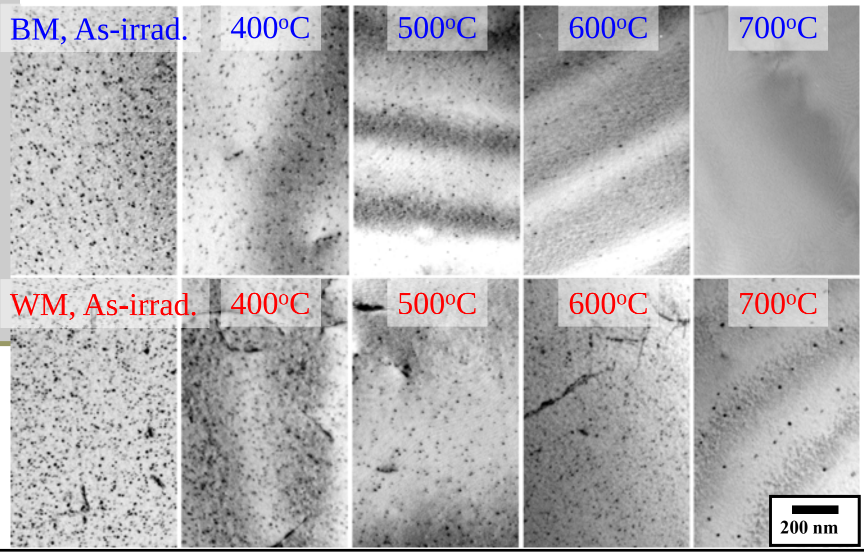
- It is well known that irradiation hardening induces brittle fracture
- In all the irradiation conditions, irradiation hardening in weld metal was 19~39 % larger than base metal
- Irradiation hardening is caused by irradiation defects, and described by Orowan's model

$$\Delta Hv = C\, M \alpha \mu b \sqrt{Nd}$$

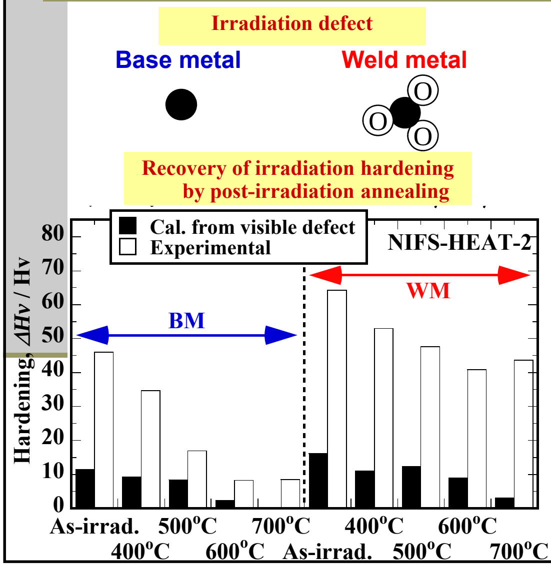
C: Constant = 3/9.8 Hv / MPa
M: Taylor's constant = 3
μ: Shear modulus = 46.7 GPa
b: Burgers vector = 0.26 nm
} Fixed

α: Strength of defect
N: Number density of defects
d: Defect size ~ 5 nm
} Variable

Irradiation defects are more stable to thermal decomposition than base metal



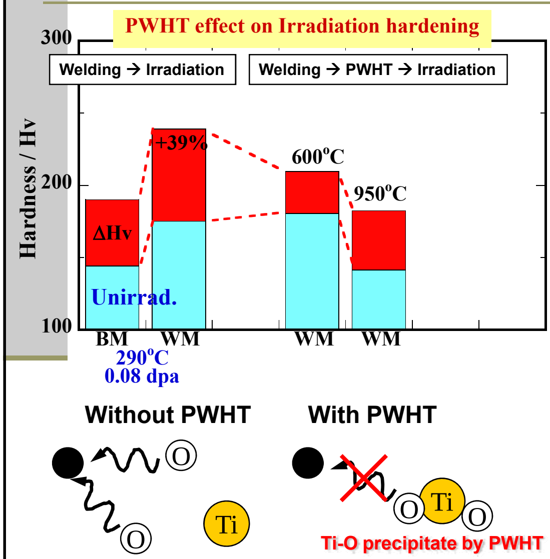
Degradation of fracture energy was induced by accelerated irradiation hardening in weld metal



- Irradiation defects in weld metal was more stable to thermal decomposition
- It was clarified that defect strength, α, was 25% higher in weld metal than base metal
- It is considered that defect strength is increased by decoration of oxygen atoms in weld metal
- 20~30 % of the hardening is understood by the visible defects
  - Invisible (< 5 nm) defects or impurity precipitates are indicated

    → Further investigation
  - Example: Defects or precipitates with 1 nm and 1 x 10^{23} m^{-3}

Irradiation hardening can be suppressed by post-weld heat treatment before neutron irradiation

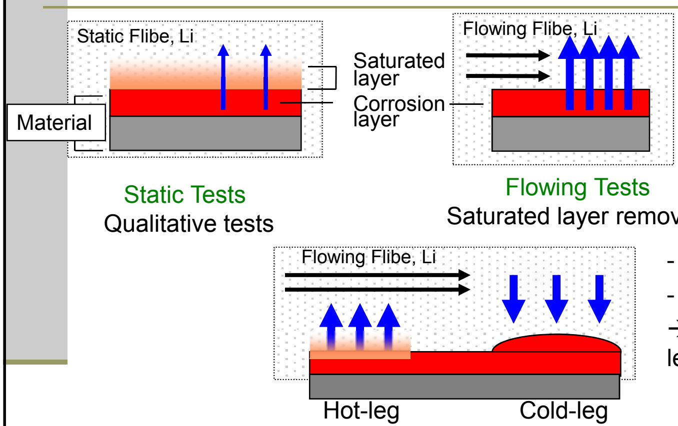


- Fracture energy degradation in weld metal was caused by accelerated irradiation hardening
- The irradiation hardening in weld metal was suppressed by post-weld heat treatment (PWHT) above 600°C
- Solid solution oxygen in weld metal is precipitated out by PWHT, and does not form defect-oxygen cluster anymore
- Further irradiation tests are planned to confirm the improvement of fracture energy by PWHT before neutron irradiation

Summary of welding study

- NIFS-FERC promoted an initiative for large-heat project, NIFS-HEAT-1 and -2, which enabled welding study
- Welding of V alloy became possible by reduction of oxygen impurity
- Weld metal of V alloy exhibited resistance to neutron irradiation up to 0.98 dpa (0.1 yr in 1 MW m^{-2}), while it was brittle at 8.5 dpa
- One of mechanisms of the brittle fracture was accelerated irradiation hardening by oxygen and irradiation defect interaction
- Suppression of irradiation hardening was demonstrated by post-weld heat treatment (PWHT) before irradiation, which will improve the ductility of neutron-irradiated weld metal further

4. Corrosion: Blanket condition is a combination of flowing and temperature gradient



Static Tests
Qualitative tests

Flowing Tests
Saturated layer removed

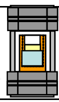
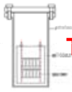
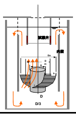
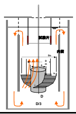
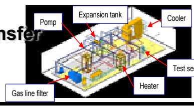
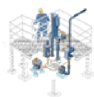
- No saturation of dissolution
- High velocity
Mechanical removal of corrosion layer
→ Erosion

- Dissolution at hot-leg
- Precipitation at cold-leg
→ Mass transfer from hot-leg to cold-leg

Flowing Test with Temperature Gradient
Blanket condition tests

- Static tests provide fundamental corrosion mechanism
- Blanket condition requires both flowing and temperature gradient

NIFS-FERC is starting material corrosion test under flowing conditions

	Molten salt Flibe	Liquid metal Li
Static pot test ΔT=0 [°C] V=0 [m/s]	2 cc Fluoridation Electrochemical corrosion 	100 cc Liquid metal corrosion Decarburization 
Natural convection loop test ΔT = 50～100 [°C] V= 0.01～0.05 [m/s]	200 cc + Mass transfer 	700 cc + Mass transfer 
Forced convection pot test ΔT=0 [°C] V=0.1～1 [m/s]	100 cc + Erosion 	100 cc + Erosion 
Forced convection loop test ΔT = 50～100 [°C] V=0.1～10 [m/s]	100 L + Mass transfer + Erosion 	10 L + Mass transfer +Erosion 

Today's talk

We are here

- Forced convection loop is required for blanket condition test
- NIFS-FERC is making step-by-step approach by using natural convection loop and forced convection pot

NIFS and The University of Tokyo has established Flibe purification system in Japan

Corrosion agent	Source and typical amount	Purification process
HF	(1) T generation Li + n → T + He $T^+ + F^- \rightarrow TF$ ~ 30 ppm / day (2) Initial loading impurity ~ 200 ppm	REDOX (REDuction-OXidation) control $2TF + Be \rightarrow BeF_2 + T_2$
O	Initial loading impurity > 500 ppm	HF bubbling $BeO + 2HF \rightarrow BeF_2 + H_2O$
Ni, Cu	Initial loading impurity ~ 10 ppm	H_2 flowing $M_xF_y + y/2H_2 \rightarrow xM + yHF$
Fe, Cr, W	(1) Initial loading impurity ~ 10-100 ppm (2) Dissolution from RAF steel > 100 ppm	H_2 flowing $M_xF_y + y/2H_2 \rightarrow xM + yHF$

- HF reduction in Flibe by REDOX control has been successfully demonstrated in USA by JUPITER-II program (Japan-USA Program of Irradiation Test for Fusion Research)
- In order to reduce initial loading impurities, NIFS has established Flibe purification system in Japan by the collaboration with The University of Tokyo

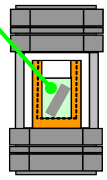
High purity Flibe has been successfully produced

High purity Flibe

Impurity level for Flibe (wppm)

	Fe	Cr	W	Ni	Cu
Flibe #1, 50 g	4	3		<1	
Flibe #2, 50 g	4	13	<1	<1	<1
Flibe #3, 150 g	23	5		4	
Petti, US, 2006	260	16		15	

Test capsule



- High purity LiF and BeF_2 were melted in high purity He gas
- The composition of Flibe was $2LiF + BeF_2$
- Purified by HF gas bubbling and H_2 gas flowing at 600 °C
  - Oxygen reduction

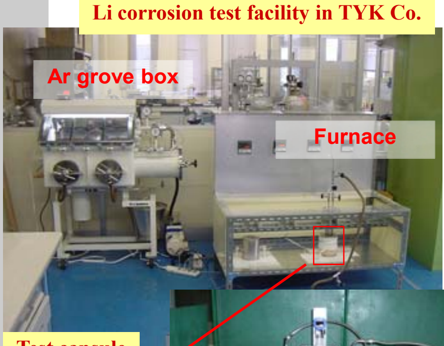
  $2HF + BeO \rightarrow BeF_2 + H_2O$
  - Metal impurity reduction

  $M_xF_y + y/2H_2 \rightarrow xM + yHF$
- Fe impurities were successfully reduced to 3-10 times lower than the conventional Flibe
- It is necessary to confirm if the purity is enough for initial loading to blanket

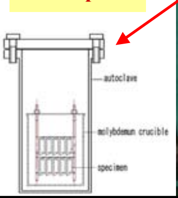
→ Corrosion tests were started from static pot test

NIFS-FERC has established Li corrosion test facility by collaboration with TYK Co., Japan

Li corrosion test facility in TYK Co.



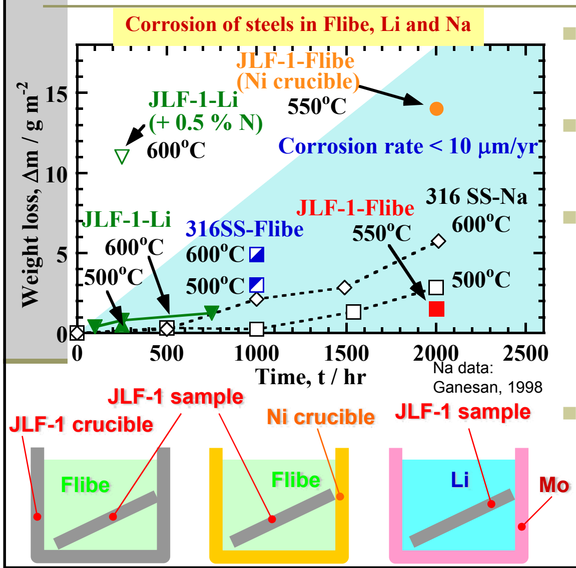
Test capsule



Li natural convection loop in NIFS

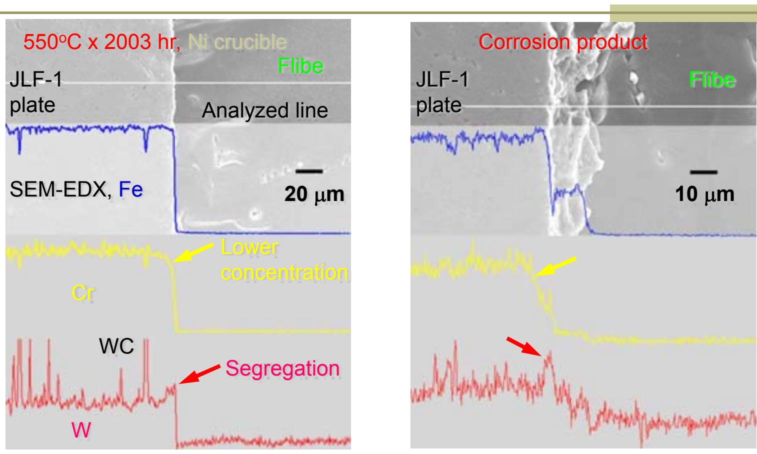
- Li exposure test has been performed on V alloy in USA by JUPITER-II program and US-DOE program
- Li technology is also expected from IFMIF
  - Li flowing test in 316SS loop has been conducted in Osaka University, Japan by IFMIF-Key Element Technology Phase activity
- NIFS-FERC initiated Li exposure test on RAF steel to investigate the feasibility of RAF steel-Li blanket as proto-type of V alloy-Li blanket
- Flowing corrosion test is starting in NIFS-FERC

Corrosion rate of JLF-1 below 600 °C was less than 10 μm/yr at static condition



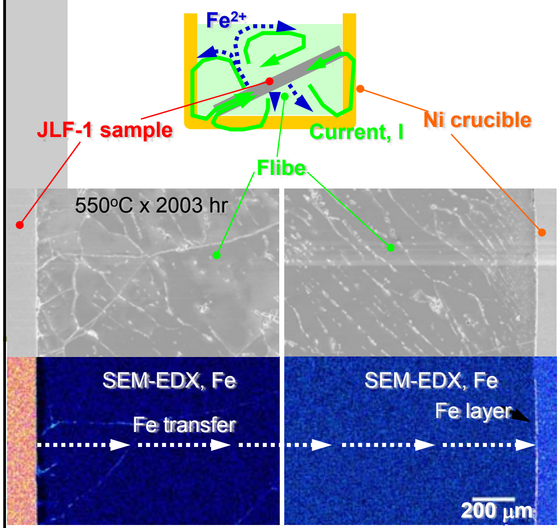
- Weight loss of JLF-1 in Flibe and Li was similar to that of 316 SS in liquid Na (FBR cooling system)
- The present Flibe and Li is expected to be enough pure for the initial loading to blanket
- Future work
  - Corrosion test under flowing condition
  - Large-scale purification
  - Real time impurity sensor and purification under flowing
- On the other hand, corrosion was enhanced by more than 10 times, when …
  - JLF-1 contacts Ni in Flibe
  - Li is contaminated with N

Base corrosion mechanism in Flibe is corrosion product formation and its dissolution



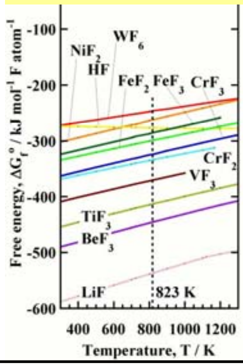
- Corrosion products were observed at the surface of JLF-1
- Cr showed selective dissolution
- W was segregated at the edge of the plate
  - W is expected to be resistant to Flibe, and its coating will be effective to corrosion

Dissimilar metal contact enhances Fe transfer by electrochemical corrosion

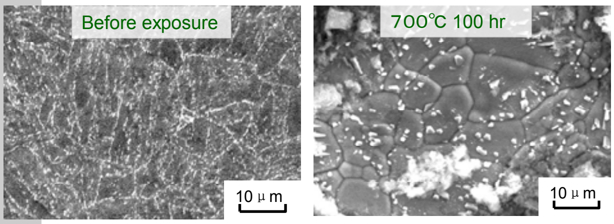


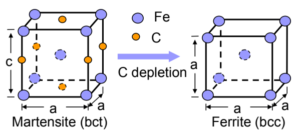
- Ni metal is nobler in Flibe than Fe, because formation free energy of fluoride is larger
- Contact of Ni and Fe produces electrochemical corrosion

Free energy of fluorides



Loss of carbon from the surface occurred in Li, but is limited in 100 μm for 10 yr





(wt%)

Materials	Composition	C	Cr	W	Phase transformation
Before exposure	Fe-9Cr-2W-0.1C	0.09	8.92	2.00	
700°C 100h	Fe-9Cr-2W-0.1C	0.03	8.88	1.95	100μm from the surface

- Base corrosion mechanism in Li is liquid metal corrosion (alloying in liquid phase)
- It was found that phase change (Lattice structure change) from martensite to ferrite occurred by loss of the carbon at the specimen surface
- Ferrite phase formation may induce degradation of strength, but is not critical because the depth is estimated as 100 μm after 10 yr
- On the other hand, N contamination enhanced weight loss by intermetalic compound formation
  - $2Li_3N + Fe \rightarrow Li_3FeN_2 + 3Li$, $5Li_3N + Cr \rightarrow Li_9CrN_5 + 6Li$: Purification control is necessary

Summary of corrosion study

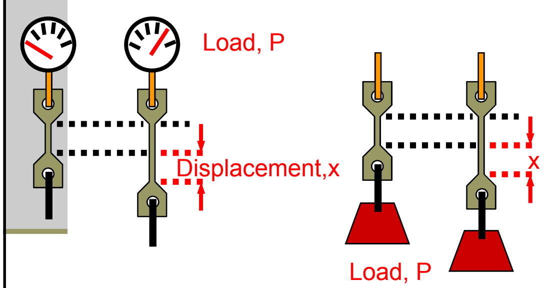
- From the static corrosion test, corrosion rate of JLF-1 in Flibe and Li was less than 10 μm/yr
  - Typical wall thickness in blanket is ~ 5 mm
  - Assuming 1 mm corrosion is acceptable, 100 yr is lifetime
- Corrosion mechanisms were investigated
  - Flibe: Corrosion products formation, electrochemical corrosion
  - Li: Liquid metal corrosion, carbon loss, intermetalic compound formation
- Corrosion tests under flowing condition are starting
  - Generally, lifetime for corrosion is decreased under flowing condition
  - NIFS-FERC is making step-by-step approach by using natural convection loop and forced convection pot
  - Forced convection loop is necessary for corrosion test under blanket condition

T. Nagasaka, Review meeting, Dec. 13 / 2008 , Takayama

5. Thermal creep: Creep test simulate long-term deformation in blanket condition

Tensile test: 1~5 min

Creep test: 1 day~1 year



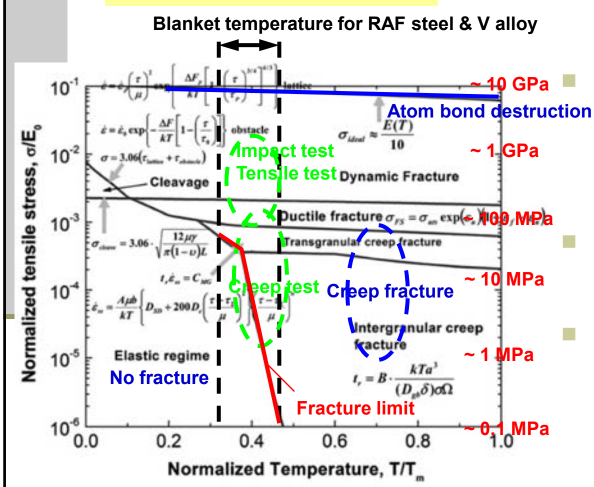
dx/dt = const.
P = f(x)

P = const.
x = f(t)

- Typical stress for structural material is less than several 10 MPa
- For that stress level, low activation materials are deformed, but the deformation is fully recovered if the stress is removed in short time
- If the stress is kept for long time, the deformation is increased, and finally the material is fractured
  - This is creep deformation and fracture
- The typical creep deformation rate is as slow as 0.01~1 %/day
- Creep lifetime determines the upper limit for operation temperature of blanket

Blanket operation temperature and stress is determined by creep fracture of materials

Fracture map by theories

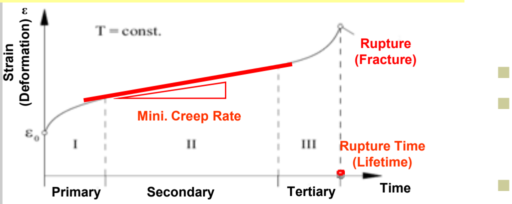


M. M. Li & S. J. Zinkle, 2007

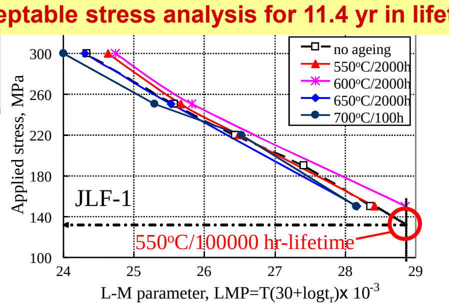
- Several GPa is necessary to fracture materials by atom bond destruction
- Materials are fractured by much lower stress because of defects
  - Crack
  - Dislocations (line of crystal defects)
- Fracture limit for blanket temperature range is determined by creep fracture
- Blanket operation stress is set in
  - No fracture area
  - Or, enough long-life (> 10 yr) area for creep fracture

Acceptable stress of JLF-1 for 11.4 yr-lifetime was estimated as 135 MPa at 550^{o}C, and was slightly affected by aging

Typical creep deformation curve



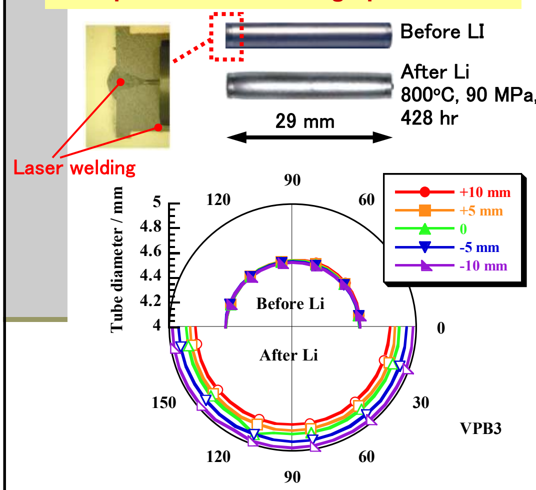
Acceptable stress analysis for 11.4 yr in lifetime



- Acceptable stress for 100000 hr (11.4 yr)-lifetime is required for design of blanket
- 11.4 yr is too long to test everything
- Usually, the acceptable stress is extrapolated from shorter creep test data than 10000 hr (1.14 yr).
- NIFS-FERC has started thermal creep study with the shorter test Data from ~500 hr (~ 20 day)-test is available at this moment
- From the data, acceptable stress of JLF-1 for 11.4 yr-lifetime was estimated as 135 MPa at 550^{o}C
  - Longer test is undergoing
- Effect of thermal aging at higher temperature was also investigated
  - The contribution of the aging was limited in +/- 15 MPa

Creep test on V alloy under Li condition was performed by creep tube

Creep tube filled with high pressure He



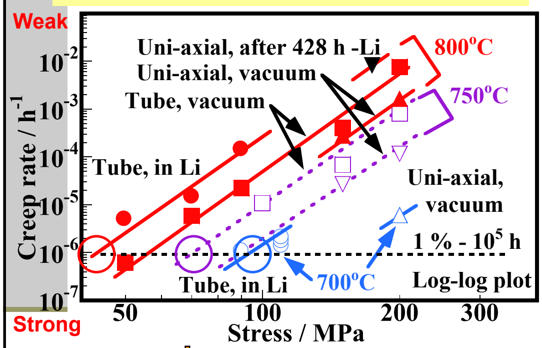
Diameter change of creep tube

- Tubing of V alloy became possible because of workability improvement by reduction of oxygen impurity
- Creep tube test is popular in steels for creep test under irradiation condition, where no loading mechanism is available
  - Tube is filled with high pressure He at room temperature
  - He pressure is increased by increasing temperature
  - Hoop (expansion) stress by He pressure produces creep deformation
- Creep tube is also useful for creep test under Li condition

T. Nagasaka, Review meeting, Dec. 13 / 2008 , Takayama

Creep test on V alloy under Li condition was performed by creep tube

Creep rate of NIFS-HEAT-2



- Tube test exhibited larger creep rate than uni-axial test
  - Hoop stress estimation maybe smaller

    → Stress calculation analysis
  - Bi-axial stress may enhance creep deformation

    → Investigation of deformation mechanism
- Creep deformation is enhanced in Li condition
  - It was found that oxygen impurity transfer from V alloy to Li degraded creep rate
- Oxygen impurity increased creep strength
  - It is a trade-off between creep strength (high O) and ductility (Low O)
- Assuming 1 % deformation is equivalent to fracture, acceptable stress for 100000 hr (11.4 yr)-lifetime was estimated as 90, 70, 40 MPa at 700, 750 and 800 °C, respectively

Summary of thermal creep study

- Acceptable stress for 100000 hr (11.4 yr)-lifetime was estimated from shorter creep test
  - JLF-1: 135 MPa at 550°C
  - NIFS-HEAT-2: 90 MPa at 700°C, 70 MPa at 750°C, 40 MPa at 800°C
  - Longer time tests are ongoing to confirm the obtained acceptable stress
  - Mechanism of creep deformation is being investigated to understand the difference between uni-axial and tube test condition, and between vacuum and Li environment

- Improvement of creep property is being tried to increase lifetime and operation temperature
  - Advanced work hardening process
    - Example: Hardening by TiO_2 precipitates in V alloy
  - Strengthening element addition
    - Example: High Cr- V alloy, Nano-particle-dispersed V alloy

6. Summary

- NIFS-FERC promoted an initiative for V alloy large-heat project, NIFS-HEAT-1 and -2.
- Welding of V alloy became possible by reduction of oxygen impurity. Weld metal of V alloy exhibited resistance to neutron irradiation up to 0.98 dpa (0.1 yr in 1 MW m^{-2}).
- From the analysis on the mechanism for irradiation effect, it is believed that higher irradiation resistance is obtained by appropriate post-weld heat treatment before neutron irradiation.

- NIFS-FERC established corrosion facility for Flibe and Li
- From the static corrosion test, corrosion rate of JLF-1 in Flibe and Li was less than 10 μm/yr. Fundamental corrosion mechanisms were clarified.
- Forced convection loop is necessary for corrosion test under blanket condition. NIFS-FERC is making step-by-step approach by using natural convection loop and forced convection pot.

- NIFS-FERC has been started long-term creep test to investigate thermal creep of low activation materials.
- Acceptable stress for 100000 hr (11.4 yr)-lifetime was estimated from shorter creep test. Longer time tests are ongoing to confirm the obtained acceptable stress
- Mechanism of creep deformation is being investigated to understand the difference between uni-axial and tube test condition, and between vacuum and Li environment.
- Further improvement of creep property is being tried to increase lifetime and operation temperature

- For long-life blanket, the above long-life material technology will be integrated with the other research activity in NIFS-FERC and universities.
  - Coating study: MHD coating, T permeation coating, Unti-corrosion coating, 1st wall coating
  - Thermofluid study
  - Tritium study
- As a result of the integration, we really hope blanket mock-up in future

4. Resume of NIFS Special Review Meeting

Dec 13, 2008 (Sat.) 8:30 - 17:30

Special Conference Room 3F, HIDA Earth Wisdom Center, Takayama, Gifu, Japan

- Reviewers: (w/o title of honor)
  C.Alejaldre, G-S Lee, H.Takuma, J.W.Van Dam, K.Nishikawa, M.Tendler, R.Wolf, S.Itoh, T.Klinger,

- NIFS members:
  O.Motojima, S.Sudo, A.Komori, H.Yamada, S.Imagawa, N.Nakajima, S.Okamura, M.Sato, A.Sagara, S.Sakakibara, R.Sakamoto, M.Yokoyama, T.H.Watanabe, T.Nagasaka, Y.Kainai

Self-introduction by each member

chaired by S.Sudo

<u>**Presentation by S.Sudo: Introduction of NIFS activities**</u>

Van Dam: What are activities of Public Relation office ?

Sudo: We started many years ago, For citizens, PR office assists in their visits to the institute with appropriate explanation, NIFS web server, and recently Kids Science Museum has started. I think it has been working well . Do you have additional comments, Sato sensei?

Sato: I will explain later about it, such as on science communication.

Tendler: In relation to Deuterium experiments, PR is very important. What is near-term plan?

Sudo: In addition to the PR office, a special team led by Komori has been making the general explanation of DD experiments to citizens with many town meetings and the negotiations with local governments. This team is prepared separately from the PR office because of the special importance of the DD experiment campaign.

Alejaldre: In ITER, we have a special division for safety. I'm happy to help you on this regard. Do you have collaboration with Naka for ITER-related matter?

Sudo: In NIFS, we have an internal group for ITER-related works. We also established the Rokkasho research center for ITER-related subjects. We will soon have a room at the building in Rokkasho and relation with ITER will go ahead.

Motojima: We have formal regular meetings 3-4 times per year with JAEA. Collaboration with JAEA is included in the NIFS collaboration program.

Klinger: For bilateral collaboration. What is important to you about QUEST ?

Komori: Construction of the QUEST is completed this March. First plasma was produced in June. They use already OH and rf current drive. For bilateral collaboration, NIFS is a center of Univ., and NIFS is controlling all budget and experimental plan. For QUEST, Kyushu Univ.

proposed machine and we discussed the plan and made decision for the construction and all-Japan structure.

Motojima: On the process, I should mention Emeritus Prof. Itoh's decision to shutdown TRIAM-1M to make the start of new experiment possible.

<u>**Presentation by A.Komori: Large Helical Device (LHD) Project**</u>

Klinger: It is nice to see you are approaching to closed divertor design. What is the status of design work and future plan? Will you stop the experiment for the installation?

Komori: Design study has been almost completed. New design will be made within next year.

Klinger: Do you plan to stop machine?

Komori: We will have no long stop. The installation will be made in the maintenance period. 1-sector installation will be made next year, and test the function. Then we will increase the number of sectors step by step.

Klinger: Did you make EMC3-EIRENE simulation in your divertor design?

Komori: We thank you very much for that, the code was very useful for us.

Wolf: Can you maintain the condition of impurity hole for long time period?

Komori: During NB injection, we can maintain it almost in steady state in high-Ti phase.

Wolf: In the impurity-hole experiments, it seems that anomalous convection of impurity also gives effects on electron density profile. How do you think about it?

Yamada: Convection for hydrogen species is almost zero, while impurity's outward convection is clearly high.

Tendler: I suggest the study of correlation with impurity transport and the plasma rotation.

Tendler: In your nearest plan page, what is time schedule?

Komori: NBI upgrade plan in 3 years, divertor in 4-5 years, deuterium experiment, hard to say, because of the discussion with local government. But after we get the contract with local government, we will need 3 years to start the experiment.

Tendler: Can you say about the cost?

Komori: Total costs would be 200 M dollars for all programs listed in page 14.

Tenlder: What Q value will you get after these plans?

Komori: About 0.3, and hopefully we will extend to 1.

Van Dam: Will the beta value go up with no limit with additional heating?

Komori: Magnetic surface will be good only up to 7 %.

Van Dam: Will you control Rax by vertical field?

Komori: Yes, we will do that and maybe we will get 10 % with that capability.

Van Dam: In the mitigation of CDC event, how do you consider the effect of elongation?

Komori: Sakamoto will explain that in his talk this afternoon.

Klinger: I will ask about the fluctuation measurements, it is clear that the impurity hole phenomena includes anomalous effects, do you have a plan to measure fluctuations in those experiments?

Komori: Yes, we plan that. For the general discussion about the MHD fluctuations, you should wait for Sakakibara's talk.

Sakakibara: I will explain in the afternoon.

Wolf: In your divertor design, what is the heat flux limit ?

Komori: It is 5 MW/m^2.

<u>**Presentation by N.Nakajima: Simulation Science Project**</u>

Van Dam: I appreciate very much your nice work in experiments and simulation study. In your future plan (page 19), where are you? This morning, I received information from ITER integrated-modelling working group. The activities in NIFS simulation science division are worth considered to form a strong part of it.

Nakajima: Yes we are strongly trying to contribute to it.

Alejaldre: I worked in theory for many years. I remember that, in old times, theory predictions gave generally unstable results for stellarators, e.g., Mercier, ballooning instabilities. However experiments have succeeded to break them. How do you think about the limitation of theory work in stellarators?

Nakajima: I can give one example shown in page 3. This calculation shows unstable region. But in the experiments, real plasmas show that such unstable region is removed in high beta stage.

Motojima: We had the prediction of 5 % at the time of start of the LHD experiment. Equilibrium was one of the problems, but we could solve it thanks to Prof. Todoroki. I want to acknowledge also Prof. Hayashi for his HINT-code work in high beta calculation.

Alejaldre: I am working in ITER for licensing matter. I would suggest that, on the process of your reactor work shown in page 20, safety problems should be solved in early phase.

Motojima: Regulation issues depend on countries. I think we will make different regulations from fission reactors.

Nishikawa: I think your hierarchical code development is very nice. Do you have near-term targets in the simulation work for the LHD experimental results like IDB and impurity-hole phenomena?

Nakajima: We have strong collaborations with LHD experiments and theory and data analysis division in LHD project. We will continue such collaborations and analysis of physical mechanism of the experimental results.

Nishikawa: I think the main objectives of LHD experiments are to understand the physics mechanism of interesting results from LHD. For such physics understandings, small-scale experiments like CHS, which was stopped some years ago, will be very useful. I would like to hear the opinion of NIFS director-general.

Motojima: We have new plans to build small experiments. I will continue to encourage young scientists for raising new proposals. Although we have a budget problem, we will continue to work and we have several candidates in hands.

Tendler: You have made good results from LHD which have good diagnostics like electric field etc. You should be able to make comparison studies of theories and measurements using various numerical codes.

Nakajima: Yes we will make efforts for that type of works. However one limitation is a number of people for those works. We cannot do everything. We need to make wise selections.

<u>Presentation by M.Sato: Coordination Research</u>

Klinger: It is impressive that you are making variety of outreaches. I would like to ask about patents. Could you give me some numbers?

Sato: We have different types, patents from our own researches and those with outside companies. Roughly 50% of patents are produced from microwave-related studies and another 50% from fusion-related collaborations. We have some profit but not much from them.

Alejaldre: I would like to give comments on tritium stuff on your page 18. We will inject an order of 100 g tritium in ITER per one discharge with the burning consumption of 0.4 g. This amount will be much bigger in the future DEMO. The impacts of tritium problem to the public society will be very large. We need to enhance the efforts for understanding various aspects of tritium handling. It is very important to continue such research activities in your group.

Wolf: It is very important to get students/researchers into fusion research. Because you have so wide connections with various fields, please tell us what program do you have in this aspect?

Sato: In my opinion, we have focused only on the researches of core elements of fusion research, e.g., plasma and materials. We have to proceed to the system design of fusion reactors with such core materials. In this phase the most important aspect is engineering. We plan to proceed to such research phase in our coordination center.

Motojima: I would like to give general comments on the coordination center. The primary objective is developing spin-off researches of fusion. This would be strong message from fusion to the public. 50 years ago, in Geneva, 6000 people got together including scientists and business people. Recently I gave two lectures to bankers. They are interested in fusion now.

Van Dam: On fusion science archives in page 41, why the number goes to small level (even zero?) after 2005?

Sato: It is just because of the time delay of the archiving work. We have, of course, materials to be archived.

Van Dam: I ask about the organization. What is the relation between your center and the fusion engineering research center on PWI and the tritium inventory studies? What is the relation with DSS on the laser work?

Sato: We work for rather basics objects on tritium research.

Nakajima: Prof. Sakagami belongs to DSS and he also work on laser simulation in the group in the coordination center with experimental people for the target design.

Tendler: I heard nice results of lithium coating from TJ-II experiment in Toki conference. How do you think about the good scientific work in small machines?

Komori: I think they made good results. We will consider such a wall conditioning technique in future experiments in LHD.

<u>**Presentation by A.Sagara: Fusion Engineering Research**</u>

Wolf: In your roadmap, you show various relations with your program plan and ITER experiments. What type of research link do you expect with ITER results?

Sagara: One example would be neutron flux effects on materials.

Wolf: Actually how will you introduce the information from ITER experiments?

Sagara: We are considering the relation with the numerical test reactor. Predictability is very important from the model calculations.

Sudo: We have already scientific link with ITER activities in the physics of alpha particle physics in the simulation study.

Lee: Here, I learned many good results from LHD experiments and simulation science. We can go ahead such researches in parallel with tokamak research for fusion reactor development. Numerical test reactor is also useful with the activities of numerical tokamak research. By the way, how do you think about the impact of the delay of the IFMIF project on various fusion researches?

Sagara: I think it is ok for the database aspects, but I think that the licensing problem would be more serious.

Lee: We are concerned very much about licensing problem for DEMO phase.

Motojima: I think that task of the IFMIF is to find the best material, but we can use better material.

Wolf: 14-MeV neutron source you talked, how much DPA will it produce?

Nagasaka: We expect 10^-3 dpa fluence. It is designed for basic study. For the actual material testing, 100 dpa will be required.

Motojima: About IFMIF, could somebody give the information for the present status?

Sudo: I think the preparation for starting design is going well, considering the present BAactivity.

Nagasaka: I think that licensing procedure has not been fixed. JAEA is starting discussion on licensing. For the question about the effect of delay in the IFMIF research, my understanding is that there are two choices. One is just to wait for IFMIF. This results in delay in the whole schedule. The other is to keep going with available irradiation data. In fission reactor, for example, surveillance specimens are installed on the pressure vessel. We can start fusion reactor operation with a short-time license and surveillance specimens, and can stop it when the specimens make some dangerous signal for embrittlement (degradation of fracture energy). The license will be expanded later, if the IFMIF data become available.

Presentation by S.Sakakibara: High Beta and Related 3-D MHD Characteristics

Klinger: You are nicely making use of HINT results with your experiments. How do you plan to include the bootstrap effect?

Sakakibara: We are trying to include it with a first step by modeling it with multi-filament currents.

Motojima: Do you think the effect of bootstrap current is large?

Sakakibara: Yes, I think it is large, especially for considering such as magnetic island formation in high beta plasmas.

Tendler: I think you are successful in taking advantage of stellarator concept with current-free toroidal confinement proposed by Spitzer 50 years ago. This is an important milestone. Congratulations. I suggest you to discuss further with the consideration of electric field gradient profile at the interface of ergodic layer, as I reported in the Toki conference. This will give you more subtle knob.

Alejaldre: What is the density profile for high beta plasmas?

Sakakibara: Typical example is shown in the presentation. Our stability calculations are with the density profile from the measurements.

Van Dam: It is nice to see good interplays between theory and experimental groups.

Presentation by R.Sakamoto: High Density Operation and Its Prospect for Helical Reactor

Klinger: After making long way of developing the repetitive pellet injector, it is so nice to see to achieve new regimes of helical plasmas.

Tendler: I understand it is physically important to observe the toroidal rotation for high density plasmas. Have you tried? For the discussion of particle heat and momentum transport you should try it even if it is difficult.

Sakamoto: Since diagnostic beam cannot penetrate, we don't have information on that.

Wolf: Do you have information on impurity transport? Low Zeff or do you have accumulation problem?

Sakamoto: It is rather difficult to measure impurities in IDB plasmas, but we have some indications of low level of impurities in the core plasma. The simulation study has also shown the impurity shielding by ergodic layer.

Lee: In page 15, you show an optimum kappa value of 1.2 for creating high density plasmas. What is the mechanism to make kappa of 1.2 be optimum?

Sakamoto: CDC has been observed when the Shafranov-shifted axis reaches 4.1m. With the elongation, we can reduce the Shafranov shift. In the same time, extreme elongation leads to the MHD activity. Thus, elongation must be smaller that kappa of 1.2 because of the stability aspect.

Lee: What kind of MHD ?

Yamada: Too much elongation raises, usually, the interchange mode.

Lee: Do you have a modelling for the stability?

Yamada: Yes, we have Mercier calculation. But this is sufficient condition and not the necessary condition. Liner stability analysis suggests that substantial growth rate is expected for D_I in Mercier calculation of 0.2 or 025.

Motojima: Could you tell your feeling for the difference between high density plasmas and high beta plasmas (with low B field)?

Sakakibara: For IDB plasmas, the interchange mode in the core is stable due to the magnetic well, although it is not (in linear calculations) for high beta plasmas. In IDB case, the plasma periphery is unstable (in linear calculations) but MHD fluctuations are in small level compared to standard high-beta case.

Motojima: Present pellet velocity is about 1 km/s. Is it possible to increase it to 10 km/s for getting better penetration?

Tendler: How do you plan to extend it for the use in DEMO?

Sakamoto: The improvement of penetration given by the velocity increase depends with the scaling of (velocity)^0.3 power. So it is not beneficial to increase the velocity.

Motojima: How about 100 km/s?

Sakamoto: It will be technically difficult because the hydrogen ice pellet is not tough enough for such a high speed. Pellet penetration can be improved utilizing the drift movement of plasmoid in the plasma.

<u>**Presentation by T.H.Watanabe: Turbulent Transport and Zonal Flows**</u>

Klinger: It is a beautiful result. In inward shifted case you found larger zonal flow amplitude. With the E field effect on zonal flow, you also made good results. Can you combine two effects consistently?

Watanabe: Yes, we will proceed to include multiple-helicity model. I expect the inward-shifted configuration, the effect of E field on zonal flow creation would be stronger.

Klinger: It is nice for stellarator community to know that the non-ambipolar E field makes turbulent suppression.

Tendler: Including E field effects on the zonal flow, can you make the self-consistant modeling?

Watanabe: We will try to do it by involving the feedback from both physics elements.

Tendler: How do you include E shear effect, which provides turbulent suppression?

Watanabe: In our simulation work, effect of E field on zonal flow is stronger than the stabilization effect of the E field shear. We will proceed to include the E field shear for the next phase of our work, but we are going first to concentrate on the analysis of E filed effect on zonal flow

Lee: Your work on ETG is in the early stage based on the slab model. This is very expensive study and nice results. Do you think that your ETG work is applicable for toroidal geometry?

Watanabe: Toroidal damping of ETG is important. We will try but not very soon.

Alejaldre: For the better understanding of LHD results, calculations for outward-shifted case are also important. I also suggest you try to calculate TJ-II case because we have measurement of E field profile.

Klinger: Do you need higher computing power for making further step?

Watanabe: I think we have been able to calculate ITG mode with the existing computers. For making further study, like ETG in toroidal geometry, I think we need more power.

Van Dam: It is really very strong work. Year ago, I recall that you didn't have consistent simulation results with LHD experiments. Now the drift motion is included and you made a success. How about making a next step for making a proposal to the experiment to check simulation results?

Watanabe: Our present concern is the turbulent evaluation with Er. We would like to make a prediction for LHD deuterium experiment where the isotope effects make the E field different from the hydrogen experiment.

Nakajima: We need global simulation to include the E field shear effects. We will go step by step. Watanabe-san is now making ITG and ETG simulations separately. For hierarchy simulation, we will calculate both simultaneously, but again we will go ahead step by step.

Tendler: In EU, we have a new supercomputer. You can be the big user of that.

Lee: Electron anomalous transport is another big problem. We hope you can give a good insight for that. Also the impact of turbulence on particle transport must be the important issue for the next target in your work.

<u>**Presentation by T.Nagasaka: Development of Long-life Liquid Blanket**</u>

Klinger: You are making deep studies of blanket in collaborations with university people and companies. Could you tell your present situation?

Nagasaka: Yes, we have much collaboration with universities and companies. Our business is the integration of fundamental research and elemental technology. Generally university people are not organized in a project. They want to do what they want to do. We need management for research subjects, planning and framework. We are satisfied with the collaboration studies, but we need more. Recently we have reached the step of fluid convection study. It needs larger budget and more number of people. I think we need to grow the community up now.

Klinger: For your engineering collaborations, with who are you collaborating, nuclear engineering people or what university groups?

Nagasaka: We have common research issues with fission reactor and other material people. Ferritic steels including molybdenum were developed in fission reactor material research. In fusion material, molybdenum was replaced by tungsten from the aspect of low activation. It was found that the ferritic steel containing tungsten showed larger creep strength than the molybdenum steel. So, people started to consider the tungsten steel as fission reactor materials, turbine materials and etc. This is a good example of our communication to other research fields.

Alejaldre: For the simulation study of the interaction of neutrons with materials, do you have the collaborations with theory people?

Nagasaka: We have to extrapolate the present fission reactor data to high dpa case. In order to clarify the mechanism, we have activity of computer simulation. We have numerical work for the fundamental processes in multi-scale modeling activity.

Lee: ITER would be the last chance for testing liquid blanket. How do you select the final candidate of blanket among many candidates? For liquid blanket, how will you test it in the ITER experiment?

Nagasaka: In ITER, the TBM was limited by the technologies available at this moment. JAEA people expect 3 campaigns in ITER-TBM experiments. The 1st TBM starts at ITER Day 1^{st}, and ends at the end of D-D experiment. 2^{nd} one is the same TBM as the 1^{st} one, and starts with D-T experiment and will be operated for several years. The 3^{rd} one will be different from them, and is recognized as advanced type. I expect that we can test our liquid breeder TBM in the 3^{rd} campaign. It will be around 2020.

Lee: Replacing TBM itself would be possible, but there is no possibility of changing the blanket concept because it would be difficult to change the whole heat cycle system for the blanket.

Motojima: ITER design has been made with the primary target of testing fusion reactor concept. The limitation of budget made such a decision. In this context, I recall the same problem for material selections: whether we should select stainless steel or the low activation material.

Sagara: We have been discussing so many years about the blanket design. We do not have enough databases to make a correct final decision.

Lee: I am responsible for TBM type selection. I have to say that putting just a TBM in ITER is possible but sufficient physical testing of that is not possible.

Alejaldre: I think that the solid TBM has passed licensing procedures. For liquid type design, an additional licensing process would be needed.

Motojima: Neutron flux is not sufficient for blanket test in ITER. It is better to open the possibility of selecting various types of blankets for university people.

Final session for the review

Tendler: I was deeply impressed with the results achieved in NIFS. Fantastic achievement of new regime in stellarator research has been made. These good results were made strategically, i.e., well arranged combination of theory and experimental works. I would like to suggest an important subject you can proceed, which is the momentum transport discussion.

Wolf: Concerning your future upgrade plan, it might be very good subject to have the steady state divertor operation. You have made great achievements of high beta plasma production and high density plasma operations with. It would be nice if you could discuss integrated approach to reactor-relevant regime. Creating the ITB is good result and I would like to hear the discussions for its physical mechanism. I am envious to know your status of good collaboration with scientists in fields of the nuclear engineering and technology.

Sudo: Thank you very much. I think, in Karlsruhe, for example, you also have good collaboration works with engineering and technology, where I visited two days ago for the BA meeting.

Klinger: I am honored to join this review meeting. LHD is no doubt a leading stellarator in the world. I think you should continue your direction. Pellet injection development, which has been continued many years, have now led to a new regime of stellarator plasmas. Beta limit study marked a good achievement. Systematic progress in heating power has been made. I observed also growing technology developments in universities and companies, whose products are nicely involved in LHD experiments. Understanding IDB and CDC may need further collaborations of theory and experiments. Closed divertor is in the step by step progress. I see strong activities although I am not a specialist for this field. NIFS is certainly a center of collaboration with 140 universities and institutes. Today young scientists made nice presentations for remarkable results.

Takuma: Thank you very much for preparing nice presentations. They were all well prepared. I see young excellent scientists have grown up. What we hoped for LHD in the discussions at the starting stage has been now established by NIFS people. We hope LHD experiments go ahead further.

Itoh: During last six years, by the direction of Motojima sensei the many great results came out from LHD and also high grade works were output from the other groups. I would like to say congratulation to Motojima sensei and all of the staff of NIFS.

Nishikawa: When I looked the program of this meeting, I thought the morning session would be understandable because the talks would be for general topics. However I felt that the talks in the afternoon would be too difficult for me because the topics would be on details in the research. I was afraid that I could not follow them. Now I found the case was opposite. Talks in the afternoon from young scientists were very nice. I thought about making nasty comments but I realize that I can give only awarding comments. I was a chairman of review committee for the discussions to decide the start of the LHD project. We made lots of discussions about feasibility of superconductors, steady state operations, physical problems, high Ti achievement, high beta, high Te with electron root. Now it seems that all items were completely accomplished.

Alejaldre: I am very much impressed by the presentations. In the last two years, I was away from stellarator research and did not follow it closely. I have been engaged in the licensing work of the ITER, which gave me good experiences. Disruptions, instabilities, runaway electrons in ITER are big issue. I realize the potentiality of LHD is great. So I will introduce such nice achievements to tokamak community to convince them. Comparison study of two concepts would give good understanding of physics. Finally I suggest you, say, for the next time, to present a long-range plan of the institute, which is not only for 5 years but longer plan, about how you can contribute to ITER. It would be a difficult job for the next director-general.

Lee: I am very much honored to come to Takayama for this review committee. I give comments and recommendations I prepared by the request from Sudo sensei. Significant maturing of LHD experiment is very good. Machine itself is in a high level of heating and diagnostics. Simulation studies have been grown up and they are one of main part in NIFS, which is almost equal level to LHD experiment. Two departments were nicely organized. Positive feedback is very nice between simulation and experiment. I encourage this way strongly. I observe much improvement from the time of my first engagement. I notice that turbulence study in momentum andparticle transport is important. I realized a growing integrity in fusion engineering field. It is impressive to know outward spin-off in the fusion engineering and reactor study. We should be careful for liquid blanket research. It needs to be looked carefully with timeline, and consider how to test it if it were not applied to ITER. I would like to listen to your insights on this topic. In conclusion, I congratulate to Motojima san for his 6-years great work from the construction to realization of scientific activities in the institute. Our fusion research is a sort of marathon or relayed running. To keep momentum is important and leadership with future vision is important. We should go together with multiple generations.

Van Dam: I repeat the sayings all reviewers made already. I appreciate your good hospitality. Similar to Prof. Lee, I have been for 5 years in this review committee. At 5 years ago, the results were nice but they keep getting better. I learned nice results in gyrokinetics, multi-scale and hierarchy simulation, micro turbulence, energetic particles, macroscopic MHD, laser plasma simulations, and reconnection studies, etc. In JIFT program we have had productive collaborations. I like such an informal style of the review meeting this year, full day meeting is much better than sequence of half day meetings. PR, outreach including kids science museum are highly recognized. Very interesting LHD experimental results will be studied by theory and simulation people in NIFS. Talks in the afternoon were very good. I expect NIFS could have much more number of good talks in the same level. I confirmed the publication records are increasing. NIFS' presence at the last IAEA-FEC meeting were very impressive. Motojima sensei has been an excellent leader. I have been observing him for the education of myself.

Nishikawa: LHD program was discussed at the initiation phase, based on pure scientific arguments. I encourage young scientists to do the same thing: discuss among yourself, discuss from the pure scientific point of view, w/o concerns on budget, politics, discuss the future plan.

Tendler: Now stellarator has become from “Plan B” to “Plan A” under the Prof. Motojima’s strong leadership. Congratulations.

Closing address

Motojima: Thank you very much. I have been very much excited here. I express again thanks for all coming to Takayama. Your comments encourage us and stimulate our research. It is 20 years after the NIFS was founded. It is short in some sense and very long. I feel time flies. 20 years is enough to establish LHD experiment and simulation, to make the scientific framework. It is fun to see young people grow up and improve their capability. Within 3 months I will complete my work as a director-general for 6 years. I want scientists in NIFS to keep the momentum to realize fusion (in my calculation it will be 27 years and 1 month). I might be at the position of review committee member from outside of the institute. Finally I would like to give my sincere thanks to my wife. Without her support I could not have survived.

Inter-University Research Institute Corporation
National Institutes of Natural Sciences
National Institute for Fusion Science
322-6 Oroshi-cho, Toki, Gifu, 509-5292, Japan
http://www.nifs.ac.jp/