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Institute of Advanced Energy
Kyoto University

ANNUAL REPORT

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京都大学エネルギー理工学研究所

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Institute of Advanced Energy
Kyoto University

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Japan

CONTENTS

FOREWORD

The FY2006 was a milestone year for the Institute of Advanced Energy, Kyoto University. On May 13, 2006, the institute celebrated the 10th anniversary together with the Graduate School of Energy Science which was also established on the same day, May 11, 1996. During this decade, the condition concerning the world energy has become greatly tighter and even worse for Japan due to the sky-rocketed increase of the world energy demand caused by drastic increase of population and outbreak of economic activities of several countries. The institute faces the unprecedented challenge as the significance of the institute has increased as never before.

There is another challenge: the personnel and research fund from the government to the former national universities have decreased consecutively since FY2004. The institute has tried its best to increase research activities to the great extent through the striking increase in the competitive research funds in various energy-related fields, resulting in a number of distinguished achievements.

The prospect, however, of the future world energy as well as the environmental deterioration induced by the global warming calls for the urgent proposals and timely actions by the new energy system based on the innovative energy related technologies. We thus need to work hard to cope with these critical energy issues in the next decade, and to seek for the “Sustainable Energy System” worldwide. We strongly believe that it is our mission to challenge this difficult task and contribute to the benefit of the future generation.

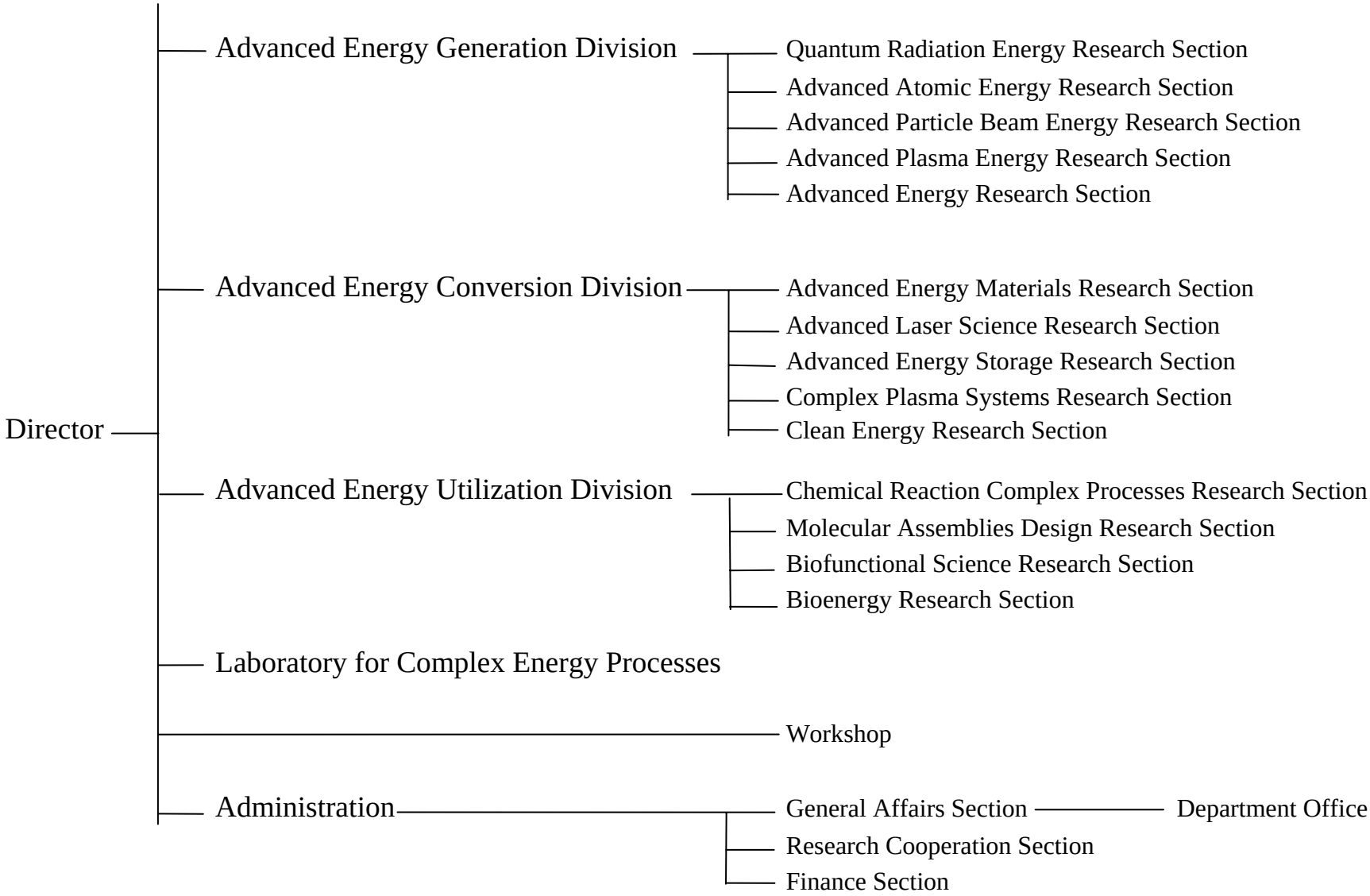
It is our great pleasure to present this updated booklet to provide you with a better understanding of the current activities of Institute of Advanced Energy, Kyoto University.

March 2007

（署名）

Kiyoshi YOSHIKAWA
Director
Institute of Advanced Energy
Kyoto University

ORGANIZATION CHART OF THE INSTITUTE OF ADVANCED ENERGY



BRIEF HISTORY OF THE INSTITUTE OF ADVANCED ENERGY

The Institute, established in 1971 as the Institute of Atomic Energy, was renamed on May 11, 1996, to the Institute of Advanced Energy with the consolidation of Plasma Physics Laboratory, to represent its research interests in advanced and socially acceptable energy systems in the entire processes of energy generation, conversion and utilization. The former Institute of Atomic Energy, the predecessor of which was the Engineering Research Institute founded in 1941 as originally seeking to carry out synthetic studies of engineering through the cooperative work of specialists in different fields, has sought since 1971 to assume part of the responsibility for peaceful applications of atomic energy and has performed various kinds of fundamental researches in nuclear engineering.

The recent rapid expansion of the research fields at the Institute of Atomic Energy toward various fields of energy sciences, such as systems engineering for social and environmental energy systems, advanced energy conversion researches in quantum engineering, physico-chemistry and materials science, consequently has brought about the new institute, i.e., the Institute of Advanced Energy in search of advanced and socially acceptable energy systems.

The Institute of Advanced Energy had joined to the Kyoto University 21st Century COE program named "Establishment of COE on Sustainable Energy System" from 2002 with Graduate School of Energy Science and Radio Science Center for Space and Atmosphere, Kyoto University. The 21st Century COE program was successfully completed in FY 2006. At the moment, extension of the COE program, International New Energy Cooperative Organization is going to be established.

In FY 2004, the structural reform of the national universities has started to introduce innovative and reasonable systems, completely different from the old systems.

Professors of the Institute give lectures on their specialized fields to students of the Graduate School of Energy Science. Graduate students in various specialized fields of energy science prepare their theses for Master's or Doctor's degree at the Institute under professorial guidance. The Institute also provides research opportunities to those who specialize in advanced energy science and engineering, and related fields covered by the academic staff. The educational activities of the staff are described in their respective sections.

The institute is located on the Uji campus of the university about 20 km south of Kyoto city. Additional facilities, for researches such as advanced materials, advanced chemistry, magnetoplasma, plasma direct energy conversion, plasma physics, and fusion engineering, are located in the campus with individual buildings.

The publications are renewed into the followings;
(1) Annual Report of the Institute of Advanced Energy, Kyoto University, (in English).
(2) Research Report of the Institute of Advanced Energy, Kyoto University (occasionally, in English).
(3) News Letter of the Institute of Advanced Energy, Kyoto University, (three issues a year, in Japanese).

The Institute consists of the following three main research divisions each containing four research sections, and an attached laboratory, with two visiting staff research sections in addition.

It is strongly encouraged for every research section or division to make joint collaborative researches with other divisions, to cope with, in particular, energy-related interdisciplinary critical issues we are facing at present or in the future to come.

I. ADVANCED ENERGY GENERATION DIVISION
(study publicly acceptable high quality energy generation of advanced energy)
- (a) Quantum Radiation Energy Research Section
- (b) Advanced Atomic Energy Research Section
- (c) Advanced Particle Beam Energy Research Section
- (d) Advanced Plasma Energy Research Section
- (e) Advanced Energy Research Section (foreign visiting professor)

II. ADVANCED ENERGY CONVERSION DIVISION
(study of improvement of efficiency and other performances in the functional energy conversion processes)
- (a) Combines and Varying Conversion Processes Research Section
- (b) Advanced Laser Science Research Section
- (c) Advanced Energy Storage Research Section
- (d) Complex Plasma System Research Section
- (e) Clean Energy Research Section (domestic visiting professor and associate professor)

Ⅲ. ADVANCED ENERGY UTILIZATION DIVISION
(study processes for high performance energy utilization)
- (a) Chemical Reaction Complex Processes Research Section
- (b) Molecular Assemblies Design Research Section
- (c) Biofunctional Science Research Section
- (d) Bioenergetics Research Section

IV. LABORATORY FOR COMPLEX ENERGY PROCESSES
(promote equipment designing, software development, and collaboration with domestic and foreign institutions for high quality energy processes, including generation, conversion, and utilization)

RESEARCH ACTIVITIES

Advanced Energy Generation Division

Quantum Radiation Energy Research Section

T. Yamazaki, Professor
H. Ohgaki, Associate Professor
T. Kii, Assistant Professor

1. Introduction

Coherent-radiation energy with wide wavelength tunability, high power and high efficiency is quite promising in the 21st century that is sometimes called the "era of light".

The research in this section aims at developing the technology to generate new quantum-radiation energy and apply the radiation in various fields; atomic energy including plasma heating, energy transportation in the universe, material science, material synthesis, electronic device, medical and biological science, etc.

Free-electron laser (FEL) is one of the powerful candidates for the new quantum radiation, and it is sometimes called the light source of next generation.

2. Construction of an IR-FEL facility KU-FEL

FEL is regarded as a light source of the next generation because of its wide wavelength tenability where the conventional lasers cannot reach, potential high efficiency, and high power. However, the system is usually much larger and the cost is higher than conventional lasers. We are going to overcome these difficulties by exploiting an RF (radio-frequency) gun, energy recovering system, etc.

The FEL system consists of a 4.5 cell thermionic RF gun, 3 m accelerator tube, beam transport system, and an undulator. Fig. 1 shows a schematic drawing of the system. The FEL system has been almost completed in the Laboratory for Photon and Charged Particle Research.

2.2 Beam commissioning

Beam commissioning was almost finished by the end of Mar. 2007. Electron beam of 9 MeV was successfully extracted from the RF gun, and of 40 MeV was obtained at the exit of the undulator.

2.3 Observation of spontaneous radiation

Spontaneous radiation was successfully observed in Dec. 2006. Fig. 2 shows an experimental setup for spectrum measurement. Optical resonator, a monochromator : DK240 (Digikrom Inc.) and an InSb IR detector : J10D-M204-R01M-60 (Judson Inc.) were aligned using a semiconductor laser. Electron beam trajectory was carefully controlled to optimize strength of spontaneous radiation using beam profile monitors and steering magnets.

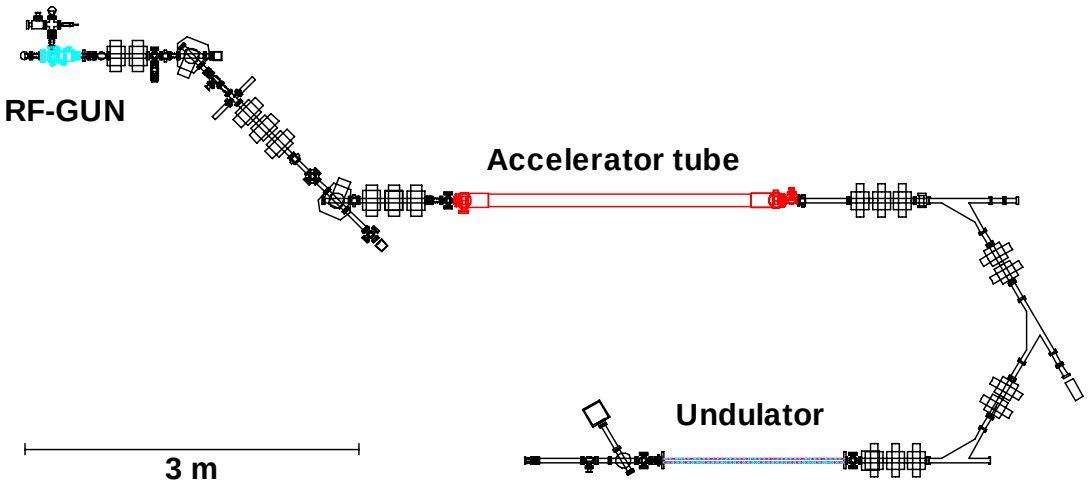


Fig. 1 Schematic drawing of the KU-FEL

2.1 KU-FEL

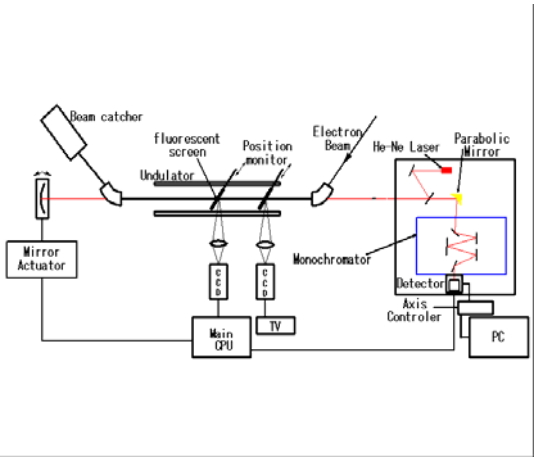


Fig. 2 Experimental setup for measurement of spontaneous radiation

Spectra measurements were carried out for the electron beam of 41.5 MeV and the undulator gap of 26.0 mm. The undulator parameters are listed in Table 1. Measured spectra and calculated spectra of spontaneous

Table 1 Parameters of the original designed undulator of KU-FEL

Length	1.6 m
Period	40 mm
Number of period	40
Gap	26 - 45 mm
Maximum magnetic field	0.25 - 0.045 T
K-value	0.95 - 0.17

radiation which is given by a simulation code SRW are shown in fig. 3.

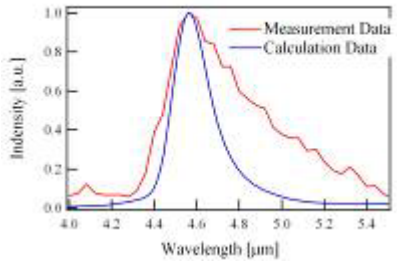


Fig. 3 Spectrum of spontaneous radiation

3. Improvement of thermionic RF gun

A thermionic RF gun is suitable for a compact and economical FEL system. However it is difficult to produce electron beam of pulse width longer than a few μsec with constant energy owing to inherent back-bombardment effect. To overcome the difficulty, we tried to reduce beam energy degradation due to the back-bombardment effect by feeding modulated RF power into a thermionic RF gun. In addition, we have performed a self-consistent transient analysis which took into account the backbombardment effect during macro pulse duration by using an equivalent circuit model and a thermal conduction.

3.1 Experiment

Fig. 4 shows the experimental setup. The cathode is of 6-mm diameter made of porous tungsten impregnated with barium. RF power fed into the RF gun is controlled by remotely adjusting the reactors in the pulse forming network (PFN) with stepping motors. The effect of the modulated RF input was evaluated experimentally by comparing the electron beam profiles when flat and modulated RF was fed to the RF gun. The profiles of the electron beam current were measured with current transformers (CT) and Faraday cups (FC). The energy spectrum of the electron beam was analyzed with a bending magnet, beam slit and CT2.

Fig. 4 Experimental setup

3.2 Results

We have succeeded to keep the peak energy of the electron beam constant in 4 μsec by feeding a modulated RF power into a RF gun. Fig. 5 shows the flat RF power waveform and the modulated RF power waveform fed into the RF gun. Fig. 6 shows the beam current waveform whose peak energy is 8.6 MeV at CT2. Fig. 7 shows the time evolution of the peak energy in macro pulse duration.

As shown in Fig. 6 feeding modulated RF power into a RF gun was an effective way to extend the macro pulse duration and to increase the beam current. As shown in Fig. 7 the beam energy which had been degraded in the latter part of the macro pulse duration was kept constant by feeding modulated RF power.

In order to confirm the validity of calculation model, experimental and calculated reflecting RF power waveform were compared. Fig. 8 shows the measured and reproduced reflecting RF power waveform when the modulated RF power was fed. Experimental and calculation results agree very well. We also estimated how long time the peak energy of the electron beam could be kept constant by using the KU-FEL 4.5 cell RF gun. We found that the degradation of the peak energy could be kept below 100 keV in the macro pulse duration of 8.0 μsec.

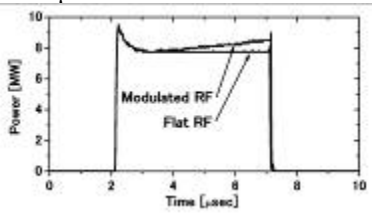


Fig. 5 Input RF power fed to the RF gun

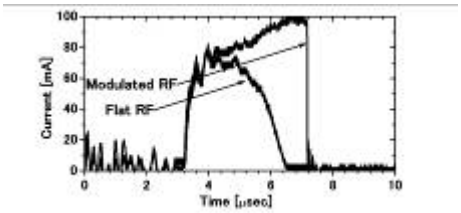


Fig. 6 Beam current for the different RF waveform

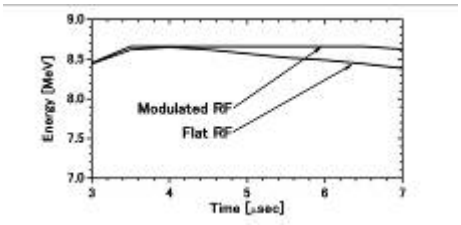


Fig. 7 Time evolution of the peak beam energy

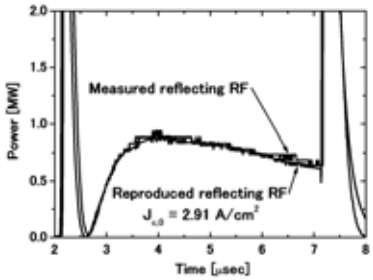


Fig. 8 Measured and reproduced reflected RF waveform form the RF gun

4 ESTIMATION OF FEL PERFORMANCE

We have calculated FEL gain and saturations to optimize beam parameter and optical resonator to obtain the maximum performance of the KU-FEL. The axial symmetric 3D code TDA3D was used to calculate FEL gain and saturation.

At the 180-degree arc between the accelerator tube and the undulator shown Fig. 1, we can control the electron beam parameters for the optimization. Among the electron beam parameters, a peak current (40 A), transverse emittances (11 πmm-mrad in horizontal, 10 πmm-mrad in vertical), and an energy spread (0.5%), which are evaluated by PARMELA, are fixed during the calculation. The other electron beam parameters, electron beam sizes and Twiss parameters are optimized to obtain the maximum FEL gains in three electron beam energies, 25, 30, 35 MeV. Electron beam sizes are RMS values. Twiss parameter α_y is set to zero due to the natural focusing of the undulator field. Optimization of the parameters of the optical cavity is also essential to enhance the FEL gains. We also optimized the optical parameters, Rayleigh range and beam waist position, for three electron beam energies. The optical cavity of the KU-FEL system has been designed taking into account the diffraction loss and the out coupling. The laser field is assumed to be the Gaussian in the calculation optical loss. The out coupling hole is 1mmϕ located at the upstream mirror. As the result, the curvature of upstream mirror is calculated to be 2.58 m and that of downstream mirror is 1.92 m. FEL gains with optimization of both of electron beam and of optical cavity are shown in Table 2. The realistic FEL gains are lower by a few % than those based on the design magnetic field distribution.

Table 2 Result of optimization

Beam energy (MeV)	25	30	35
Beam size in x (mm)	0.65	0.60	0.55
Beam size in y (mm)	0.33	0.36	0.36
Twiss parameter α_x	1.9	2.0	1.9
Twiss parameter α_y	0	0	0
Rayleigh range		0.40 m	
Beam waist position		0.60 m	
Wavelength (μm)	12.3	8.6	6.3
Out coupling (%)	4.0	2.5	0.8
Diffraction loss (%)	5.6	6.0	7.0
Total loss (%)	9.6	8.5	7.8
Gain of design undulator (%)	89	65	49
Gain of real undulator (%)	87	64	49

5 DESIGN STUDY ON HIGH-TC SUPERCONDUCTING MICRO-UNDULATOR

5.1 High-TC superconducting micro-undulator

A micro-undulator or short period undulator will be a useful device for a compact FEL device and/or a short wavelength FEL.

When a high energy electron beam moves in the periodic magnetic field, resonant wavelength emitted from the undulator λ_R is written by following well-known equations.

$$\lambda_R \cong \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \tag{1}$$

$$K = \frac{e \cdot B_0 \cdot \lambda_u}{2\pi \cdot m_0 c} \approx 93.36 B_0 \cdot \lambda_u \tag{2}$$

Here, λ_u is the undulator period and γ is Lorentz factor, K is the undulator parameter, e is the charge of the electron, B_0 is the maximum transverse magnetic field strength of the undulator, m_0 is the electron mass and c is the speed of light. To obtain shorter wavelength radiation, undulator period should be short or electron energy should be high. Thus, if the λ_u is limited, high energy electron beam is required for short wavelength FEL such as X-FEL. In other word, if a short period undulator realizes, high energy electron is not required. Moreover since the FEL gain increases as the number of period of undulator increases, the short period undulator will have advantage.

However, if we need K=1 for short period undulator of 5 mm, B_0 should be almost 2 T. Thus, to realize micro

undulator or short period undulator, strong transverse magnetic field is required.

To obtain transverse periodic magnetic field in a short period, we introduce following micro-undulator as shown in Fig. 9.

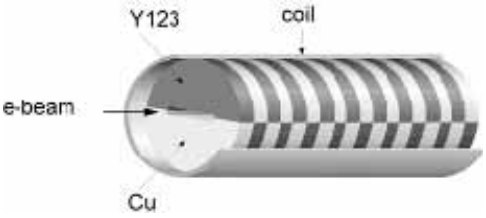


Fig. 9. Conceptual drawing of the high T_C SC undulator.

High Tc bulk superconducting materials are stacked in the solenoid. First, these superconducting pieces are cooled down below the critical temperature T_C. Then, a solenoid field is applied. As a result, density modulation of the magnetic field is produced, and thus the periodic transverse magnetic field is generated on the electron beam axis. To realize shorter period, in vacuum structure is planned. If we can control the magnetic field precisely, extreme good electron beam confinement can be realized.

5.2 Experiment

To confirm the proposed micro-undulator, a preliminary experiment has been performed. In this work, $YBa_2Cu_3O_7$ (YBCO) ceramic was selected as the high T_C superconducting materials, because it is easy to obtain, and Tc is higher than the boiling point of liquid nitrogen. Presintered YBCO powder made by Furuuchi Chemical Corporation was used for sample fabrication. Test peaces were made as following. The powder was pressed into disks and sintered in an oxygen-containing atmosphere for 12 hours at a temperature of 900° C, and annealed for 48 hours at a temperature of 500° C. Diameter of the test pieces was 27 mm and thickness was 2.5 mm. Superconductivity of the test pieces were checked by the Meisner effect and pinning effect using small permanent magnet on the cooled test material. Schematic drawing of the superconducting test piece is shown in Fig. 10.

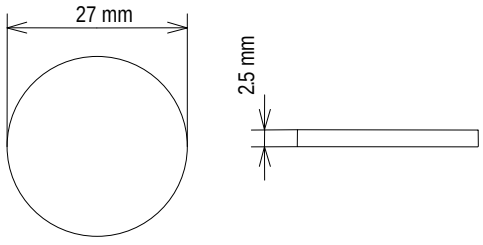


Fig. 10 Schematic drawing of the YBCO test piece.

Transverse magnetic field produced by the cooled ceramics was measured with a dipole magnet and a 3-Channel Gaussmeter Model 460, manufactured by Lake Shore Cryotronics, inc. Experimental setup is shown in Fig. 11.

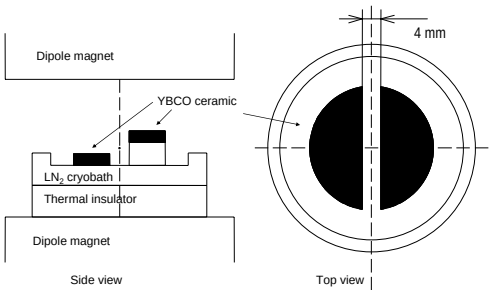


Fig. 11 Experimental setup.

Test piece was cut into two ‘D shapes’ for the transverse magnetic field measurement. The test pieces were cooled down to 77 K in a LN_2 cryobath. After cooled down below the critical temperature, they were moved into the gap of the dipole magnet. Longitudinal magnetic field of the strength in the range of 2 mT to 15 mT was applied. The magnetic field strength was measured using a Hall probe. The measured strength was about 0.5 mT, and did not depend on the amplitude of the longitudinal magnetic field.

To overcome this problem, strong pinning center should be introduced. Then the penetration of the vortex lines would be suppressed. Doping of Praseodymd is planned to introduce pinning center and increase critical current density. Although, zero-field cooling is introduced in this work, filed cooling is also considerable to produce transverse magnetic field. If the each superconducting pieces with strong pinning center are cooled in the strong solenoid field, each pieces work as strong permanent magnet of several T after the solenoid field is turned off. Such strong permanent magnet would increase the performance of hybrid staggered undulator. Although the peak field depends on the trapped magnetic field by the superconducting pieces, recently typical trapped field is greater than 2T, thus the peak field of greater than 1T is expected.

Advanced Atomic Energy Research Section

S. Konishi, Professor
Y. Yamamoto, Associate Professor
Y. Takeuchi, Assistant Professor

1. Introduction

The major objective of the study in this field is to research advanced energy technology for sustainable growth under global environmental constraints. The studies described below are featured by the consideration between technical possibility of better suitable energy generation and conversion systems with advanced technology, and socio-economic analysis of future society and markets that actually requires and utilizes such energy. The activity of advanced atomic energy research section covers wide areas of science and engineering based on plasma physics, atomic physics, and nuclear physics. Presently, following topics are studied in this research section:

(1) Assessment of fusion energy and energy system desuign
(2) Study of the compact neutron source using Inertial Electrostatic Confinement Fusion(IECF) by simulation and experiment
(3) Study of fusion reactor blanket with LiPb liquid metal.
(4) Development of Intermediate Heat Exchanger for advanced nuclear energy with SiC composite.
(5) Hydrogen production from biomass using high temperature heat from fusion reactor

In the fiscal year 2006, various interesting results were obtained in these activities. The followings report some of the topics.

2. Assessment of fusion energy

This study intends to analyze the future fusion electricity market in developing countries, where electrical characteristics of the grid is anticipated to be rather different from the ones in developed countries such as Japan. This year's activity in this field was focused as a part of the concluding work of the 21COE program, where this task is expected as summarizing the entire plasma (artificial solar energy) task area.

In the previous year, we suggested the adoptability of fusion energy in the developing countries based on the analysis of the electrical grid in Thailand. The network capacity in the developing countries are usually small, however it has better flexibility due to its composition based on hydro and fire powered stations that has less ration of the so called "base load" that is supplied by nuclear in the case of Japan. This feature is advantageous for fusion that requires large amount of starting power. However it is also suggested that reduction of starting power, stability and load-following capability of operation, high temperature heat generation as a the energy product, are remained importa21COE program in Kyoto, and our study integrated their results into a unified concept of the fusion energy system for future energy systems in the developing countries.

3. Study of the compact neutron source using Inertial Electrostatic Confinement Fusion (IECF) by simulation and experiment

An IECF(Inertial Electrostatic Confinement Fusion) device is small and simple, and is expected to be used as a compact neutron source. We propose a modification of cylindrical device that has some advantages for practical neutron use, and conducted the experiment and numerical study to optimize the configuration and operating condition.

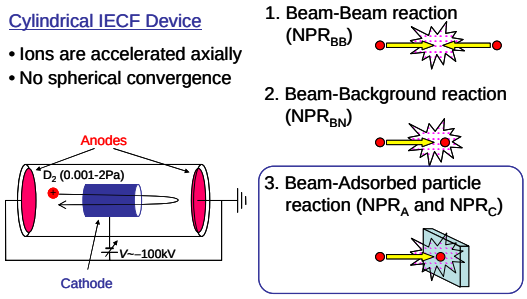


Fig.1 Collision processes in IECF device.

We have developed a particle-in-cell simulation code and analyzed the phenomena in IECF device. Our previous calculation estimated the contribution of the nuclear reaction rates of beam-baem (collision between high energy ions), and beam-background (collision between ion and neutral gas molecules) contribution of the atomic processes in the device, and pointed out that beam-beam reaction was not significant even in the low gas pressure range with assisted grow discharge. The low gas pressure is advantageous to reduce the charge

exchange between insufficiently accelerated ions and background neutrals, but at the same time the total number of collisions also decreases. We have further modified the code to take the wall – particle reaction into the account, and revealed that the reaction on the electrode surface plays a significant role, because the population of the adsorbed deuterium atom on the surface is not significantly affected by the pressure. Figure 2 shows the effect of this type of fusion reaction enhanced by deuterium density on the electrode surface on neutron production rate (NPR).

In this calculation, the surface of the electrodes are assumed to be covered with monolayer of deuterium atom.

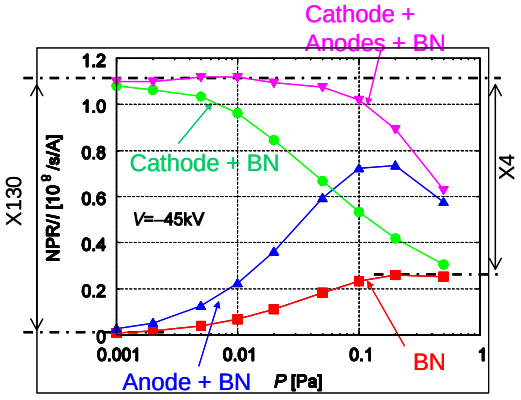


Fig.2 Calculated neutron production rates by various combination of surface reactions.

The calculation results showed the increase of NPRs on both anode and cathode, suggesting different pressure dependence, and the peak NPR increases by a factor of 4 . At 0.001Pa, where little collision between ions can be expected, NPR including reactions on electrode surfaces is enhanced by the factor of 130.

Based on this numerical prediction, we proposed a new type of device with titanium coated electrodes. The experimental evaluation by using a cylindrical-IECF device, with the various combination of electrodes has been conducted with an apparatus shown in the fig.3. As seen in the figure, the device is a cylindrical discharge chamber, with the electrodes made of stainless steel and coated with Ti by sublimating filament under vacuum.

Experiments were carried out with the combinations of the anode and/or cathode with coatings under the applied voltage up to 30kV and the pressure range 0.01 to 1 Pa. ECR ions source is used for the supply of ions to start discharge. Chamber is filled with deuterium gas, and the electrodes, when it is coated with titanium, adsorbs deuterium up to TiD2 hydride ratio.

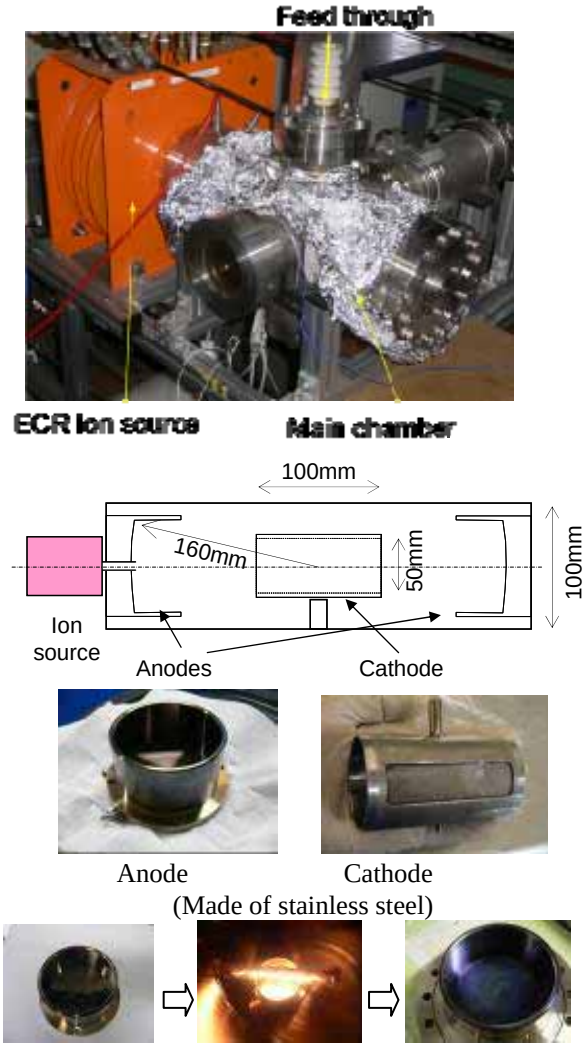


Fig. 3. New type of fusion neutron source with Ti coated electrodes.

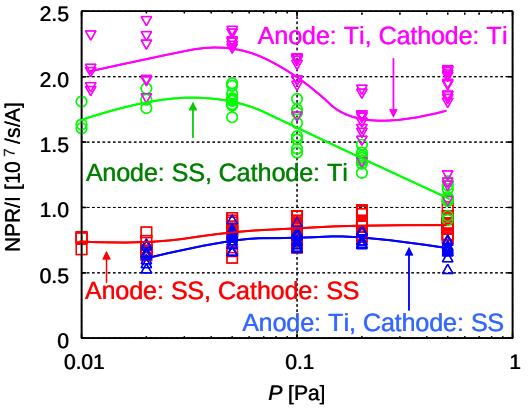


Fig.4 Experiments on neutron production rates by various combination of surface reactions.

As seen in the figure, enhanced neutron production by the Ti coating on the electrodes were proved. While cathode coating was effective, coating on only anode indicated almost no increase of the neutron. It was suspected heating of the electrode by the back bombardment by the electron resulted the desorption of the deuterium.

4. Study of fusion reactor blanket with LiPb liquid metal

Blanket is one of the most important technical issue of the fusion technology to utilize the fusion energy to convert from fast neutron to electricity or hydrogen. We propose the concept of the high temperature advanced blanket with the combination of liquid LiPb, SiC composite material, and helium coolant that can be operated at the temperature up to 900 degree C. This concept can be tested in the phase of the ITER Test Blanket Module (TBM) as one of the most conservative configuration with available technology, and at the same time has a capability to be gradually improved to utilize high temperature heat using advanced ceramic composite of SiC/SiC. The figure 5 shows the concept of the blanket we propose. The outer vessel is made of ferritic/martensitic steel cooling panel with proven technology. The tritium breeder and multiplier is LiPb eutectic to be slowly circulated to recover the fusion heat at the temperature as high as 900 degree C. SiC cooling panel made of the NITE composite developed by the Kyoto university works as an insulation to maintain the temperature of the outer vessel below 550 degree. The research activities in our laboratory on this concept covers wide range of the technical subjects such as;

1) design and numerical calculation on neutronics and thermal hydraulics,
2) material compatibility
3) MHD effect measurement
4) hydrogen behavior and control in SiC-LiPb system,
5) LiPb loop technology.

In this section, some of the recent results are presented.

Figure 6 and 7 show the typical thermal design of the blanket module. The breeder is designed to generate sufficient tritium at the ratio TBR>1.2 that can be designed with the neutronics code. In this case, 1D transport code ANISN was used to evaluate the tritium production from the neutron comes from the left side. Heat generation is at the same time obtained, and the figure 6 shows the temperature distribution calculated as the result of the nuclear heat and its removal by the helium flow so that cooling in the SiC channel will maintain the left side at 550 degree C that is below the limit for ferritic steel material.. Figure 7 summarizes results of the calculation showed such a cooling can be

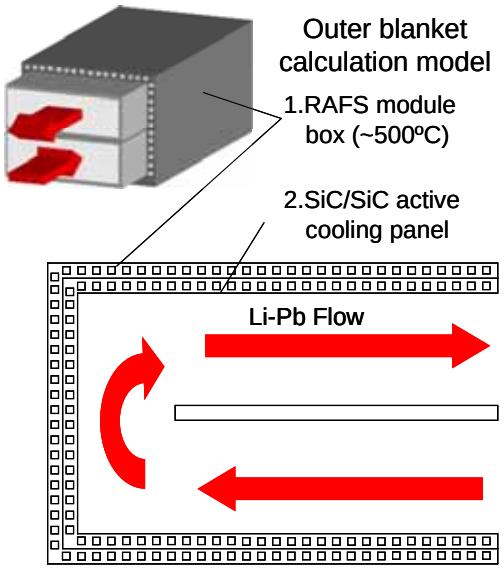


Fig.5 Cylindrical IECF device with energy spectrum analysis system.

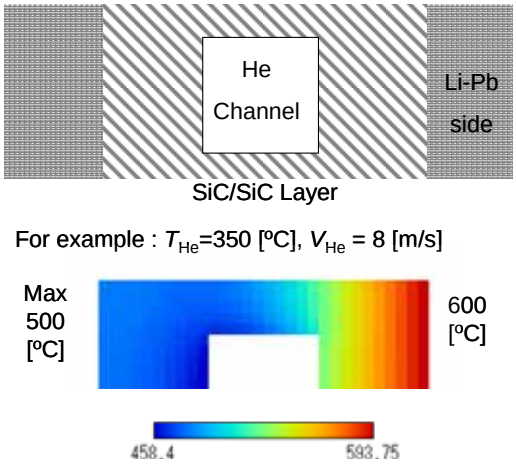


Fig.6 Temperature distribution in the SiC cooling panel. The right side faces 900 degree LiPb while the left is maintained below 550 degee.

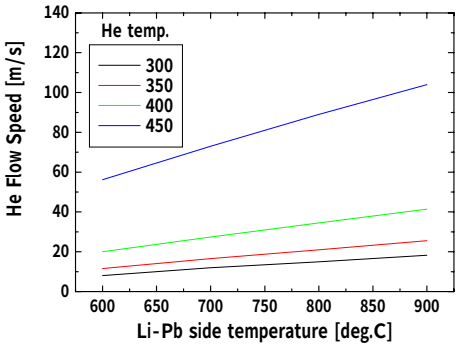


Fig.7 He flow speed and possible blanket temperature.

provided with reasonable flow speed of helium, while LiPb temperature is maintained high. This analysis showed it is possible to design such a device to achieve high temperature blanket with existing technology.

Tritium permeation is one of the important issue to realize the high temperature blanket. In our laboratory, we started the measurement of hydrogen permeation through advanced materials as shown in the Fig. 8. Disk samples dividing the high pressure and low pressure side of the apparatus is fixed with VCR fitting, and the amount of permeating gas through it was measured with quadrupole mass spectrometer.

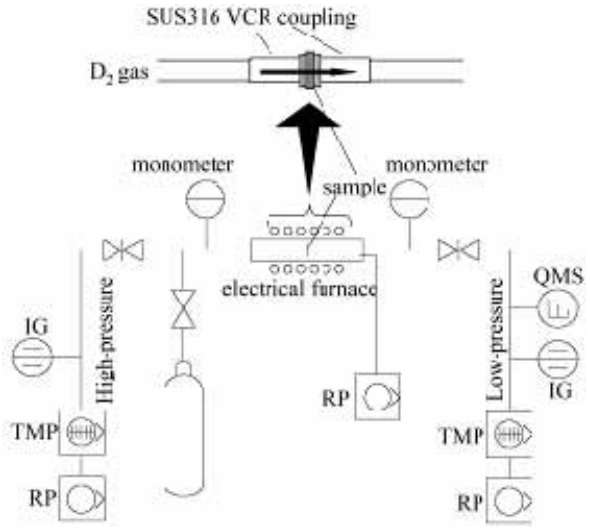


Fig.8 A schematic diagram of the experimental setup for hydrogen permeation through blanket materials.

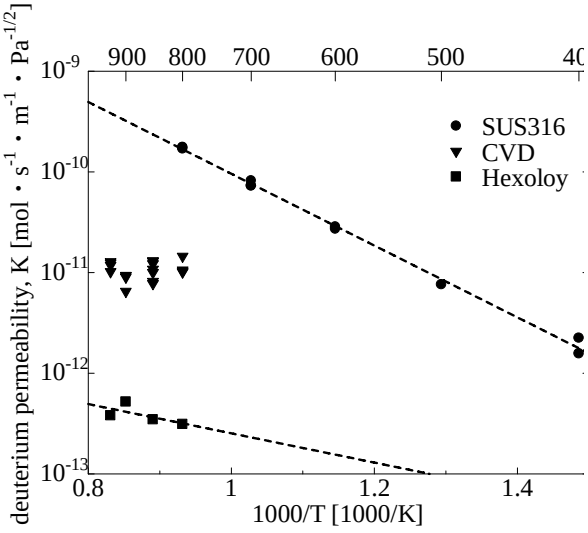


Figure 9 shows the temperature dependence of deuterium permeation in Arrhenius form. It was expected that SiC provides a very low permeability of tritium, but the present study showed the large difference between Hexoloy, (sintered alpha-SiC) and CVD beta SiC. Further measurement will continue to optimize the SiC composite material to be used.

5. Development of high temperature compact intermediate heat exchanger with advanced composite material

From early 2005, a new research project started in this division under a contract with the MEXT and JST on the development of compact intermediate heat exchanger with SiC composite material for high temperature use. This contract has subcontractors Japan Science and Technology Agency and Mitsubishi Heavy Industries. This is a 5 year program and 2004 and 2005 are its first and 2nd year, however the results can be opened for the public reporting only after it is approved. Therefore we introduce only the project outline and its very early results.

This project aims at the high temperature heat exchanger to provide heat transfer media of above 900 degree C to industrial level generation plant. In the previous studies, for instance in the case of High Temperature Gas Reactor, nuclear heat is used in a direct cycle that can be contaminated with fission product such as tritium and the generation plant required a control as a part of reactor system. With SiC composite, it is possible to have low tritium permeability and high temperature strength compact heat exchanger that can provide cleaner heat transfer media. High temperature gas is a primary target, but due to its chemical stability, liquid metal, water or other coolant is also expected to be used.

Figure 10 shows the typical structure and the example of the cooling channel. The project include development of fabrication process, test in liquid metal loop, compatibility and permeability test, heat transfer experiment, system design and analysis, and in-service inspection technique.

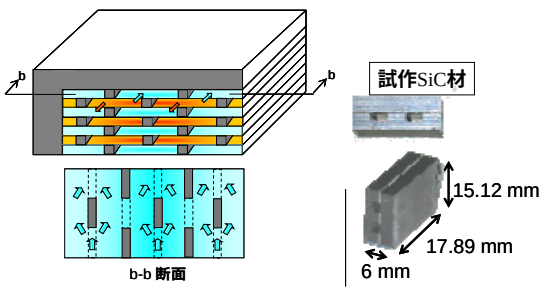


Fig.10 typical structure of the compact heat exchanger and the sample of the SiC composite cooling channel structure.

Advanced Particle Beam Energy Research Section

K. Yoshikawa, Professor
K. Masuda, Associate Professor

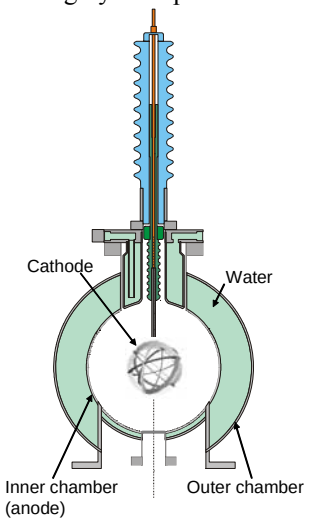
1. Introduction

Highly advanced and innovative control methods for the collective behavior of charged particle beams are being pursued, in particular, for a compact and portable neutron/proton sources driven by fusion plasmas for versatile uses such as humanitarian landmine detection, detection of explosives and illicit drugs and medical care, direct energy conversion of charged particle beams into electricity, highly brilliant relativistic electron beam production for advanced light sources such as free electron lasers. Studies of space-charge dominant interactions between energetic charged particles and electromagnetic fields are particularly emphasized. The educational function specializes in energy conversion, and electrical engineering in the graduate and undergraduate schools.

Main research subjects are now strongly focused on the followings; discharge-based compact fusion neutron/proton sources driven by inertial electrostatic confinement fusion (IECF), low-energetic metastable helium beam production for spectroscopic diagnostics of electric fields in plasmas and in vacuum, and highly brilliant electron beam production and diagnostics for free electron lasers.

2. Inertial Electrostatic Confinement Fusion (IECF)

An inertial electrostatic confinement fusion (IECF) device is a discharge-based compact fusion neutron/proton source. The IEC fusion device consists of a spherical vacuum chamber as an anode at ground potential, and a highly transparent central cathode grid at a large negative potential. Ions are accelerated to the center as they gain energy from the applied electric fields and the spherical focusing of ions results in a high ion density inside the grid. The use of a highly transparent cathode grid minimizes the ion loss to the grid and allows the significant recirculation of energetic ions.



A new IECF device has been manufactured as a compact neutron source. This device consists of double jacket chambers to provide sufficient water cooling, having the diameters of inner and outer chambers of, respectively, 20 cm and 30 cm as shown in Fig. 1. The effective water-cooling enabled the IECF device to operate at high cathode current of more than 80 mA. A target neutron yield of 1×10^7 has been achieved for cathode voltage of 80 kV and (cathode) current of 80 mA. Moreover, the IECF device employed a NEG pump as a main exhaust pump, which works as a deuterium gas source at the same time. A NEG can greatly reduce the weight of an IECF device and it could be an advantageous feature when the IECF device is applied for portable neutron source. Fig. 2 shows a typical run of the IECF device with NEG pump. The

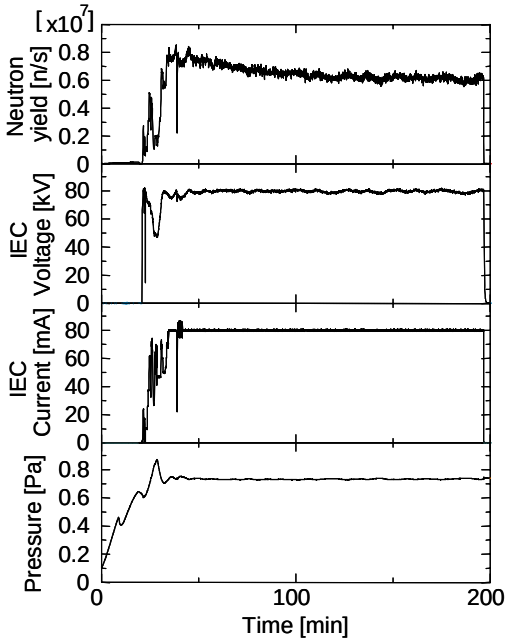


Fig. 2. A typical run of the NEG-based IECF device

stable run continued for more than 3 hours, producing a neutron yield of 0.6-0.8×10^7 n/sec. First, it took 30 minutes in order to heat NEG to suitable temperature, and then, glow discharge took place in the IEC device. After that, it took to maintain a target operation condition which is bias voltage of 80 kV and cathode current of 80 mA. As a consequence, it was found that the NEG pumping system can produce sufficient deuterium gas for the IEC neutron source.

The water jacket of a 5 cm width was designed as well to assure the sufficient reflection of 2.45MeV D-D neutrons downward, where a thinner 1cm thick water jacket is installed at the bottom. This non-uniformity of water jacket thickness resulted in multiplied neutron flux downward as shown in Fig. 3. In that figure, both of experimental and numerical results of neutron count rates obtained by ^{3}He proportional counter are shown as a function of vertical angle of counter position (angle between the vertical line from the center of the chamber and the line from the center of the chamber to the neutron counter). The results revealed that the non-uniformity of water jacket thickness results in non-uniform neutron flux density as expected.

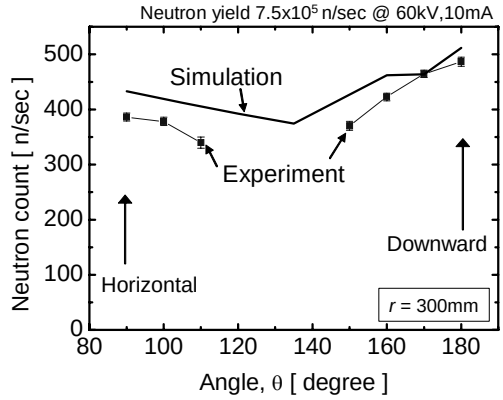


Fig. 3. Experimental and numerical results of neutron count rates obtained by ^{3}He proportional counter

Operated using D_2-^{3}He fuels, an IECF device can produce high fluxes of neutrons and protons from D-D and D-^{3}He fusion reactions. The following equations show the fusion reaction channels for D_2-^{3}He fuels.

$$D + D \rightarrow {}^3He\ (0.82\ MeV) + n\ (2.45\ MeV) \quad (1)$$
$$D + D \rightarrow T\ (1.01\ MeV) + p\ (3.03\ MeV) \quad (2)$$
$$D + {}^3He \rightarrow \alpha\ (3.52\ MeV) + p\ (14.7\ MeV) \quad (3)$$

Of particular interest, the protons from D-^{3}He reactions are highly energetic and can potentially be used to produce radioisotopes for medical use, e.g. Positron Emission Tomography (PET).

Last year we measured protons from D-^{3}He reaction by using solid state detector (SSD) and succeeded to reconstruct the spatial distribution of the reaction by analyzing the experimental results with and without 3 kinds of circular masks.

In the previous analysis, we assumed that the volumetric part inside IECF device was spherical symmetry. However, feedthrough (a cathode supporting rod in Fig. 4) can be a source of D-^{3}He proton's origin because it is made from Mo, which is the same material as cathode rings, and can be collided with a mass of accelerated ions. We found that the resolution near the center of cathode was insufficient in the previous analysis, because the circular mask is too large to resolve the center of cathode.

Fig. 4: Picture of cathode and feedthrough

So we manufactured a new proton counting system shown in Fig. 5 and could resolve these two critical problems. We obtained the result shown on Fig. 6 by a new proton counting system, which improves S/N ratio and the resolution. It shows that almost all (over 99 %) D-^{3}He nuclear reactions take place on the metal surface including the feedthrough.

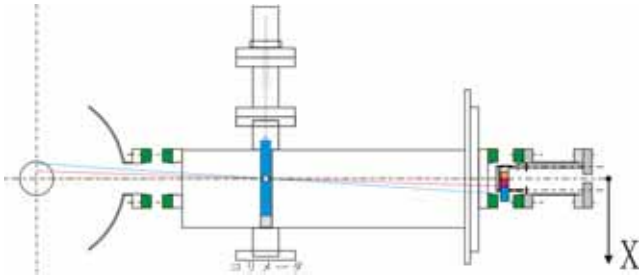


Fig. 5: Schematic view of a new counting system

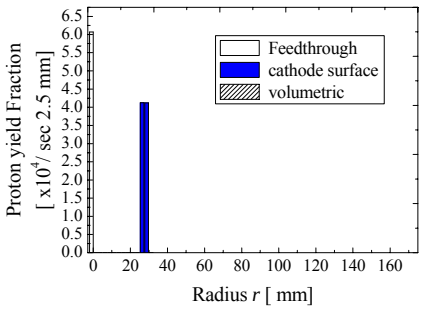


Fig. 6: Reconstruction of D-^{3}He proton distribution (the bias voltage at -51 kV, grid current at 28.5 mA, and P_{3He}/P_{total}=0.75)

3. Low-Energetic Metastable Helium Beam Production for Spectroscopic Diagnostics of Electric Fields in Plasmas

The Laser-Induced Fluorescence (LIF) method could be an efficient tool for understanding the electric potential formation in Inertial Electrostatic Confinement (IEC) fusion plasmas. Our LIF diagnostics system making use of the Stark effects in forbidden transition of He I has successfully revealed potential profiles in helium discharge IEC plasmas under relatively high operating gas pressure, where ample 2^1S metastable atoms are provided by the IEC discharges themselves. To extend its application to lower pressure operational plasmas and deuterium plasmas, we intensively develop a pulsed beam injector of low-energetic 2^1S helium atoms (see Fig. 7). The key R&D issue is to generate the pulsed metastable helium beam for LIF measurement. The measured LIF data are available for layout approximation of our devices.

Recently in this year, we generated the pulsed metastable helium beam without a skimmer and measured LIF signals (see Fig.8). It is found that there is a correlation between LIF intensity and exciter current. Furthermore, exciter current increase sharply if beam density exceed its threshold level.

We then developed a new layout (see Fig.9) to increase the beam density at the exciter, i.e. the excitor upstream of the skimmer. In this layout, we expect significant increase of the LIF signal owing to the aforementioned nonlinear dependence of the exciter current.

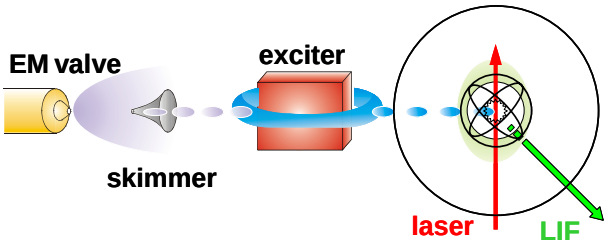


Fig. 7: Schematics of a pulsed injector of a supersonic metastable helium beam as a beam probe for the Laser-Induced Fluorescence method

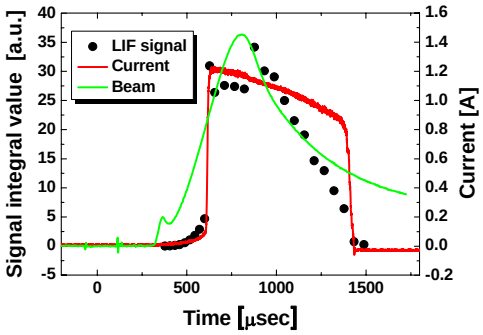


Fig. 8: Time distribution of exciter current and LIF signals by pulsed helium beam

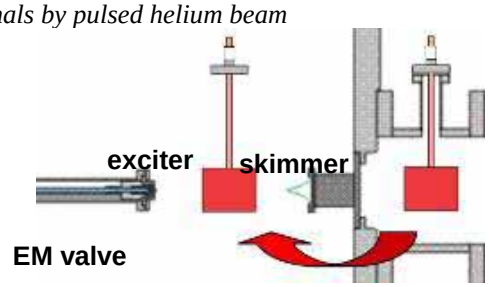


Fig. 9: A new developing layout of exciter for increase of the LIF signal

4. Highly Brilliant Electron Beam Production and Diagnostics for Free Electron Lasers

An electron beam with a high brightness and high averaged current is preferred for high power free-electron lasers (FELs). Rf guns can produce such electron beams in a compact system using resonance cavities. Particularly by the use of thermionic cathodes, rf guns show advantageous features compared with photocathode ones such as easy operation, low cost and high averaged current, which are suitable for their application to FELs for various uses. In long-pulsed operation of the conventional thermionic rf guns,

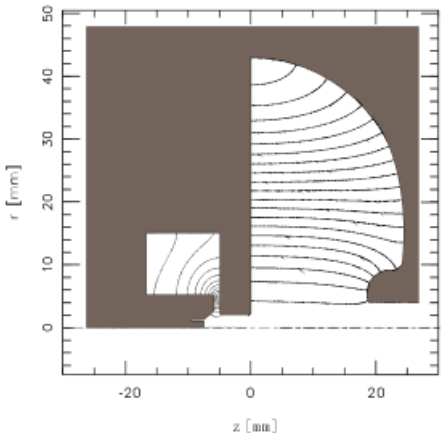


Fig. 10: Schematic cross-section of an rf gun with an rf-powered triode structure.

Table 1: Comparison of back-bombardment powers and output beams by conventional and triode rf guns.

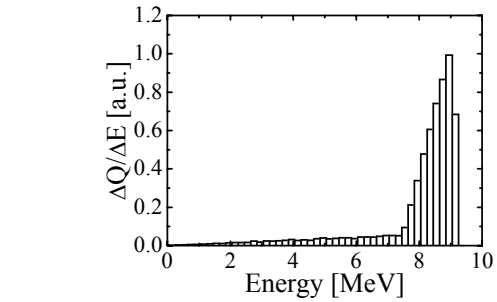
	conventional	triode
charge per bunch [pC]	29	29
transverse normalized rms emittance [π mm mrad]	2.0	1.3
longitudinal rms emittance [psec keV]	38	1.5
back-bombardment power [kW]	18	1.7

however, the back-bombardment of the electrons causes heating of the cathode surface, which destabilizes the electron beam extraction, and accordingly degrades the output beam properties. Several methods have been proposed to mitigate this problem with limited successes. As a result, the maximum pulse duration of the rf gun operation is limited to several microseconds, while a longer pulse duration would be desired for the FEL operation.

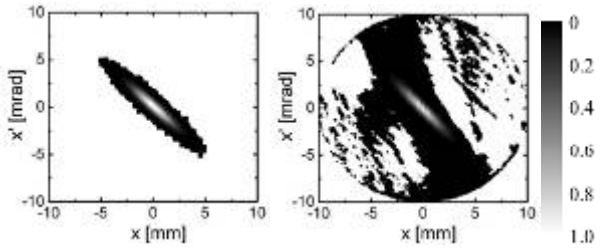
Against this adverse effect, we plan to introduce a new concept, rf triode structure in the 4.5-cell rf gun for the KU-FEL by replacing the thermionic cathode by an assembly of a cathode with an additional coaxial cavity (see Fig. 10), where the electron extraction from the thermionic cathode can be controlled by the rf phase fed to the additional cavity with respect to the main accelerating cavities. Design study by the use of two-dimensional numerical simulations has predicted a significant reduction of the back-bombardment power without degradation in output beam properties as summarized in Table 1, with a moderate rf power of several tens kW fed to the additional extraction cavity. The rf feed and control system are being installed for proof-of-principle experiments planed in FY 2007.

It is also very important for generation of highly brilliant electron beam and estimation of the FEL gain to evaluate experimentally the transverse phase space distribution of electron beam. Transverse phase space tomography method by the use of a set of a quadrupole magnet (QM) and a profile monitor is very useful method for this purpose.

Last year, we evaluated the effect of energy distribution on the tomographic method by using numerical simulation. The simulation results showed that the low energetic electrons, so called low energetic tail, inherently produced by thermionic rf gun severely distort the measured results (see Fig. 11).



(a) Simulated energy distribution



(b) Given distribution (c) Reconstructed distribution

Fig. 11: Condition and result of simulation.

This year, we have carried out experiments to measure the transverse phase space distributions and emittances at the exit of rf gun, where the low energetic tail is contained in the beam, by the tomographic method. For comparison and verification of the method, we also measured them by using single slit method which is not distorted by energy distribution of electron beam. Figure 12 shows the schematic view of experimental setup. The quadrupole magnet 1 (Q1) and beam profile monitor 1 (BPM1) were used for tomographic method. Movable slit and BPM1 were used for single slit method.

Figure 13 shows the experimental results of tomographic method and single slit method. The emittances were measured as 82 π mm-mrad and 2.8 π mm-mrad respectively. There was some difference between the two results. There are weak and scattered signals in Fig. 13 (a), but there are no such signals in Fig. 13 (b). The results are consistent with simulation results shown in Fig. 11. We also measured transverse phase space distribution by tomographic method after the energy filtering section which consists of dipole magnet and slit. The result is shown in Fig. 14. The measured beam had no low energy tail after the energy filtering section, and weak and scattered signals were not observed in reconstructed results.

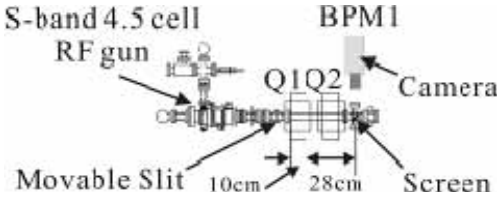
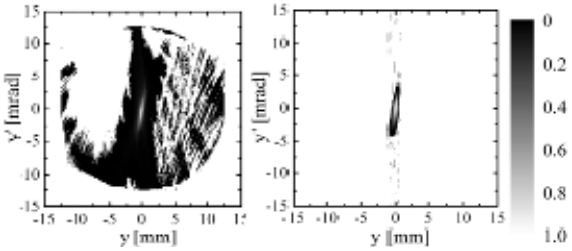
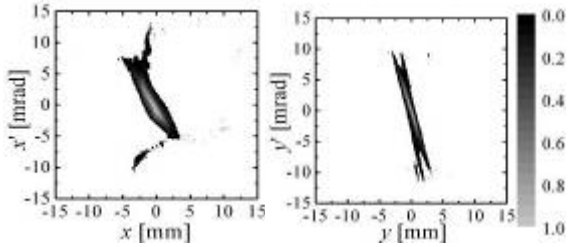


Fig. 12: Geometry of our experimental setup.



(a) Tomographic method (b) Single slit method

Fig. 13: Experimental results of tomographic method and single slit method.



(a) Horizontal (b) Vertical

Fig. 14: Experimental result of tomographic method after the energy filtering section.

Advanced Plasma Energy Research Section

T. Mizuuchi, Professor
K. Nagasaki, Associate Professor
A. Fujisawa, Lecturer
S. Kobayashi, Assistant Professor

1. Introduction

The current subjects of this research section are to study the properties of high temperature plasmas in order to control and improve the plasma energy confinement from the physical viewpoint of nuclear fusion research. The experimental and theoretical researches for the optimization of the helical-axis heliotron configuration are in progress under the collaboration with other groups including the bilateral-collaboration program among National Institute for Fusion Science (NIFS), other universities and institutes.

In this report, we describe some results obtained in the Heliotron J experiment in FY2006 focusing on (1) control of non-inductive current in Heliotron J, and (2) condition of spontaneous transition in NBI plasmas of Heliotron J.

2. Control of Non-inductive Current in Heliotron J

Control of non-inductive toroidal current is one of key issues to realize high performance plasmas in toroidal fusion devices. In helical systems, the toroidal current such as Ohmic current is not required for plasma equilibrium since the confinement magnetic field is generated by external coils. However, finite plasma pressure inherently drives non-inductive current, so called bootstrap current, which affects the equilibrium and stability due to the change in rotational transform. Theories predict that the bootstrap current can be suppressed by optimizing the magnetic field spectrum. From the diagnostic point of view, helical systems are advantageous to precise measurement of the total plasma current because of no inductive current. Small current of less than 1 kA order is possible to measure by using conventional Rogowski coils.

Electron cyclotron current drive (ECCD) is recognized as a useful scheme for controlling rotational transform and magnetic shear related to the heat/particle transport, equilibrium and stability. In helical systems, ECCD is considered to suppress the bootstrap current in order to tailor the current density profile. Furthermore, the detailed study on ECCD in helical system deepens our understanding of the ECCD physics in toroidal devices.

When the magnetic field at the magnetic axis is set at B = 1.25 T, which corresponds to the condition of ω_0/ω =0.50, a ray tracing calculation using the TRECE code shows that the EC power is deposited at off-axis of ρ = 0.2 due to the Doppler shift resonance, $\omega - k_{\parallel} v_{\parallel} = 2\omega_{ce}$. Here, ω_0 and ω are the electron cyclotron frequency on the axis in the straight section and the injected wave frequency, respectively. When the magnetic field strength is set lower as ω_0/ω = 0.49, the resonance layer moves toward the helical coil so that the EC power can be deposited at on-axis. Electron cyclotron emission diagnostic using a multi-channel radiometer confirms that centrally peaked T_e profile was formed at ω_0/ω = 0.49. Transmitted-wave measurements shows that the single pass absorption rate is estimated about 90 % consistent with the ray tracing results, indicating the single pass absorption has main contribution to plasma heating.

Figure 1 shows the density dependence of the measured toroidal current at ω_0/ω = +0.50 and ω_0/ω = -0.50 at the medium bumpiness (ε_b = 0.06) configuration. Here the plus (minus) sign denotes the clockwise (counter- clockwise) direction of magnetic field looking from the top of the torus. The positive current in the positive magnetic field increases the rotational transform. It is noted that the achievable line-averaged density is $n_e \sim 2.0\times10^{19}$ m^{-3}, limited by radiation collapse. In ECH plasmas, the toroidal current is composed of the bootstrap current and the EC current. The flow direction of the bootstrap current depends on the field direction and is changed by reversing the magnetic field, while that of the EC current is independent of the field direction. Therefore, these two components can be evaluated separately by comparing the experimental results from almost the same plasma discharges in positive and negative magnetic fields, We confirmed that the other plasma parameters such as stored energy were almost the same for both experiments. The bootstrap current increases with the electron density due to the increase in plasma pressure gradient, but it is saturated at $n_e > 1.0\times10^{19}$ m^{-3}. The plasma becomes more collisional with electron density, giving rise to the suppression of the bootstrap current.

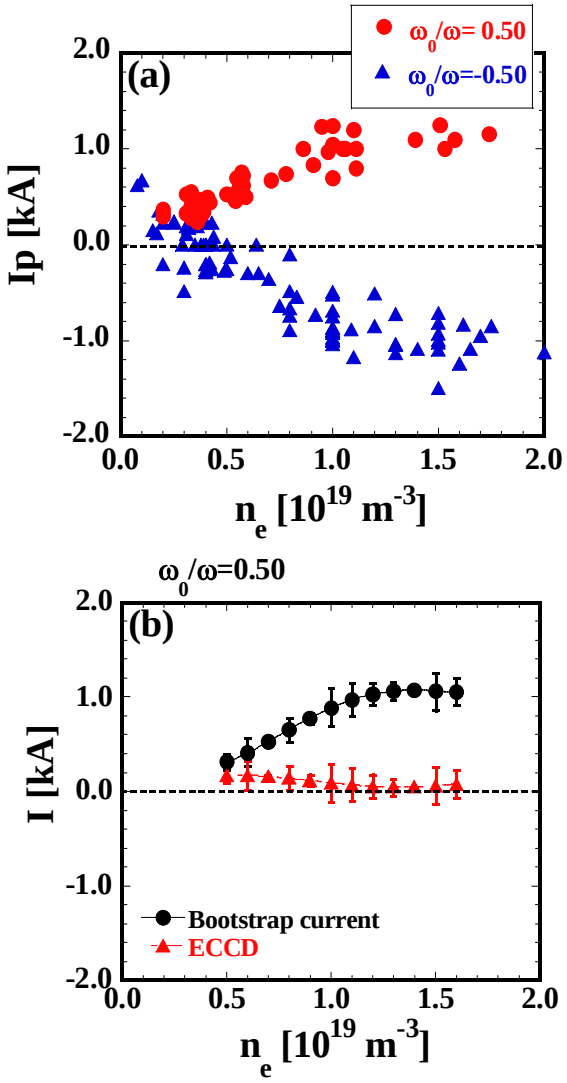


FIG. 1. Density dependence of non-inductive current at medium configuration, (a) measured total toroidal current at ω_0/ω = +0.50 and ω_0/ω = -0.50, (b) estimated bootstrap and EC currents.

The EC current is less driven for the whole density region under this condition.

Around ω_0/ω = 0.49, a large toroidal current has been observed, and the flow direction is changed by the bumpiness conditions of the confinement field. Figure 2 shows the density dependence of the EC current at ω_0/ω = 0.49 for different three bumpiness conditions. Here, the bootstrap current and the ECCD are separated. The positive EC current is driven at the high bumpiness (ε_b = 0.15) condition, while the positive EC current is driven at the low bumpiness (ε_b = 0.01) one. The decrease in EC current at $n_e < 0.2\times10^{19}$ m^{-3} is considered to be due to the reduction of single pass absorption. The maximum toroidal current of -4.6 kA has been observed at ε_b = 0.01 configuration, which is higher than the current including the bootstrap current and NB currents in NBI plasmas at high density of $n_e >$ 2.0×10^{19} m^{-3}. The maximum current-drive figure-of-merit is $n_e RI_p/P_{EC} = 8.4\times10^{16}$ A/Wm^2 (I_p = 3.2 kA, $n_e = 0.7\times10^{19}$ m^{-3} and P_{EC} = 320 kW). Here we take the injection power as EC power. This current-drive efficiency is lower than the linear theory, suggesting that the linear approach is not valid for 3-D magnetic field structure of Heliotron J.

One reason for the current reversal is that velocity space effects are responsible for the ECCD. The Fisch-Boozer effect considers the perpendicular excursion in velocity of a group of electrons with positive $v_{\|}$. Acceleration of these electrons causes an excess of electrons with positive $v_{\|}$, resulting in a current in the negative toroidal direction. On the other hand, the Ohkawa effect drives current in the direction opposite to the Fisch-Boozer current. Asymmetry in $v_{\|}$ is lost due to bouncing in the magnetic ripple, and a deficit in velocity space generates an electrical current in the positive toroidal direction. As shown in Fig. 3,

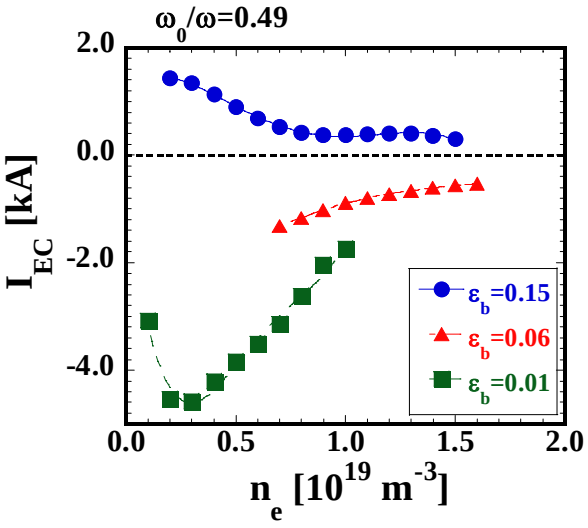


FIG. 2. n_e dependence of ECCD at ω_0/ω = 0.49 at several field configurations.

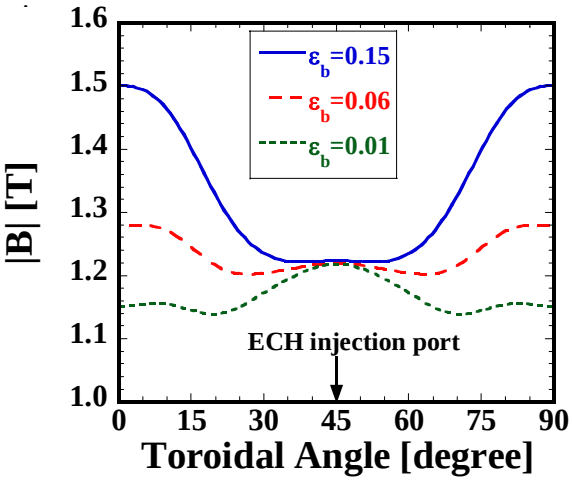


FIG. 3. Magnetic field strength along magnetic axis. The arrow denotes the EC wave injection position.

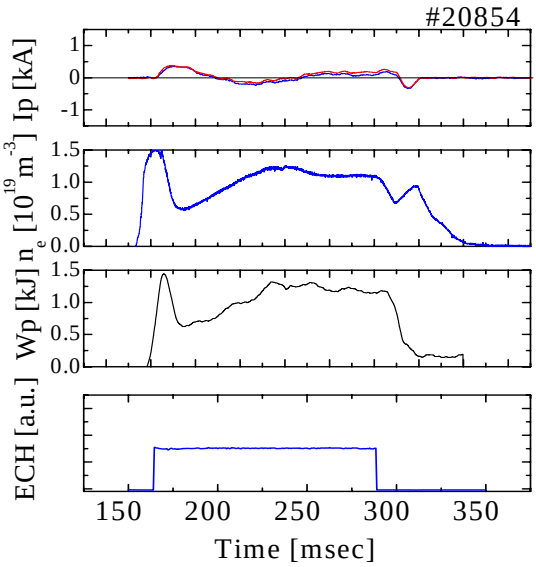


FIG. 4. Time evolution of ECH plasma with net free current.

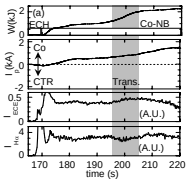
the electrons are heated at the ripple top in the low bumpiness configuration, and hence the Fisch-Boozer effect would be strong. On the other hand, in the high bumpiness configuration, the electrons are accelerated at the ripple bottom, and they tend to be trapped in the ripple, making the Ohkawa effect stronger. These qualitative predictions are consistent with the measured ECCD direction. The Ohkawa effect is comparable to the Fisch-Boozer effect in Heliotron J, and the ECCD direction is determined by the balance between them.

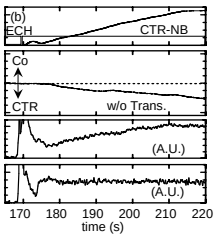
The bootstrap current can be cancelled by ECCD. Figure 4 shows time traces of the toroidal current, the electron density and the plasma stored energy at ω_0/ω =0.49 in the low bumpiness condition. Net zero current state ($|I_p| < 0.4$ kA) is maintained during the discharge by controlling the ECCD condition. Although local cancellation may not be fully realized by this ECCD because of their different current profile shapes, the EC current is comparable with the bootstrap current, and the ECCD has a potential to tailor the rotational transform profile to avoid rational numbers in rotational transform.

3. Condition of Spontaneous Transition in NBI Plasmas of Heliotron J.

The control of the toroidal current by the neutral beam driven current (NBCD) is important in conjunction with the bootstrap (BS) current control by changing the bumpy field component because of the low magnetic shear configuration of Heliotron J. In the previous study of the spontaneous transition in ECH plasmas of Heliotron J, the enhancement factor of the plasma confinement after the transition has been discussed from the viewpoint of the rotational transform at the plasma edge. The toroidal current by NBCD can be controlled by changing the beam power and injection direction. In this section, we present the results on the condition for the appearance of the spontaneous transition in neutral beam injection (NBI) plasmas of Heliotron J.

The power scan experiments were carried out in the Co- and Counter-NBI plasmas in the three bumpy magnetic filed configurations at ε_b = 0.15 (high), 0.06 (middle) and 0.02 (low). The edge rotational transforms in these configurations are close to m/n = 7/4 rational surface, where m and n are the poloidal and toroidal mode numbers, respectively. Figures 5(a) and 5(b) show the time evolutions of the plasma stored energy, toroidal current, intensity of electron cyclotron





emission and Hα line emission in the (a) Co- and (b) Counter-NBI plasmas at the standard configuration (medium ε_b) of Heliotron J. The plasma was produced by the 70GHz ECH for several ms, after that, the neutral beam was injected into the plasma. The beam power in the two cases was almost the same; 530kW and 550 kW in the Co- and Counter-NBI cases, respectively. The electron densities were around 2.0 ~ 2.5×10^{19} m^{-3}. Only in the Co-NBI plasmas, a sudden drop of the Hα intensity followed by increases in the stored energy and ECE intensity was observed at t = 195 ms. These phenomena are similar to those of the H-mode transition obtained in tokamak devices. In this configuration, since the direction of the bootstrap (BS) and the neutral beam driven currents (NBCD) are the same one, the toroidal current was reached up to 1.5 kA in the Co-direction but it was around 0.7 kA at the drop of the Hα intensity. In the Counter-NBI case, on the other hand, no clear transition was observed.

The time delay of the drop of the Hα intensity after the NBI turned-on is shown in Fig. 6 as a function of the input power of NBI (P_{INP}) at the standard (medium ε_b) and the high bumpiness (high ε_b) configurations. These data was obtained at the almost the constant density around 1.5 ~ 2.0×10^{19} m^{-3} in the Co-NBI plasmas. The delay time in the two configurations decreased with the injection power. In the standard configuration, the delay time was about 20 ms around P_{INP} = 500 kW. On the other hand, it was elongated longer than 40 ms in the low injection power around 200 kW. In the compact helical system (CHS), the medium sized helical device R/a = 1/0.2 m, an edge transport barrier (ETB) has been observed and its threshold on power and density has been reported by S. Okamura et al. (Nucl. Fusion 45 (2005) p863). The delay time dependence on the power is similar to the Heliotron J result.

The influence of the low-order rational surface on the transition to the high confinement modes has been

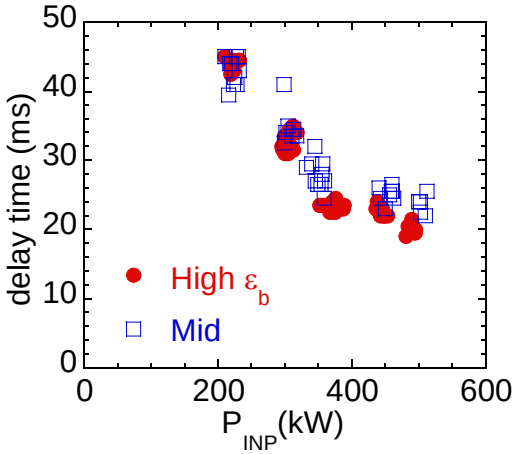


FIG. 6. Time delay from NB turn-on to the drop of Hα line intensity as a function of NB power.

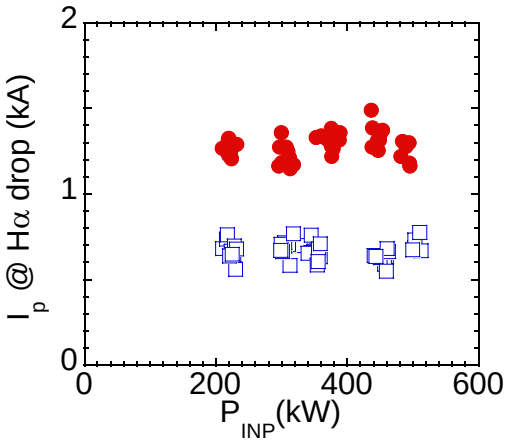


FIG. 7. Plasma toroidal current at the drop of Hα line intensity as a function of NB power.

discussed in several devices. In order to investigate the relation, we examined the plasma toroidal current at the occurrence of the spontaneous transition. Figure 7 shows the dependence of the toroidal current at the drop of the Hα intensity on the injection power. In the Heliotron J device, the effect of the toroidal current on the change in the magnetic configuration is sensitive because of its low magnetic shear. These data were obtained at B_T = 1.25T and the averaged beta around 0.3 %, meaning that the beta effect on the configuration is not so serious as compared with the toroidal current. Clear characteristics of the toroidal current are found, that is, the spontaneous transition was occurred at a fixed toroidal currents of 0.7±0.1kA in the middle ε_b case and of 1.3±0.2kA in the high ε_b case, respectively. According to numerical calculations of the BS current, the direction of the BS current in the middle and high ε_b cases were the same as that of Co-NBCD. The positive toroidal current has a possibility to change the rotational transform profile, resulting in the appearance of m/n = 7/4 surface. The magnetic shear $\Delta\iota/\iota(a)$ in the high ε_b configuration is higher than that in the medium ε_b one. Accordingly, the differences between the m/n = 7/4 rational number and the rotational transform at r/a = 0.5 are 0.025 and 0.017 in the high and medium ε_b cases, respectively, which may be the cause of the differences in the toroidal currents at the occurrence of the transition in the two configurations. Note that no clear transition was observed in the low ε_b configuration under the same experimental conditions of the heating power and plasma density, although the edge iota is almost similar to that of the other two configurations. In the low ε_b configuration, the BS current was expected to be relatively low or in the opposite direction to Co-NBCD. These results suggest that the existence of m/n=7/4 rational surface may have a contribution to the occurrence of the spontaneous transition.

Advanced Energy Research Section

Alexander E. Kaplan, Foreign Visiting Professor
(Professor, Department of Electrical Engineering,Johns Hopkins University, Baltimore, MD, USA)

1. Introduction

It was my first visit to Kyoto University and to Japan in general. I met Prof. Miyazaki long time ago in Germany, and was glad to have an opportunity to work with him and his group during this summer of 2006. I was familiar with his exciting experimental work on ultrafast effects due to by femtosecond laser pulses, and for me it was a rare chance to collaborate with his group. To me, the most attractive feature of Prof. Miyazaki's research is that he seems to always target the front-line and very advanced subjects. Some of his most recent research was on high harmonics generation in molecules and on sub-wavelength, nano-ripples formation on the surface of diamond-like carbon films irradiated by a train of superimposed femtosecond pulses. The latter one seemed to be the most interesting subject for our collaborative research.

2. Nano-structures on laser-irradiated surfaces

It was well known for about 25 years that a surface of almost any known solid-state material irradiated by sufficiently long (usually nanosecond) laser pulses of high intensity forms the so called ripples, i.e., corrugated wave-structures, with the spacing between individual ripples being of the order of laser wavelength. The literature on the subject is huge; many groups have contributed in the study of that universal phenomenon; the generally accepted explanation of it was formulated by leading theorists in the field including Siegman, Sipe, an others. That explanation relies on the mechanism whereby ripples are due to the interference between incident wave and surface scattered wave, with the material pattern being formed mostly by ablation.

An unexpected recent discovery, of which Prof. Miyazaki's group made one of pioneering contributions, was that if the irradiation is done by much faster pulses (100 femtosecond and faster), thin films made of various materials exhibit formation of spatially periodic structures with the period significantly shorter than the laser wavelength, to the order of magnitude in the extreme cases. These new structures can be called nano-ripples, since their period is in the nano-scale domain. The observation of this effect signified a very fundamental change of our understanding of the processes involved; besides, it holds a promise for new applications, such as e. g., efficient laser-based fabrication of nano-structures, diffraction gratings and mirrors for extreme ultra-violet and soft X-ray domains, holographic etching for the same domains, etc. In spite of quite a few experimental publications by now by a few groups, no physical explanation of the effect has transpired, and no theoretical model or mechanism of the effect has been put forward.

We set out to make a collaborative effort do identify the major mechanisms of the new effect, and to develop, if feasible, its theoretical model that would allow one to understand and control the growth of the nano-ripples and their parameters.

3. Current progress in model development

We first identified a few most representative features of the phenomenon, which are listed here in the order of their "universality": (1) nano-scale and sub-wavelength ripple spacing; (2) nano-ripples always run normal to the polarization of linearly polarized light, no ripples are formed in circularly polarized light; (3) non-resonant behavior with respect to the laser frequency; (4) nano-ripples appear at the intensities below the critical intensities needed to single-shot

ablation; (5) they always need to have an "incubation" period or number of laser shots; thus they have accumulation nature, and show structural irreversible memory; (6) their special period generally is the smallest near the lower threshold of the laser power needed to excite them, and increases as the laser power is increased. (Other features are more material-specific.) There is no doubts that the comprehensive theory of the phenomenon should be quite complicated, but we set out to explain first at least the major two (#1 and #2) features, and then move further on to build up a "block-model" that but will clarify the major avenues for possible experimental developments. Next goal would be to make sort of a road-map to full understanding of the nature of nano-ripples; the ultimate goal is to develop their robust model and use it for practical and research purposes.

Thus, the major effort of my research has so far been concentrated on the powerful near-field interaction between laser-driven free electrons in very thin layers using low-dimensionality approximations. It have already revealed previously unknown phenomenon, which I would call laser-induced "nano-stratification" of electron gas. It is based on very strong dipole-dipole interaction between near-located electrons, that goes beyond the well-known effect of the so called local field (i.e., the one resulting in the Clausius-Mossoti relationship for dielectric constant of sufficiently dense materials). The main assumption on the local field theory is that the dipole-dipole interaction results in showed, however, that at certain conditions on the frequency, electron density, and temperature, this uniform polarization becomes spatially unstable, and can produce traveling or standing spatial waves with very short spacing between their maxima or minima, comparable with the mean distance between free electrons. These standing waves can then in turn cause strong local heating resulting in irreversible thermal expansion and/or structural changes. Furthermore, our theory of these excitations based on both analytical approach and numerical simulations, showed that the nano-ripples are strongly anisotropic with respect to the laser polarization: their spatial period along the direction of polarization is much shorter than in the direction normal to the polarization.

At relatively low temperature or high electron density these structures can essentially be viewed as the standing excitation waves of Wigner crystal (and thus may be called a "Wigner excitons"; they are also reminiscent of the waves related to Frenkel excitons). However, at higher temperatures, more relevant in the case of pre-ablation laser pulses, they represent even more interesting phenomenon of well-defined and well-ordered spatial waves of the amplitude of laser-driven electron oscillations of highly exited electron gas rather than Wigner crystal or liquid.

4. Plans for further collaborative research

We are planning further collaborative research, to be continued along a few lines: (i) to complete the efforts on current theoretical model and prepare and submit the pilot paper(s) on the subject for publication; (ii) to develop more detailed plasma and solid-state approaches aimed to bring the results to a form that would allow the model to be comparable and verifiable through experiment; (iii) if the spatial frequency & polarization properties of the nano-stratification appear to be consistent with experimental data, to develop the model of the irreversible structural changes and "memorization" of the nano-ripples at the surface of material, their amplification during incubation period, etc.

Advanced Energy Research Section

In Sup Kim, Foreign Visiting Professor
(Korea Advanced Institute of Science and Technology, Daejeon, Korea)

Professor Akihiko Kimura invited me at IAE, Kyoto University from January 1 to March 31. The aim was to intensify and develop further the cooperative research program between KAIST and IAE, which has been carried out since 2002, mainly through CUP program. Although the present invitation period was 3 months, an inevitable program change in KAIST, forced to reduce to 2 months. Yet the original aim was successfully achieved by intensive efforts.

Between Professor Kimura and myself, there has been a cooperative research program on irradiation effects on cladding stainless steel of pressure vessel steels and on oxide dispersed steels. Both materials have been irradiated in Hanaro in Korea and JMTR of JAERI, after which the investigations were carried out both in KAIST and in IAE. So far 4 research papers have been published in International Journals as listed below.

J.S. Lee, In Sup Kim, R. Kasada and A. Kimura, " Influence of neutron irradiation on hardening and embrittlement phenomena in reactor pressure vessel cladding material," Materials science forum, Vol. 40, P. 4477-4482, 2003.

Joosuk Lee, In Sup Kim and A. Kimura, " Application of small punch test to evaluate sigma phase embrittlement of pressure vessel cladding material, " Journal of Nuclear Science and Technology, Vol. 40, P. 664-671, 2003.

In Sup Kim, J. S. Lee, and A. Kimura, " Embrittlement of ER 309 stainless steel clad by sigma phase and neutron irradiation," Journal of Nuclear Materials, Vol. 333, P. 607-611, 2004.

J. S. Lee, In Sup Kim, R. Kasada, A. Kimura," Microstructural characteristics and embrittlement phenomena in neutron irradiated 309L stainless steel RPV clad," Journal of Nuclear materials, Vol. 326, p.38-46, 2004.

For the present visit of two months, we proceeded to produce some outputs from the on going project on the embrittlement and hardening during thermal aging of the oxide dispersed strengthening steels.

1. Introduction

Since ODS steels have been developed for high temperature applications from 400 to 700 ^{o}C, they will experience thermal aging at prolonged service period.

It is known that aging of high Cr ferritic steels can form coherent particles of (Cr-rich ferrite) with an increase in ductility and tensile strength [1]. The embrittlement is observed in Fe-Cr steels [2, 3]. However, limited data are available for microstructural and mechanical property changes of high Cr ODS steels after thermal aging. The effects of thermal aging treatment on the microstructural stability and mechanical property changes of ODS steels were observed through TEM, Microhardness and small punch (SP) tests.

2. Experiment

Five kinds of ODS steels(K1 – K5) with different Cr contents were tested. Thin foils for TEM were made in a twin jet polisher with 10% perchloric acid and 90% ethanol at -30 ^{o}C. Disk type small punch and tensile specimens were sampled from the extended rod so that the axis direction is parallel to the transverse and longitudinal to the extruded direction.

SP tests were performed at a cross-head speed of 0.2 mm/min. at temperatures from 20 to -196 ^{o}C. Specific SP energy was determined by the area under the load-deflection curve per unit thickness of the given specimen, and the SP ductile to brittle transition temperature (SP-DBTT) was defined as the temperature where the specific SP energy was the average of the maximum specific SP energy and the lower shelf energy. Specimens were thermally aged in a vacuum chamber at temperatures from 430 to 475 ^{o}C up to 1000 hours.

Vickers micro-hardness tests were carried out with a 500 g load at room temperature. At least 8 measurements were made on each sample.

3. Results

SP load-deflection curves as a function of test temperature, before and after aging treatment at 437 ^{o}C for 322 hours, are shown in Fig. 1.

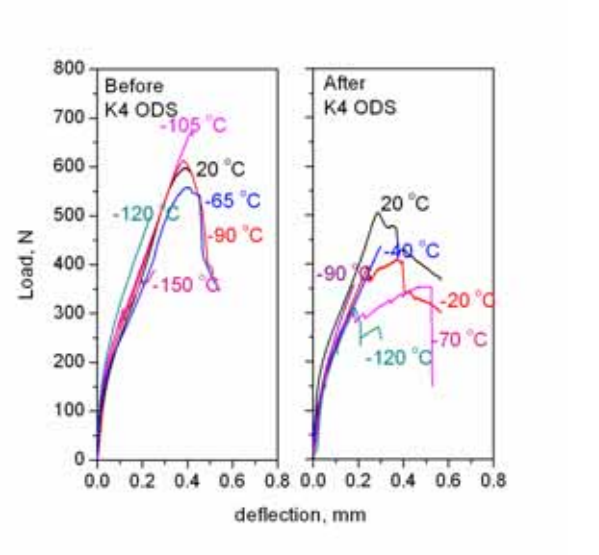


Fig. 1. SP load-deflection curves of 19Cr ODS (K4) steel before and after thermal aging treatment at 437 °C for 322 hours.

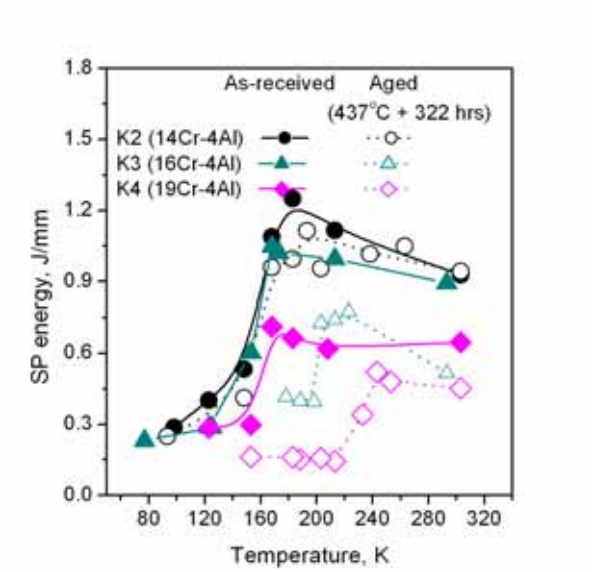


Fig. 2. Effects of thermal aging treatment on the specific SP energy of the ODS steels as a function of test temperature, for samples thermally aged at 437 ℃ for 322 hours.

After aging, the sample revealed a significantly embrittled nature such that the maximum SP load was greatly reduced and complete brittle fracture was observed below -40 ℃.

The changes in SP energy by thermal aging are summarized in Fig.2 showing an increase in SP-DBTT and a reduction in upper shelf energy. The hardening of each ODS steel by aging treatment at 475 °C, is presented in Fig.3. As aging time increased to 1000 hrs, the hardness increased exponentially. When Cr content

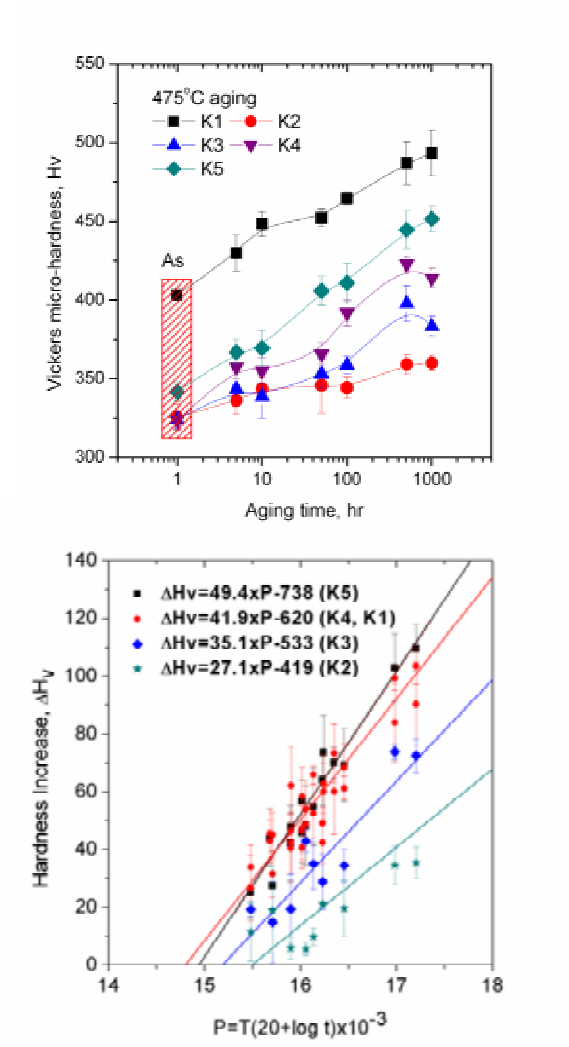


Fig. 3. (a) Vickers micro-hardness (Hv) as a function of the aging time in each ODS steel, thermally aged at 475 °C and (b) increase in Vickers micro-hardness (ΔHv) as a function of the aging parameter P, $P=T(20+\log t)\times10^{-3}$, where T is the temperature and t is the aging time.

increased from 14 to 22 %, the hardness increased from 30 to 110. The hardening behaviors of ODS steels as a function of aging parameter of ODS steels as a function of aging parameter, P, are poltted in Fig. 3(b). P is the Larson-Muller parameter divided by a factor of three, and

$$P = T(20 + \log t) \times 10^{-3}.$$

The ΔH_V in each ODS steel revealed a linear relationship with the parameter P.

Gradual microstructural changes were identified, depending on the aging time, when the samples were thermally aged at 475 °C. Fig. 4 shows the formation of

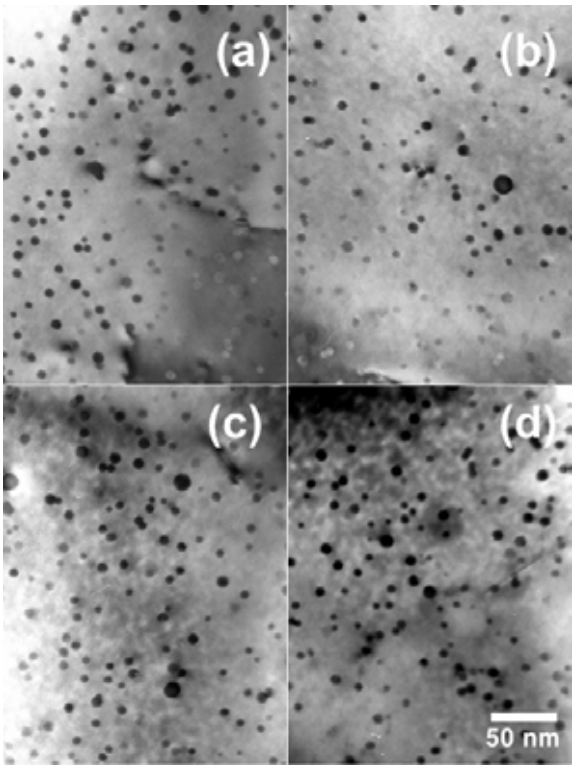


Fig. 4. Transmission electron micrographs, showing a thermally aged 22Cr (K5) ODS steel at temperature 475 °C up to (a) 5, (b) 50, (c) 505 and (d) 1000 hours, respectively, black dots=oxide particles, bright field images.

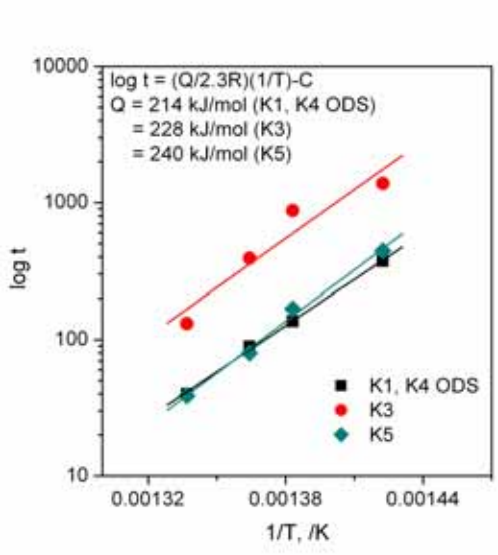


Fig. 5. Activation energy of each ODS steel determined by micro-hardness data based on Arrhenius type rate equation.

a two-phase modulated structure (gray and white) in the ferrite matrix as aging time increased. Based on the EDS line scanning element profiles, we could know that it resulted from the formation of Cr-enriched and separate Fe-enriched zone. But, the number density and size of the oxide particles remains the same under the current aging conditions.

The activation energy of each ODS steels was determined by microhardness data based on Arrhenius type rate equation, which is shown in Fig.5 as 214 ~ 240 kJ/mol.

4. Summary

After thermal aging treatments at temperatures from 430 to 475 °C, the degree of embrittlement increases with Cr content such that the increments in SP-DBTT were about 10, 50 and 73 °C in 14, 16 and 19 Cr ODS steel, respectively.

Based on the TEM investigations, the main cause of embrittlement is the formation of Cr-rich coherent ferrite phase, α' phase.

The apparent activation energy of thermally activated hardening is measured in the range of 214~240 kJ/mol, which is similar to the diffusion activation energy of Fe and Cr in alpha iron [5].

1. R. L. Klueh, D.R. Harries, High-Chromium Ferritic and Martensitic Steels for Nuclear Applications, ASTM, 2001, p. 39-55.
2. M.H. Mathon, Y. de Carlan, G. Geoffroy, X. Averty, A. Alamo and C. H. de Novion, J. Nucl. Mater. 312 (2003) 236-248.
3. F. Bley, Acta Metall. Mater. 40 (1992) 1505-1517.
4. K.H. Park, J.C. Lasalle, L.H. Schwartz, M. Kato, Acta Metall. Vol. 34, No. 9 (1986) 1853-1865.
5. Browdes EA, Brook GB, editors. Smitells Metals Book. Seventh ed. Heinemann: Butterworth; 1992, p. 13.

Acknowledgments

The opportunity of staying at Kyoto University made me understand Japanese people and culture much better than the visits for meetings before. More impressed was with the latest well maintained equipments, which can produce useful results in a relatively short time, I would like to express my sincere thanks to Professor Akihiko Kimura and IAE staffs for providing me such a fine and enjoyable period.

Advanced Energy Research Section

Ki Woo Nam, Visiting Professor
(Pukyong National University, Korea)

Some engineering ceramics have the ability to heal cracks. If this ability is used in structural components for engineering uses, great benefits can be anticipated, such as an increase in the reliability of structural ceramic members, and a decrease in the inspection, machining, and polishing costs of ceramic components. Some research was studied as follows;

SiC ceramics

The test sample is SiC ceramic which exhibited the best crack-healing ability among three commercial SiC ceramics. A semi-elliptical surface crack was made at the center of the tensile surface of the test specimen using a Vickers indenter at a load of 4.9–196 N. By this method, semi-elliptical cracks of 50–700 μm in surface crack length were made. Pre-cracked specimens were healed at 1573–1773K for 40 min to 100 h in air environment. The bending test of a crack-healed specimen was carried out at room temperature 1673 K.

Fig. 1 shows the effect of crack-healing time on the bending strength (σ_B) of the crack-healed specimens at RT. Fig. 1(a) shows the test results on specimens crack healed at 1773 K. The average σ_B of smooth specimen (○) is ≈560MPa, and the σ_B of standard pre-cracked specimen ($2c \approx 200$ μm, △) is ≈180MPa. In the case of crack-healing time 40 and 60 min, the average σ_B of crack-healed specimen recovered up to 585MPa. The crack-healed specimen (▲) showed a little higher bending strength than that of the smooth specimen. Of course, this increase in the σ_B of the smooth specimen was attained by healing the small surface cracks. The specimens with (*) show that fracture occurred outside of the crack-healed zone indicating that the pre-crack was healed completely. In Fig. 1(a), two of seven samples crack healed for 40 and 60 min fractured outside the crack-healed zone, and also the σ_B exhibited a little scatter, thus it can be concluded that crack healing was complete. Nevertheless, the heat treated smooth specimen (●) exhibited the same level of bending strength up to 40 h, the crack-healed specimen (▲) over 2 h exhibited considerably lower bending strength. This decrease in bending strength means that some degradation occurred during long term crack healing. Some researchers observed significant reductions in strength of silicon-based ceramics as a result of material loss through the formation of volatile species such as SiO(g). Moreover, previous investigators observed bubbles on polycrystalline SiC and thought that they resulted from evolution of CO at the SiC/SiO_2 interface during oxidation. Therefore, it was assumed that the degradation of this SiC was occurred by the formation of volatile SiO and CO(CO_2) gas.

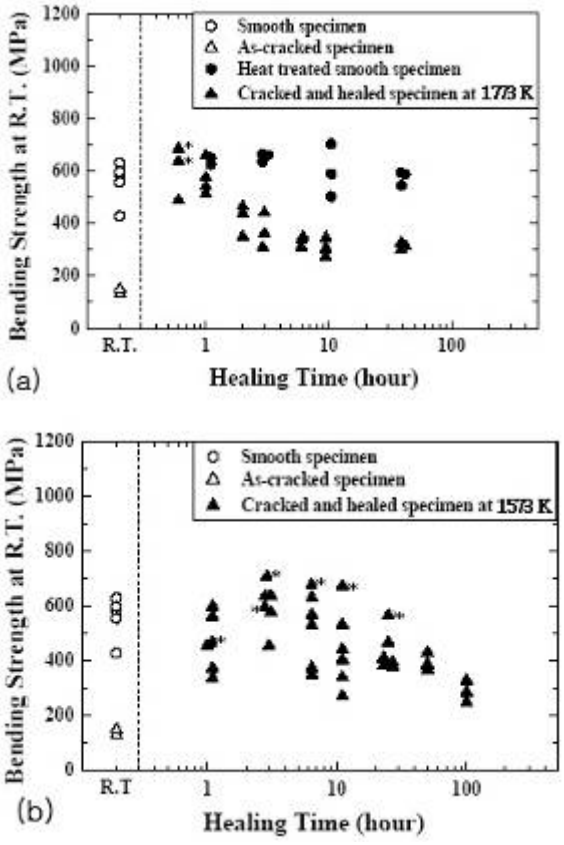


Fig. 1 Relationship between crack-healing time and bending strength at room temperature. Data marked with (*) indicate that fracture occurred outside the crack-healed zone: (a) crack healed at 1773 K, (b) crack healed at 1573 K.

Fig. 1(b) shows the test results on specimens crack healed at 1573 K. In the case of crack-healing time from 1 to 25h, the σ_B of crack-healed specimens exhibited large scatter. Six of the 30 samples fractured outside the crack-healed zone, however nine specimens exhibited lower σ_B than 400MPa indicating that crack healing was incomplete. The crack-healed specimen (▲) over 50 h exhibited considerably lower bending strength showing a little scatter in the σ_B. This decrease in σ_B also means that some degradation occurred during long term healing. Based on the σ_B versus crack-healing time at 1573–1773

K, the optimized crack-healing condition was decided as 1773 K, 1 h in air.

The crack-healing reaction of this specimen was estimated as follows: $SiC + 3/2O_2 \rightarrow SiO_2 + CO\ (CO_2)$

The SiO_2 has two phases; a glassy and a crystal phase. The amount of crystallized SiO_2 was dependent on the crack-healing time. The 1 h crack-healed specimen had a very small amount of crystallized SiO_2 compared to 40 h crack-healed specimen. Therefore, it can be concluded that this SiC ceramic recovered its bending strength by means of glassy phase SiO_2.

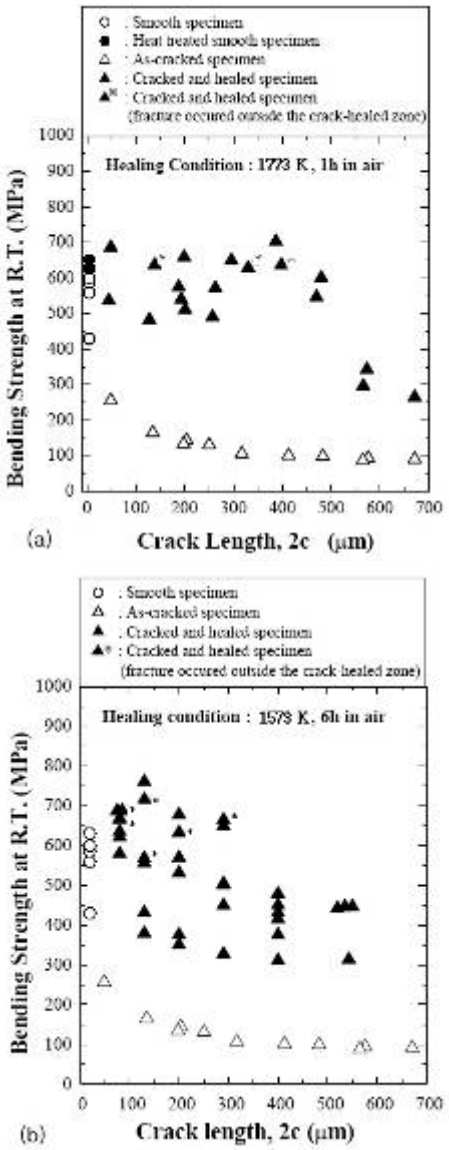


Fig. 2 Effect of pre-crack length on the bending strength of crack healed specimen at room temperature: (a) crack healed at 1773 K, 1 h, (b) crack healed at 1573 K, 6 h.

Fig. 2 shows the effect of pre-crack length ($2c$) on the crack-healing behavior at 1773 and 1573 K. In Fig. 2(a), the σ_B of cracked specimens (△) decreases with increasing $2c$. In the case of $2c \leq 450$ μm, the σ_B of crack-healed specimens exhibited the same level of bending strength to that of smooth sample indicating crack was healed almost completely. However, in the case of $2c > 50$ μm, the σ_B of crack-healed specimens decreased with increasing $2c$. Thus, it can be concluded that the maximum crack size ($2c_{max}$) that can be healed completely is $2c_{max} \approx 450$ μm in surface length when the crack is healed at 1773 K, 1 h in air. The value is twice as large compared with the others ceramics having crack-healing ability, such as Si_3N_4/SiC and Al_2O_3/SiC. As mentioned in above, SiC and O_2 is necessary for crack healing. Therefore, it is assumed that the oxidation reaction of this SiC occurred in whole of the crack surface. In contrast, the oxidation reaction of the above ceramics occurred at only SiC on the crack surface. In the case of crack-healing condition at 1573 K, 6 h in air, the bending strength showed large scatter in the $2c > 100$ μm region, as shown in Fig. 2(b). Therefore, the maximum crack size that can be healed completely is $2c_{max} \approx 50$ μm in surface length. Therefore, sufficient temperature and time is necessary for crack healing. However, the bending strength of specimens crack healed at 1573 K could not recovered despite increasing the holding time, as shown in Fig. 1(b). Therefore, it was assumed that the increasing crack-healing temperature is useful for crack healing of this SiC ceramic rather than increasing crack-healing time.

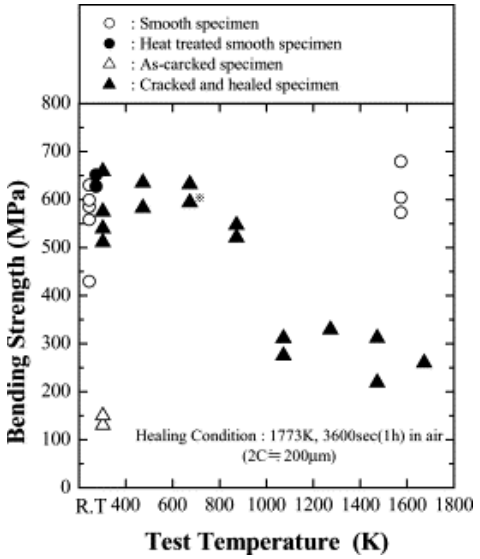


Fig. 3 Effect of test temperature on the bending strength of crack-healed specimen.

Fig. 3 shows the effect of the testing temperature on the σ_B of crack-healed specimens healed at 1773 K, 1 h in air. The smooth specimen exhibited a high bending strength (≈560MPa) up to 1573 K. However, the crack-healed specimen showed high σ_B only up to 873 K, and over 873 K, the σ_B of the crack-healed specimens decreased suddenly and exhibited low values of $\sigma_B \approx$

300 MPa. Therefore, the limiting temperature for bending strength of the crack-healed specimen was defined as 873 K. Therefore, for this crack-healed specimen of SiC ceramic it was assumed that the limiting temperature for bending strength is relatively low, because the crack-healing material of this SiC is glassy SiO_2, as mentioned in above.

Si_3N_4 composite ceramics

The oxygen effects contributing to toughening and strengthening have initially been studied with SiO_2 colloidal. The crack-healing behaviors of Si_3N_4/SiC composites with SiO_2 colloidal coating were investigated from 500 to 1300 °C.

The Si_3N_4/SiC composite ceramics were prepared using a mixture of 80 wt% silicone nitride, 20 wt% SiC powder with 8 wt% Y_2O_3 as an additive powder (Sample A). The Si_3N_4/SiC composite ceramics were prepared using 5 wt% Y_2O_3 and 3 wt% TiO_2 as an additive powder (Sample B). Colloidal with 12 % SiO_2 particle was used to heal the surface crack.

A semi-elliptical surface crack of about 100μm in surface length was made at the center of the tensile surface of specimens with a Vickers indenter, using a load of 24.5 N. The specimens cracked and as-received were mainly subjected to crack-healing treatment at 1300 °C for 1 hr in air. To compare the crack healing ability of a cracked specimen coated using SiO_2 colloidal, the crack healing was carried out in the temperature range from 500 to 1300 °C for 1 hr in air. The coating on the crack surface is 1 time and 3 times.

Fig. 4 shows the bending strength for the effect of crack-healing according to times of SiO_2 colloidal coating. The all heat treatment was carried out in air at a temperature of 1300 °C for 1 hr. The bending strength of the as-cracked specimen has nothing to do with coating times. That is, a portion of coating contributes to crack healing and the other portions crystallize to white powder on the surface. Both, the smooth specimen and as-cracked specimen with one time coating had an almost similar bending strength. The bending strength of the heat-treated smooth specimen with one time coating is superior to that of the cracked and heat treated specimen. This phenomenon is far above Sample B in one time coating. The bending strength of three time coating is similar to that of one time coating. Hereafter, all cracked specimens were experimented with one time coating.

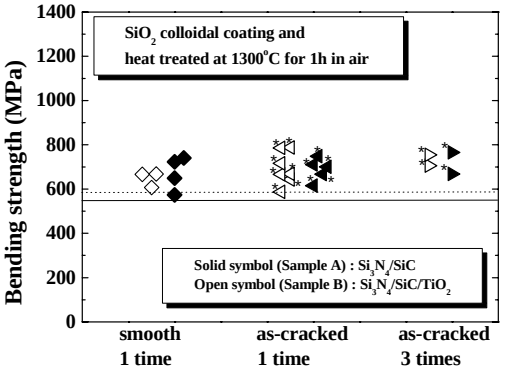


Fig. 4 Effect of crack-healing according to coating time.

Fig. 5 shows the effect of crack-healing according to the temperature of a cracked specimen with one time of SiO_2 colloidal coating. All the heat treated crack specimens were fractured from outside the pre-crack. The bending strength of the as-cracked and heat treated specimens with SiO_2 colloidal coating are increased with an increasing heat treatment temperature. In sample A, the bending strength of 900 °C is almost equal to the values of the heat-treated smooth specimens at 1300 °C. The crack-healed specimen showed dominant crack-healing ability by SiO_2 colloidal coating at 1300 °C. Sample B showed a dominant crack healing ability over 700 °C by SiO_2 colloidal coating. Moreover, dominant crack-healing ability showed at 1000 °C lower than that of sample A. As above-mentioned, this is estimated that they were piled up the growth of Si_3N_4 by TiO_2 effect on crack-healing by SiO_2 colloidal coating. SiO_2 colloidal was made SiO_2 crystal over 500 °C.

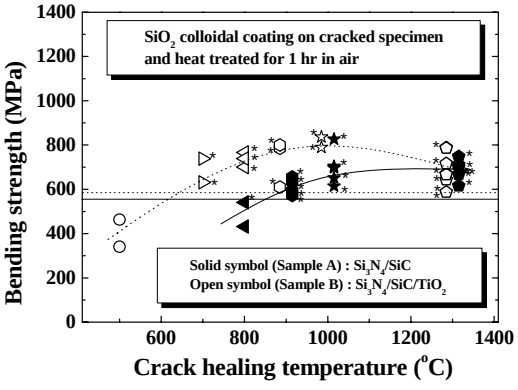


Fig. 5 Effect of crack-healing according to heat treated temperature of as-cracked specimen with SiO_2 colloidal

Advanced Energy Research Section

Qingwei Yang, Foreign visiting professor
(Professor, Southwestern Institute of Physics, Chengdu 610041 China)

1. Introduction

From Jan.1 to Mac.31 2007, I had a 3 mouths stay with Heliotron J group, Institute of Advanced Energy, Kyoto University, by the invitation of Prof. F. Sano.

During this period, I lectured 3 seminar courses for the Ph. D and master degree students, which were "Arrangement of Diagnostic systems on ITER", "HL-2A tokamak and its diagnostics" and "Active experiments on tokamaks and HL-2A".

I also attended 2 scientific meeting, which were "Three Dimensional Identification of Zonal Flows in the HL-2A Tokamak" in National Institute of Fusion Science, Mar. 8~9 2007, Toki, and "Dynamics of molecular beam injection in tokamak plasmas" in the 2nd meeting on "atom and complex plasma relaxation process" Mar.13~14 2007 Kyoto.

Furthermore, I jointed Heliotron J experiment and investigated the MHD instability.

2. 3 scientific courses

The presentation of "Active experiments on tokamaks and HL-2A" shows the active tokamaks around the world. The hot experimental topics relevant to the burning plasma, especially to meet the ITER's needs, are mentioned. Some interesting physics studies on the HL-2A tokamak are given in detail, which include SMBI (supersonic molecular beam injection), particle and impurity transport, turbulence and GAM (geodesic acoustic mode) zonal flows, disruption, electronic fishbone, etc. The detailed experimental arrangements and processes are presented as well.

In the seminar of "HL-2A tokamak and its diagnostics", it gives a brief introduction of SouthWestern Institute of Physics (SWIP), Chengdu, China, and HL-2A tokamak. In addition, the diagnostics were described in detail that including magnetics, Langmuir probes, optical detections, microwave measurement systems, and laser systems, etc. Some experimental data will be presented as well.

About the topic of "Arrangement of Diagnostic systems on ITER", the detailed description about diagnostics on ITER, which contain 4 parts of general description, port arrangement, structure of port plug and diagnostics. The preliminary engineering designs of diagnostics for ITER were presented. The designed functions, parameters, accuracy, structures, alignment and some discussions were included, according to the explanation of DDD – Diagnostics Design Document.

3. Zonal Flows studies in HL-2A

The studies of Zonal Flows (ZFs) on HL-2A were presented in the meeting that was held in NIFS, Mar. 8~9 2007, Toki. A novel design of three-step Langmuir probes (TSLPs) and the identifying of the properties of zonal flows were revealed. Three dimensional GAM features are analyzed for the first time. The simultaneous determination of poloidal mode (m~0-1) and toroidal mode (n~0) of electric potential and field perturbations are reported. Corresponding frequencies are estimated as 7-9 kHz, which are in good agreement with GAM (Geodesic Acoustic Mode) theoretical prediction. The radial scale lengths of ZFs are 2.4-4.2 cm. The formation mechanism of the flows is identified to be nonlinear three-wave coupling of ambient turbulence. The modulation effect of ZFs on ambient turbulence is also observed. Poloidal dependence of density perturbations and detailed radial structures of electric field are under consideration for next campaign while the existent evidence of the low frequency ZFs will be identified.

4. Dynamics of MBI in tokamak plasmas

The investigation of SMBI (supersonic molecular beam injection), a more efficient and deeper fuelling method than normal gas puffing, was reported in the 2nd meeting on "atom and complex plasma relaxation process" Mar.13~14 2007 Kyoto. Especially, the low temperature (liquid nitrogen temperature) SMBI is used.

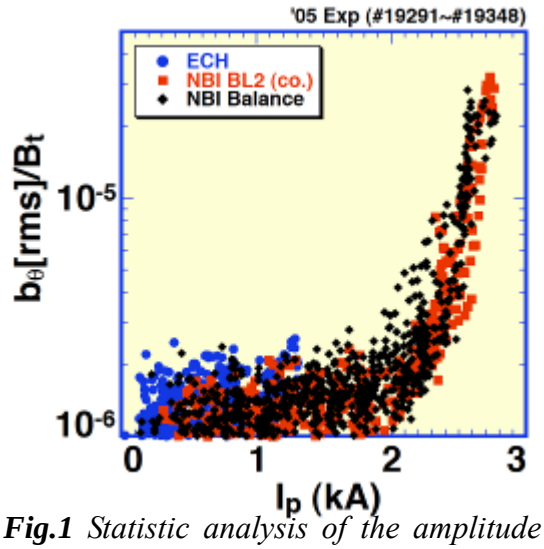


Fig.1 *Statistic analysis of the amplitude of MHD mode against the plasma current.*

It is thought that the low temperature SMBI can form the hydrogen cluster more easily, and therefore can penetrate into plasma deeper and more efficient.

The mechanism of interaction of molecular beam with plasma has been discussed. Two basic shielding models, Mass model and Electrostatic double layer-shielding model, have been suggested.

5. MHD instability on Heliotron J

The studies of ideal/resistive interchange mode in Heliotron J were carried out using the before results of theoretical and experimental studies on plasma configuration and MHD instability perturbation. According to the investigation of Ref.1, the low frequency (f < 20 kHz) MHD mode with low-n/m structure observed in the experiment shows that it is the pressure driven MHD instability, especially the interchange mode. The instability mode always appeared when the plasma current was greater than 2 kA, as shown in Fig.1. Under the statistical analysis, the dependence of the amplitude of MHD mode A_{rms} with the plasma current I_P is revealed.

The theoretical analysis of MHD instability was employed to understand the physical mechanism of interchange mode. The Mercier criterion was introduced to explain the MHD mode. We can found that the second term of below equation includes the effect of parallel current. This current can make plasma unstable when the magnetic shear is negative.

$$D_M = \frac{S^2}{4} + S\left\langle \frac{(j - I'B)\cdot B}{|\nabla V|^2} \right\rangle - \left(\dot{P}V''\dot{\Theta}^2 - \dot{P}^2 \left\langle \frac{1}{B^2} \right\rangle \right) \left\langle \frac{B^2}{|\nabla V|^2} \right\rangle + \left(\left\langle \frac{j\cdot B}{|\nabla V|^2} \right\rangle^2 - \left\langle \frac{(j\cdot B)^2}{B^2|\nabla V|^2} \right\rangle \left\langle \frac{B^2}{|\nabla V|^2} \right\rangle \right) \geq 0$$

Reference:

S. Yamamoto, K. Nagasaki, Y. Suzuki, et al., **Studies of MHD Stability in Heliotron J Plasmas**, HTTP Division Meeting, Nov. 20, 2006

Advanced Energy Conversion Division

Advanced Energy Materials Research Section

A. Kohyama, Professor
T. Hinoki, Associate Professor
H. Kishimoto, Assistant Professor

1. Introduction

The importance of the materials development for advanced energy systems including nuclear fusion and fission reactors has been rapidly growing in these years and expected to be emphasized in the coming years and the upcoming century. The mission of the Advanced Energy Materials Research Section at the Advanced Energy Conversion Division is to develop advanced energy materials to be used in advanced energy systems with the emphasis on advanced energy conversion systems. The research section is unfolding unique and extensive researches in the fields of functional and structural materials development as well as playing important roles in national and international programs for R & D of energy materials.

The current emphasis of the research section is on materials studies for nuclear fusion and nuclear fission reactors and for aerospace applications where resistance of materials under severe environments, such as high temperature, high heat flux, high energy particle irradiation, complex and variable stresses and others, are required. The ongoing research themes include (1) research and development of steels including both advanced reduced activation ferritic steels and conventional austenitic steels for fusion and fission applications, (2) research and development of silicon carbide fiber-reinforced silicon carbide matrix composites (SiC/SiC composites) for fusion and other advanced energy systems, (3) theoretical modeling and computational studies on the material behavior under high energy particle irradiation conditions, (4) development of sub-sized or miniature specimen techniques for mechanical property evaluation of structural and functional materials, (5) joining of the materials for extremely severe environment, (6) fundamental studies on the physical processes responsible for the creep and fatigue phenomena in metallic materials, and (7) experimental and theoretical studies on the heat transfer through liquid coolants in the high-efficiency energy conversion systems.

The research section is functioning as one of the central organizing bodies of fusion materials research in universities. The current JAPAN/USA Collaboration program, “Dynamic behavior of fusion materials and their response to varying and complex irradiation conditions”, so called JUPITER program, is one of the most important activities and the program has been strongly related with scientific, engineering and technological studies on interactions of materials with energetic particle bombardments, such as neutron irradiation and charged particle irradiations. JUPITER program finishes in March, 2007. The new collaboration program, so called TITAN program, is going to start in 2007.

2. On-going and up-coming projects

Under the title of “Fundamental R&D on Advanced Material System for (High Efficiency Environment-conscious) Very High Temperature Gas-cooled Fast Reactor Core Structures,” a new R & D activity to establish core structure for gas-cooled fast reactor (GFR) using SiC/SiC composites has been established for the research period in December, 2002 through March, 2006, as one of the programs of Development of Innovative Nuclear Energy System Technique supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT).

The novel processing called Nano-powder Infiltration and Transient Eutectoidic (NITE) Processing has been developed based on the liquid phase sintering (LPS) process modification in the program. The NITE processing can achieve both the excellent material quality and the low processing cost. The productivity of the processing is also excellent, and various kinds of shape and size of SiC/SiC composites can be produced by the NITE processing.

Based on the fruitage, the other major two projects related to GFR started in December, 2005, as one of the programs of Development of Innovative Nuclear Energy System Technique supported by MEXT. One is “Development of High Burn-up Composite Fuel for GFR,” through March, 2008. Basic fabrication technique of fuel for GFR will be established using high dense SiC and porous SiC.

Another project is just up-coming. New program having a title of “Industrial User Support Program for Research of Invention and Maintenance of Materials for Energy Applications” starts in April, 2007. This project promotes sharing our excellent equipments and research accumulation of energy materials with industry for the benefit of public. The project named “ADMIRE”, which is short for “Application of DuET and MUSTER for

Industrial Research Engineering", is going to continue for next 5 years.

3. Development of advanced SiC/SiC composites for nuclear energy systems

Advanced nuclear energy systems, such as gas cooled fast reactor (GFR), very high temperature reactor (VHTR) and fusion reactor are potential candidates for sustainable energy systems in the future. In order to realize these attractive energy systems, structural materials must be responsible to keep their performance under very severe environment including high-temperature, high energy neutron bombardment and surrounding coolants and fuels. Today a major thrust is by the development of fiber-reinforced ceramic matrix composites (CMCs) in general and silicon carbide fiber-reinforced silicon carbide matrix (SiC/SiC) composites in particular. Because of fiber-reinforcement, SiC/SiC composites are more damage tolerant to mechanical and thermal loading (thermal shock) and have the capability for larger components than their SiC monolithic form. Also in comparison to the best high-temperature metallic alloys, SiC/SiC composites are lower density and thermal expansion, and have the potential for displaying excellent high-temperature thermo-mechanical properties under high energy neutron bombardment.

Nano-Infiltration and Transient Eutectic-phase (NITE) process is the first successful application of liquid phase sintering (LPS) for matrix densification of SiC/SiC composites. The matrix in NITE-SiC/SiC consists of well-crystallized SiC grains with small remnants of the metal oxide sintering additives. Such polycrystalline SiC matrix suggests excellent radiation resistance of the NITE SiC/SiC composites similar to that of chemically vaporized SiC/SiC composites (CVI-SiC/SiC). The differences of properties between NITE and CVI composites are mainly caused by their matrix porosities, the NITE composites are less porosity than the CVI composites. A heat flux capacity of NITE-SiC/SiC is superior in the candidates of first wall materials for fusion reactor, so that it is expected that NITE composite has an excellent figure of merit against the thermal stresses. Satisfactory results for reducing the leakage of helium gas as a coolant gas in the reactor are also reported.

4. Development of porous SiC for nuclear energy systems

Recently, there has been an increasing interest in the applications of porous ceramics as hot-gas or molten-metal filters, catalyst supports, battery electrodes, heat insulators, ion exchangers, gas sensors, and water cleaners. In particular, porous SiC ceramics are considered as functional materials of sustainable and advanced energy systems, such as perforated containment wall or flow channel inserts for blanket module of fusion reactor, and inner/outer tube of a coated particle type fuel compartment for horizontal flow cooling concept with directly cooling system on Gas-Cooled Fast Reactor, because of their low thermal-expansion coefficient, low thermal conductivity and good thermal-shock resistance as well as excellent physical and chemical stability at elevated temperature. A number of manufacturing approaches have been applied to fabricate porous SiC including polymer pyrolysis, oxidation bonding, and reaction bonding. However, their processes are complicated and conventional porous SiC shows insufficient physco-chemical stability under high temperature environment. Therefore, from the view point of safety and stability, it is necessary to develop an uncomplicated manufacturing method and to investigate mechanical properties of porous SiC ceramics.

In our group, porous SiC ceramics have been manufactured based on the Nano Infiltration Transient Eutectic process (NITE process), which is developed as a processing technique for high performance a SiC fiber reinforced SiC matrix composite . The NITE-porous SiC ceramics exhibited a substantially high strength in comparison with other conventional porous SiC ceramics, due to its robust microstructure consisted of spherical pores. In addition, it was very simple to control the porosity of porous SiC ceramics in the fabrication procedure by our new processing method.

5. Engineering research on joining of materials for nuclear energy systems

The important issues to use SiC/SiC composites for industry are the developments of joining and coating techniques. Several kinds of joining techniques have been developed to join SiC and SiC/SiC composites using polymer, glass-ceramics and reaction bonding. One of the key for the development is the stability of the joining at application temperature. For SiC or SiC/SiC composites joining, our new joint technique using SiC has an advantage at the high temperature due to the very limited CTE mismatch. Monolithic SiC and NITE-SiC/SiC composites are successfully jointed applying NITE process. These joined SiC materials by the applied NITE process show stronger strength than the SiC materials joined by other conventional jointing processes. The technique is able to apply the coating of SiC materials. Because of small CTE mismatch and its high melting point, tungsten (W) is selected as the refractory armor material for SiC. For W coated SiC, SiC, W and their interface reaction layers can be controlled to make acceptable joining, bonding or claddings by optimizing the materials used and process condition.

6. Joining and coating technologies for SiC with

dissimilar materials

Joining and coating technologies are necessary for the construction of fusion reactor by SiC/SiC composites. Fundamental study of interface of dissimilar joints or metal coated SiC materials are ongoing in parallel with the engineering developments. Tungsten is an appropriate material for the dissimilar joint and coating with SiC because of the similar thermal expansion coefficient with SiC. Recent developed newly SiC/SiC composite, NITE SiC/SiC composite has excellent resistance against high temperature and high pressure, thus, the hot-press joining is being developed. The hot-pressing is performed over 1000 °C in Ar gas flow environment. A tungsten plate or tungsten powder are put on a SiC plate and consolidated by hot-pressing. The consolidated specimens are investigated by SEM and mechanical testing. SEM investigation show that the reaction zone between tungsten and SiC grew up with the hot-pressing temperature and time. The reaction zone is investigated W-Si, this zone seems to determine the share strength of joined materials. More precise investigation and research of interface are progressing.

7. Theoretical investigation and modeling of neutron irradiation effects in energy conversion materials

Production of cascade vacancy clusters has been investigated by several kinds of experiments and demonstrated by computer simulation studies. Vacancy clusters, which are randomly produced with very high production rates and have a long lifetime, should affect the microstructural evolution and resultant property changes in irradiated materials. In current work, the experimental characterization of point defect clustering in austenitic model alloy was performed. The swelling of neutron irradiation and the loop growth in electron- and heavy ion-irradiated austenitic model alloy were investigated to accumulate the reference data for modeling.

In addition, as a part of US/Japan collaborative research activity for fusion materials study, the influences of unsteady irradiation conditions such as temperature excursion during reactor operations and / or the reactor startup and shutdown on microstructural evolution and mechanical property changes are analyzed based on the integrated reaction rate theory of irradiation effects in materials updated with the latest results from atomistic simulation studies on the displacement cascades.

8. Fundamental research of radiation damage accumulation on SiC

Neutron bombardment and helium generation in irradiated materials directly affect their material properties. In the experimental part of this work, the microstructural evolution in ion-irradiated SiC has been demonstrated as a function of irradiation temperature and damage levels. Interstitial type Frank loops on {111} crystallographic family planes were dominant defect clusters under the condition of simultaneous existence of displacement damages and helium, The frank loops changed to perfect loops by the formation of a Shockley partial dislocation in a loop at higher irradiation temperature and heavier damage level. These perfect dislocation loops are able to glide on prismatic planes, and result in the formation of dislocation networks. It was reported that the structure of the defect clusters in binary ionic compounds maintain the stoichiometric composition in their growth process, thus it is possible that the clustering behavior in SiC, which has a little ionic property, also shows a similar phenomenon. The constraint effect of Si to C ratio for the growth of Frank loops in SiC was quantitatively evaluated in this work. Because the threshold energy for the displacement of Si atoms is significantly higher than that of C atoms, it is considered that the Si interstitials are less than the C interstitials in an irradiated SiC. In this work, Si atoms were implanted to adjust the ratio of interstitials of Si and C to investigate the constraint effect for the growth of Frank loops under irradiation environments. The result showed that the frank loops under rich Si interstitials grew better than these under the lack of Si interstitials.

9. Neutron irradiation effects of advanced SiC/SiC composites on mechanical properties

In order to identify the effects of neutron irradiation on tensile and interfacial properties of advanced SiC/SiC composites, unloading / reloading cyclic tensile test was conducted and hysteresis loop analysis was applied. Neutron irradiation was performed in JOYO, and neutron fluence and irradiation temperature were 3.1×10^{25}n/m^2 (E>0.1MeV) at 740^{o}C and 1.2×10^{26}n/m^2 at 750^{o}C.

The composites in both conditions exhibited excellent irradiation resistance to changes in ultimate tensile strength and proportional limit stress. Hysteresis loop analysis indicated that the sliding stress at fiber/matrix interfaces remained almost unchanged after irradiation to 3.1×10^{25}n/m^2 at 740^{o}C, whereas it was significantly reduced by 1.2×10^{26}n/m^2 at 750^{o}C for both composites. The result of these analyses might be correlated with the swelling behavior of pyrolytic carbon, so further researches such as SEM observations of crack propagation and TEM observations of the interface itself are required to investigate the behavior of fiber/matrix interface after irradiation more precisely.

10. Irradiation effects for reduced-activation ferritic/martensitic steels

Reduced-activation ferritic/martensitic steels, RAFs, are leading candidates for the structural materials of blanket and first wall of fusion reactors, thus, the effects of displacement damage and helium production on mechanical properties and microstructures in the materials are important subjects in fusion environments. An ion irradiation method is one of the most effective techniques to obtain the systematic and accurate information about microstructural evolution under fusion environments. In this research, single- (Fe ion) and dual- (Fe and He ions) ion irradiation experiments were performed followed by TEM observation and nano-indentation to investigate the effects of displacement damages and helium. The dual-ion irradiation (15 appm He/dpa) up to 60 dpa at 420 ºC induced finer defect clusters than the single-ion irradiation. These fine defect clusters caused large increase in hardness. TEM analysis revealed that the ion radiation at 60 dpa at 420 ºC brought about the precipitation of MX type precipitates (M: Ta, W). It is possible that invisible small defects largely increased in hardness in addition to the increase by the radiation induced MX precipitates.

11. The effects of surface morphology and distributed inclusions on low cycle fatigue behavior of reduced activation ferritic/martensitic steel

The influence of surface morphology and distributed inclusion on low cycle fatigue (LCF) properties of reduced activation ferritic / martensitic (RAFM) steel was investigated by miniaturized small specimen technique. Fatigue crack initiation and propagation mechanism was also studied.

Large surface roughness clearly affected the fatigue lifetime. LCF lifetime is decrease significantly. Based on this result, it can be assumed that the fatigue lifetime of the elements of a system might be decreased significantly more than the fatigue life of a test specimen. The crack initiation mainly concentrated in working scratches, and the cracks propagated along the prior austenitic grain boundary. The fatigue cracks occurred from the inclusions, which are very important factor to decide the crack propagation path.

12. Microstructural analysis of the hardened surface layers in the core shroud of boiling water reactor made of SUS316L

In recent years, stress corrosion cracking (SCC) of boiling water reactor (BWR) internal components made of L-grade austenitic stainless steel has been a technical concern. To understand the mechanism for the initiation of SCC, a sample taken from the core shroud of BWR made of SUS316L was investigated. A sample contains the hardened surface layers connected with SCC, where the milling and the grinding weld beads were done in a manufacturing process. In this study, the hardened surface layers were observed by transmission electron microscopy to investigate the effects of the surface machining on SCC initiation.

The cracking was observed in the boundary of deformation twin bands $\{111\}\langle 112\rangle$ and shear bands in Goss orientation $\{110\}\langle 001\rangle$. Because Goss orientation band observed only in grinded surface of weld beads, this band is considered to be produced during the grinding procedure. These results show that SCC could initiate in the deformation produced microstructures by transgranular stress corrosion cracking (TGSCC).

Advanced Laser Science Research Section

K. Miyazaki, Professor
T. Nakajima, Associate Professor
K. Hata, Assistant Professor
G. Miyaji, Assistant Professor

1. Introduction

Our research interests are focused on the development and applications of advanced lasers, aiming at the goal of demonstrating the potential ability of coherent radiation to create new bases of future science and technology. The laser development is concerned with the generation of high-intensity ultrashort laser pulses, compressing the laser pulses into a few-cycle or shorter-pulse region, and extending the ultrashort pulse radiation into the extreme ultraviolet region of spectrum. Applications of the advanced laser technology are associated with the study of ultrafast, strong-field interactions with matter to develop new technology of materials control and processing on atomic and molecular levels in the strong field regime, where special attention is focused on nonlinear optical processes such as tunneling ionization of atoms and molecules, Coulomb explosion of molecules, molecular alignment, and nano-structuring on solid surfaces.

2. High-intensity ultrashort pulse laser technology

A high-intensity 40-fs Ti:sapphire laser system shown in **Fig.1** is working as one of the principal experimental apparatus in our research section. The laser system using the chirped-pulse amplification (CPA) technique consists of a mode-locked Ti:sapphire laser oscillator pumped by the second harmonic output of an all solid-state Nd:YVO_4 laser, an all-reflective pulse stretcher using a pair of grating, a regenerative Ti:sapphire laser amplifier, the second and third power amplifiers, and a grating pulse compressor. The laser system produces a peak power of 1 TW (40 mJ in 40 fs) at a repetition frequency of 10 Hz, and the center wavelength is 800 nm. This system includes a frequency conversion apparatus to extend useful high-intensity fs pulses to the blue and ultraviolet (UV) regions of spectrum. The frequency conversion apparatus employs a simple optical configuration to achieve efficient conversion in a nonlinear optical crystal. The peak power of blue fs pulses at 400 nm is 0.2 TW with the pulse width of 60 fs, and the UV power at 267 nm is 20 GW in 140 fs.

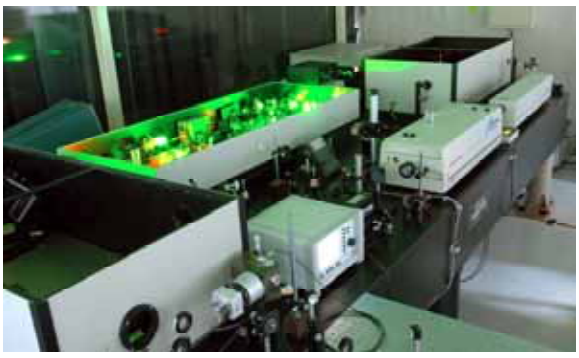


Fig.1. High-intensity fs Ti:sapphire CPA laser system.

A new Ti:sapphire laser system using the CPA technique has been developed for the purposes of advanced material processing with fs laser pulses. The laser system produces 100-fs, 800-nm pulses at 10 Hz with a well-defined intensity distribution, and good temporal and phase characteristics as shown in **Fig.2**. The output pulse duration is designed to be relatively long for the target experiment using various kinds of optical component. The system configuration is almost the same as the 40-fs laser system, consisting of a fs laser oscillator, a pulse stretcher, a regenerative Ti:sapphire laser amplifier, a power amplifier and a pulse compressor. This laser has been used for the study of nano-scale ablation of hard thin films.

3. Control of nonlinear process with molecular alignment

Strong-field interaction with atoms and molecules is the subject under investigation for applications of

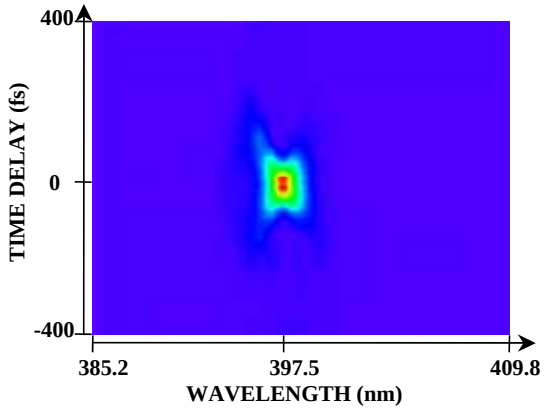


Fig.2. Example of the FROG image for the 100-fs, 800-nm laser pulse.

high-intensity fs lasers to the development of new materials-control technology. Our major interest is in nonperturabative nonlinear phenomena that can be induced with the high-intensity fs laser pulses. Recently we are focusing our attention on the molecular alignment that is nonadiabatically induced with intense ultrashort laser pulses. The fs laser-induced molecular alignment would be a promising approach to control of nonlinear processes in molecular gases. Recently we have demonstrated that high-order harmonic generation (HHG) provides a sensitive way to probe the dynamic alignment of molecules, and the characteristic harmonic signal in time and frequency domains clearly reveals coherence in the rotational wave packet. We did complete identification of frequency components according to the theory that has recently been developed, for the first time, by the collaboration with Prof.F.H.M.Faisal's group of Bielefeld University in Germany. To explain the origin of harmonic signal from aligned molecules, we focus our attention on the revival structure in the field-free alignment of a wave packet in N_2, O_2 and CO_2.

We made a pump-probe experiment using nonresonant, linearly polarized 40-fs laser pulses for the linear molecules, where the pump pulse forms a wave-packet, and the delayed probe pulse generates high harmonic radiation from the wave packet. The linearly polarized output from the Ti:sapphire laser was split into two beams to produce a variable time delay Δt between the pump and probe pulses. The two beams were recombined collinearly and focused with a 50-cm focal-length lens into a pulsed molecular beam jetted from a 1-mm-diameter nozzle. The harmonic radiation was detected by an electron multiplier mounted on a VUV monochromator, and the signal processed by a boxcar averager was stored on a personal computer. In the experiment of the polarization angle dependence of HHG, the pump polarization was rotated by an angle α to the probe pulse polarization of which direction was fixed to the direction along the monochromator slit.

Figure 3 shows a typical example of frequency spectrum for the 19th harmonic signal observed for O_2 as a function of Δt. The time-dependent signal shown in the inset of Fig.3 is often reproduced well by the expectation values $\langle\cos^2\theta\rangle$ and/or $\langle\sin^2 2\theta\rangle$ with the angle θ between the molecular axis and the field direction, where $\langle\cos^2\theta\rangle$ represents the degree of alignment with the revival period of $1/(2Bc)$ with the rotational constant B, while $\langle\sin^2 2\theta\rangle$ is empirical. The result shown in Fig.3 demonstrates that the major coherence in the harmonic signal is created through the Raman transition induced by the pump pulse, which is seen with the frequency component at $\omega_1 = (E_{J+2} - E_J)/\hbar = 2\pi Bc(4J+6)$ that gives rise to a series (10, 18, 26, 34, 42, ---) for a pair of odd J and $J\pm2$ states of O_2. This Raman-allowed series certainly arises from $\langle\cos^2\theta\rangle$. The spectrum includes additional sets of component at $\omega_2 = (E_{J+4} - E_J)/\hbar = 2\pi Bc(8J+20)$ with a series (28, 44, 60, 76, 92, ---). This coherence between the rotational states J and $J\pm4$ arises from the expectation value $\langle\cos^4\theta\rangle$ and would be created by multi-step Raman transitions during the wave packet formation. The third set of frequency component is identified to $\omega_3 = 2\pi Bc[4(J-J')]$ and $\omega_3 = 2\pi Bc[4(J+J')+12]$, which leads to a series (8, 16, 24, 32, 40, ---) with the former and a weak one (12, 20, 28, 36, ---) with the latter. This anomalous series originates from the expectation of the form $\langle\cos^2\theta\rangle\langle\cos^2\theta\rangle$.

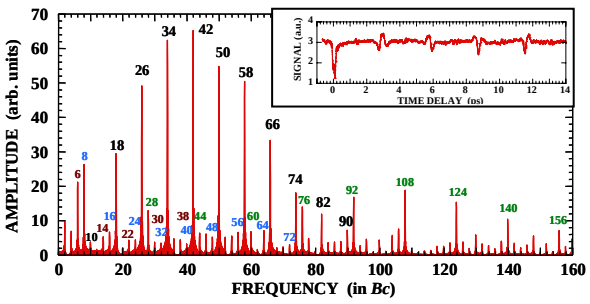


Fig.3. Example of the frequency spectrum of the 19th harmonic signal for O_2. The inset shows the time-dependent harmonic signal.

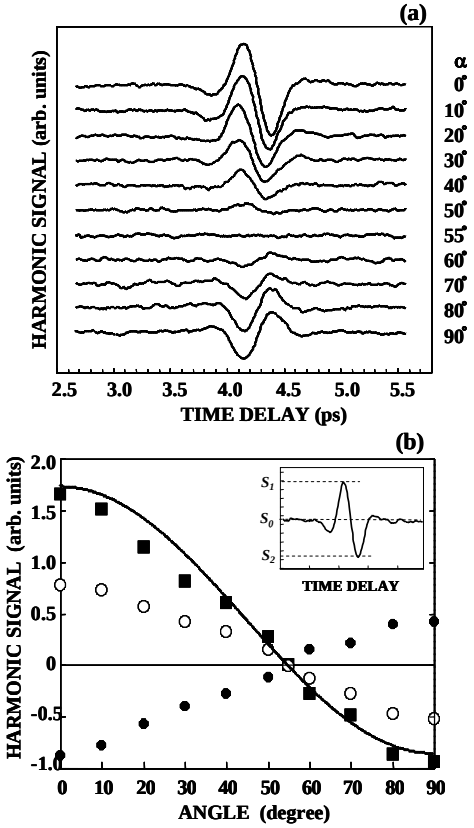


Fig.4. (a) Examples of the time-dependent 19th-harmonic signal observed around the half revival time at different angles α for N_2, and (b) the modulation amplitude $S_1 - S_2$, as well as $S_1 - S_0$ and $S_2 - S$.

Higher order coherenc is also seen with a series (6, 14, 22, 30, 38, ---), which comes from $\langle\cos^2\theta\rangle\langle\cos^4\theta\rangle$.

These frequency components observed are consistent with the theoretical result that the time-dependent harmonic signal for O_2 is dominated by the term proportional to $\langle\langle\cos^2\theta \sin^2\theta\rangle^2\rangle(\Delta t)$. The experimental results for N_2 and CO_2 have also been compared with the theoretical.

As a function of α between the pump and probe pulse polarization for N_2, O_2 and CO_2, we measured the time-dependent harmonic signals of all the harmonic orders that could be detected with our experimental apparatus. **Figure 4** shows (a) the time-dependent 19th-harmonic signal observed around the half revival time $T_{rev}/2 = 1/(4Bc)$ at different angles α for N_2, and (b) the modulation amplitude $S_1 - S_2$, as well as $S_1 - S_0$ and $S_2 - S_0$. Here, S_1, S_2, and S_0 are the harmonic signals measured at the top-alignment, at the anti-top alignment, and at the random alignment in the time-dependent degree of alignment $\langle\cos^2\theta\rangle$ with the angle θ between the molecular axis and the field direction, respectively, as illustrated in the inset of Fig.4. The modulation $S_1 - S_2$ is peaked and minimized at $\alpha = 0°$ and 90°, respectively. The α-dependent modulation demonstrates that the 19th harmonic radiation is most efficiently produced at the top alignment where molecules are parallel to the probe pulse field and suppressed at the anti-top alignment, though α does not always coincide with θ. It should be noted in Fig.4 that the modulation phase is reversed at $\alpha \sim 55^\circ$, where the harmonic signal is independent of the time delay. These α–dependent high-harmonic signals observed are well reproduced with the theory developed for N_2 and O_2. The similar angle dependent harmonic signals were measured for different molecules.

4. Nano-scale processing with fs laser pulses

In a fs-laser ablation experiment, we have found that superimposed fs laser pulses at low fluences are able to produce nanostructures with the period as small as one tenth of laser wavelength or ~ 30 nm on hard thin films such as TiN and diamond-like carbon (DLC). The nanostructuring observed with fs laser pulses has attracted much attention as a promising approach to overcome the diffraction limit of light and realize *the first nano-processing technology with lasers*. The interaction process responsible for the nanostructuring is one of the most important subjects to be investigated for further development.

To understand the dynamic process responsible for the periodic nanostructure formation, we have measured the reflectivity R of DLC film irradiated with fs laser pulses, using a pump-probe technique. **Figure 5** shows a typical example of R measured at $\Delta t = 0$ as a function of the number N of laser pulses at the fluence $F = 0.14$ J/cm^2 where we have observed the nanostructure formation with superimposed laser pulse. Note that the plot of R for parallel polarizations of the pump and probe beams shows two peaks as N increases. The peak position of R was observed to shift to smaller N as F increases. Such enhancement of R is never observed with the crossed polarizations, as seen in Fig.5. In addition, at $\Delta t \geq 0.2$ ps we did not observe the enhancement of R even for the parallel polarizations. These results suggest that the enhancement of R observed is induced through a coherent interaction between the probe pulse and the DLC surface excited with the pump pulse. Furthermore, it is clear that the enhancement of R is induced by an *incubation effect*, whereby a portion of the pump energy is accumulated in the target material, since the pump fluence used is less than the single-pulse ablation threshold.

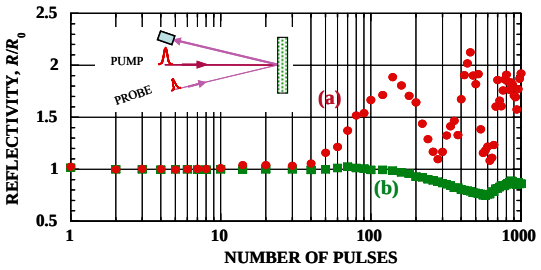


Fig.5. Example of the reflectivity of DLC film measured as a function of shot number with the pump and probe pulses.

The observed characteristic changes in R have provided a clue to the interaction process on the target surface. The detailed experimental study have shown that the characteristic reflectivity change observed is closely associated with the nanostructure formation and the bonding structure change to induce surface swelling, leading to a conclusion that the nanostructure formation on the DLC surface is certainly preceded by the bonding structure change. Furthermore, the experiment has demonstrated that a small modulation of the laser field created by the weak probe pulse with a fluence of about 1/700 ~ 1/500 of the pump is capable of producing a large morphological change or the grating through the accumulation of bonding structure changes. This is

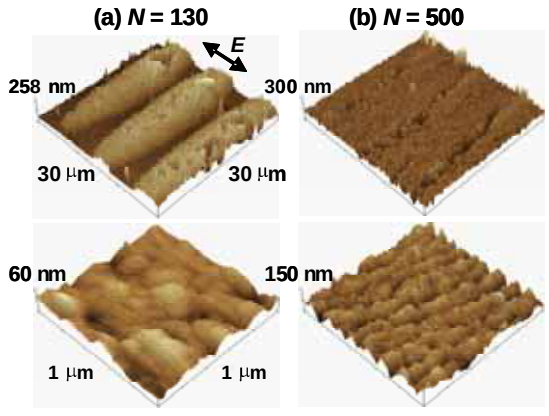


Fig.6. SPM images of DLC surfaces at 130 and 500 shots of fs laser pulses. The upper images are 30 x 30 μm^2, and the lower are 1 x 1 μm^2.

seen with the results shown in **Fig.6**, where the large fringes of 11 μm in spacing are created at N = 130, and then the nanostructure is formed on the ridge of the fringe at a larger N. The results strongly suggest that we may assume the generation of a ***local field*** to form the nanostructure.

To see the role of local field and resulting nanostructure formation on the film surface, we have been making an ablation experiment for the DLC film patterned with nanometer-size stripes. We prepared Si substrate having the nano-size Si stripes that was fabricated with electron-beam lithography and liftoff process. Each Si stripe was 0.1-μm wide, 50-nm high and 4-μm long, and was arranged in arrays at different periods of 200 – 1600 nm. DLC film of 900 nm in thickness was deposited on the patterned Si substrate. The surface roughness was measured to be less than 1 nm with a scanning probe microscope (SPM). The coated DLC stripe was observed to be ~ 500 nm in width and ~ 100 nm in height.

For the ablation experiment we used a Ti:sapphire laser system producing linearly polarized, 800 nm, 100 fs pulses at 10 Hz. The output was focused in air at normal incidence on the DLC surface with a lens of 1000 mm focal length. The focal spot was ~ 200 μm in diameter, and the polarization direction was parallel and/or perpendicular to the stripe. The laser fluence F and superimposed shot number N were varied in a range of F = 60 – 150 mJ/cm^2 and N = 0 – 1000. The surface morphology was observed with the SPM and a scanning electron microscope (SEM).

Figure 7 shows the SEM images of (a) non-pattered DLC surface irradiated with N = 1000 and (b patterned surface with N = 100, where both are irradiated at F = 80 mJ/cm^2. In Fig.7(b), the nanostructure starts to be formed only on the crest of stripes through the local ablation, whereas any structure is not created in the flat region outside the patterned area on the DLC surface. The mean spacing l and depth d of nanostructures on the stripe were measured to be l ~ 60 nm and d ~ 10 nm. The nanostructure is formed perpendicularly to the laser polarization direction. With the increase in N up to 1000, the nanostructure grew up to l ~ 160 nm and d ~ 150 nm on and along the ridge of stripe, while the smaller nanostructure of l ~ 90 nm and d ~ 60 nm was formed on the flat surface area having no stripe, as seen in Fig.7(a). We observed that the nanostructure on the flat area was increased to have l ~ 180 nm and d ~ 110 nm at a higher fluence F = 130 mJ/cm^2 with N = 1000.

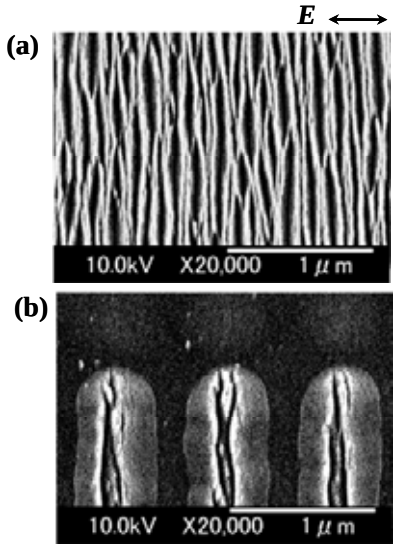


Fig.7. SEM images of (a) the non-patterned DLC surface irradiated with N = 1000, and (b) the patterned surface with N = 100. Both were irradiated at F = 80 mJ/cm^2.

These results demonstrate that the stripe patterned on the surface plays an essential role in the nanostructure formation process. The free-electron density created by the intense fs laser pulses would not be uniform on the patterned area and might be localized along the direction of laser polarization in the surface area smaller than the laser wavelength. The localized free electrons could create a local field modulated on a nanometer scale to initiate the nanometer size ablation, as observed. With an increase in F and/or N, this local field could grow to form a larger and/or deeper structure through the ablation. Thus we may conclude that the local fields created through the coherent excitation process in DLC plays the dominant role in nanostructuring on the nanometer scale.

5. Study of ultrafast laser-atom interactions

We have theoretically studied the effects of the carrier-envelope phase in the multiphoton ionization regime in terms of the asymmetric photoelectron ejection, which, although the physical mechanism is quite different from that in the tunneling ionization regime, exhibits striking effects. In addition we have successfully observed ultrafast spin-polarization using two-color fs pulses, which agrees reasonably well with our theoretical prediction.

6. Critical heat flux on inner surface of vertical cylinders

Critical heat fluxes and heat transfer characteristics on vertical cylinders of SUS304, Cupro nickel and platinum internally cooled by forced flow of pressurized water are studied for wide ranges of inner diameter, heated length, pressure, liquid sub-cooling, flow velocity, dissolved gas concentration and heating rate with rough, smooth and mirror finished inner surfaces. The purposes of this study are to clarify the effects of these parameters on the critical heat flux and the heat transfer characteristic, and to present the database to determine the most favorable conditions to realize the high flux heat removal from a divertor of a fusion test facility.

Advanced Energy Conversion Division

Advanced Energy Storage Research Section

A. Kimura, Professor
K. Morishita, Associate Professor
R. Kasada, Assistant Professor

1. Introduction

Efficient energy conversion and storage are great concerns for sound human life in the near future. This section takes up a mission of materials R & D for advanced nuclear energy conversion and storage, such as development of fusion blanket structural materials and fuel clad materials for high burn-up operation of light water reactors.

(1) ODS steels for the advanced nuclear energy systems: Oxide dispersion strengthening (ODS) steels have been considered to be very promising for application to advanced nuclear plant as structural materials, because they are highly resistant to thermal recovery of the material structure as well as to neutron irradiation embrittlement. Although the other critical issue of the ODS steels has been considered to be corrosion resistance in the super-critical pressurized water (SCPW) and Pb-Bi (LBE), no data was obtained so far. From last fiscal year, our research group has begun a MEXT project **"R&D of Super ODS steels for the Advanced Nuclear Energy Systems"**.

(2) Multi-scale modeling of fusion blanket structural materials: Reduced activation ferritic steels (RAFS) have been the prime candidate for fusion structural materials for DEMO reactor where structural materials are expected to suffer sever irradiation embrittlement. Multi-scale modeling approach is very useful to understand and reduce the embrittlement.

(3) Lifetime evaluation of nuclear structural materials: For the sake of the highly efficient and safe operation of nuclear fission reactors, the mechanisms of irradiation embrittlement and stress corrosion cracking have been investigated.

2. R&D of High-Cr ODS steels for the Advanced Nuclear Energy Systems

Development of fuel cladding materials is crucial for high burnup (more than 100GWd/t) operation of advanced nuclear energy systems, such as advanced light water reactors, super critical pressurized water (SCPW) reactors and lead bismuth cooling fast reactors. In order to overwhelm the requirements for the fuel claddings, materials R&D have been performed for high-Cr oxide dispersion strengthening (ODS) steels. Corrosion tests were performed in a SCPW (783 K, 25 MPa) environment (**Fig. 1**). The weight gains of all high-Cr ODS steels are smaller than an austenitic stainless steel (SUS316L). More uniform and thinner oxidation layers were observed in the ODS steels after corrosion test rather than in 9Cr martensitic steel and SUS316L. The effects of neutron irradiation on the mechanical properties of the ODS steels have been investigated. High-Cr ODS steels showed a significant hardening after the irradiation at 290 and 400 °C, while no effect was observed after the irradiation at 600 °C (**Fig. 2**). The irradiation hardening, however, was not accompanied by the reduction of total elongation. The nano-oxides of the 19Cr-ODS steel were cubic pyrochlore $Y_2Ti_2O_7$, while those of 19Cr-4Al-ODS steel were mainly perovskite $AlYO_3$ of which the difference can account for the difference in the tensile strength between the steels. The microstructure observation after heavy ion irradiation revealed that the dispersed oxides were stable up to a dose of 150 dpa at 973K (**Fig. 3 and Fig. 4**). The average size and number density of cavities formed in the ODS steels were twice smaller and two orders of magnitude higher than those in the RAF steel, resulting that the ODS steels had superior resistance to swelling. The particle diameter and its size distribution range decreased gradually with increasing the milling time up to 12 h and then increased drastically thereafter.

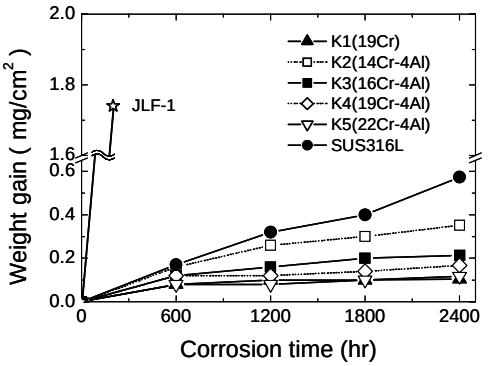


Fig. 1: The weight gains of the high-Cr ODS ferritic steels as well as those of a 9Cr martensitic steel (JLF1) and an austenitic stainless steel (SUS316L) in a super critical pressurized water (783 K, 25 MPa).

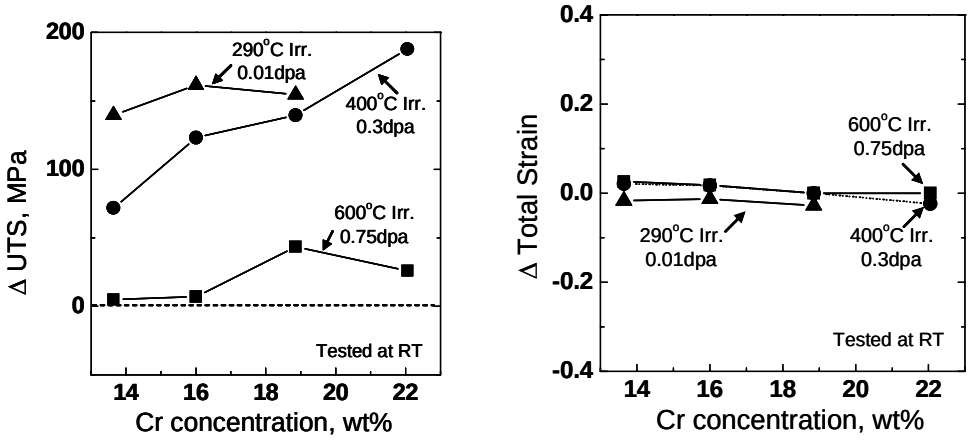


Fig. 2: Changes of a) ultimate tensile strength and b) total strain with various Cr concentrations after irradiation. Tensile test were done at room temperature at a strain rate of $6.7 \times 10^{-4} s^{-1}$.

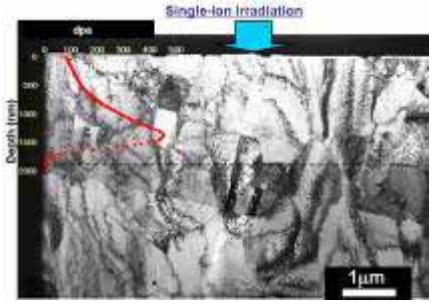


Fig. 3: Cross section of the irradiated surface of K1 ODS steel.

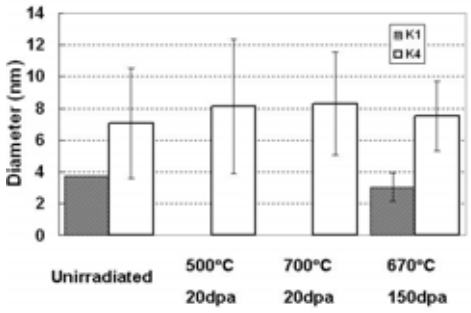


Fig. 4: Irradiation effects for diameter of dispersed oxides of both (Y, Ti) complex oxides in K1 alloy and (Y, Al) complex oxides in K4 alloy.

3. Multiscale modeling of microstructural changes in metals during irradiation

Radiation damage processes are in essence multiscale phenomena, which occur over a wide spectrum of the time and length scales. It is very difficult to evaluate the processes by experimental tehniques in particular at relatively small time and length scales. Many challenges have been made so far to understand these processes by computer simulation techniques. However, even if computational techniques are available, the time and length scales that can be simulated are very limited. For example, a molecular dynamics (MD) technique is a powerful tool to investigate displacement cascades in materials, but its simulation time is limited to 100 ps at the most. In the following studies, linking various simulation techniques was made to overcome the scale limit that individual techniques inevitably have.

He-bubbles are three-dimensional vacancy clusters containing He atoms, and are known to migrate in materials; however, bubble diffusivity is so low that the time scale of the diffusion is, in many cases, beyond the limit of the MD method. In this study, valuable attempts were made to evaluate the diffusivity of He-bubbles in bcc Fe using a kinetic Monte-Carlo (KMC) simulation technique that employs defect formation energy obtained by MD and molecular static (MS) calculations. Calculated diffusivities depend on the radius of He-bubbles, which is very consistent with the earlier results obtained using conventional continuum theory.

Thermodynamical formalization was made for description of the nucleation and growth of He-bubbles in metals during irradiation. The proposed formalization is available for evaluating both microstructural changes in fusion first wall materials where He is produced by (n, α) nuclear transmutation reactions, and those in fusion divertor materials where He particles with low energy are directly implanted. Both MD calculation and continuum theory analysis were done to evaluate nucleation barrier for He-bubbles in Fe. It showed that the nucleation barrier is significantly reduced by the presence of He and that a He-bubble with an appropriate number of He atoms depending on bubble size can nucleate without any large nucleation barriers, even at a condition where, without He, an empty void has very large nucleation barrier. With the proposed thermodynamical formalization, the nucleation and growth process of He-bubbles in Fe during irradiation was simulated by the kinetic Monte-Carlo (KMC) technique. It shows the nucleation path of a He-bubble on the (N_{He}, N_V) space as functions of temperature and the concentration of point defects in the matrix, where N_{He} and N_V are the numbers of He atoms and vacancies contained in the bubble, respectively. The Arrhenius plot of bubble growth rates depend on the nucleation path and suggest that two different mechanisms operate for

the process: one is controlled by vacancy diffusion and the other is controlled by interstitial helium diffusion. It is very consistent with many experimental observations both in fusion first wall and fusion divertor materials.

4. Lifetime evaluation of nuclear structural materials

4.1 Stress corrosion cracking of SUS316L

Stress corrosion cracking in the core shroud component of commercial BWRs have been reported as the transition of cracking path from transgranular (TG) SCC in the hardened surface area to intergranular (IG) SCC. In the present study, the effects of dissolved hydrogen on the TGSCC were investigated for the SUS316L steel with and without cold working and sensitization. **Fig. 5** shows stress-strain curves of the SUS316L with and without cold-working and sensitization obtained form SSRT in dissolved oxygen (DO) and dissolved hydrogen (DH) condition. Increasing of SCC susceptibility was clearly observed for the DH condition. As shown in the **Fig. 6**, SEM image of the specimens surface of the SUS316L tested in DH condition showed mixture of TGSCC and IGSCC. Further investigation to understand the hydrogen effects on SCC behavior of SUS316L is scheduled in the next fiscal year.

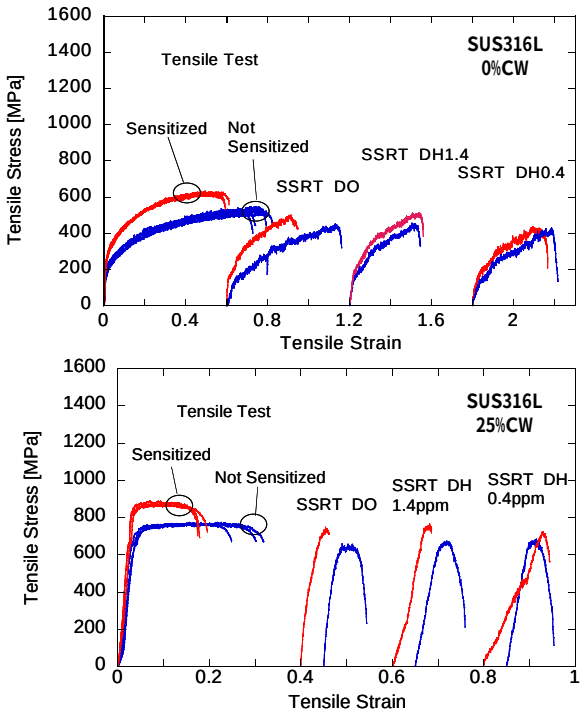


Fig. 5: Stress-strain curves of the SUS316L with and without cold-working and sensitization obtained form SSRT in dissolved oxygen and dissolved hydrogen condition.

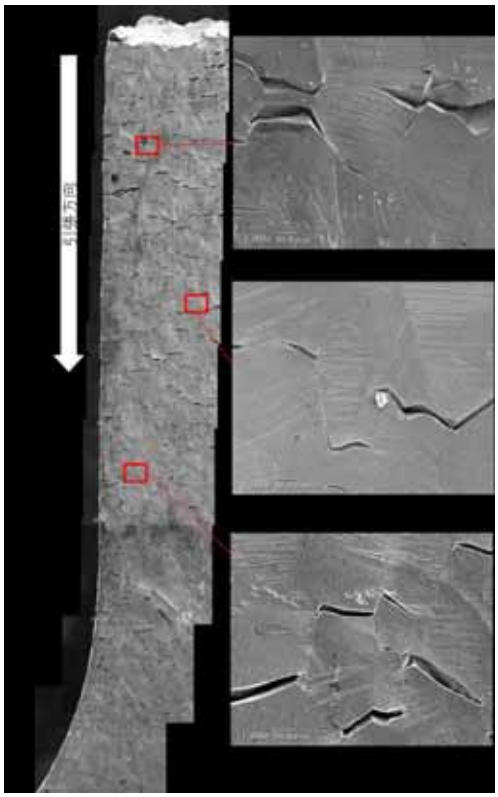


Fig. 6: SEM image of the SSRT specimen surface tested in the DH condition for the 0%CW SUS316L.

4.2 Factor controlling irradiation hardening in RPV steels –Mn-related irradiation hardening-

Irradiation embrittlement of reactor pressure vessel (RPV) steels is one of the important degradation issues in the commercial light water reactors. We have investigated effects of the alloying atoms and impurity atoms in RPV steels, such as Mn, Ni, Mo, Cr, Si, Cu, on irradiation hardening behavior of Fe-based binary model alloys irradiated in the JMTR. As a topical result, enhancement of irradiation hardening by Mn-addition to bcc Fe after neutron irradiation has been confirmed by careful experiments on many specimens irradiated up to relatively high doses. So we call it as “Mn-effect”. In this fiscal year, ion-irradiation experiments by using DuET facility have begun in order to clarify the mechanism of “Mn-effects” on the irradiation hardening behavior of Fe alloys. **Fig. 7** shows irradiation hardening behavior estimated by nano-indentation tests on pure-Fe, Fe-1.5Mn, and A533B after Fe-ion irradiation at 290 C up to 1 dpa. Whereas the irradiation hardening for Pure Fe was seen to be saturated at a dose of 0.1 dpa, that of Fe-1.5Mn was increased with displacement damage. Furthermore, it is noticed that the A533B steel shows same tendency as Fe-1.5Mn. Microstructural observation by using TEM revealed that fine dislocation loops were formed in the ion-irradiated area, as shown in **Fig. 8**. This results indicates that “Mn-effects” is strongly related with matrix damage (dislocation loops) accumulation in the Fe alloys.

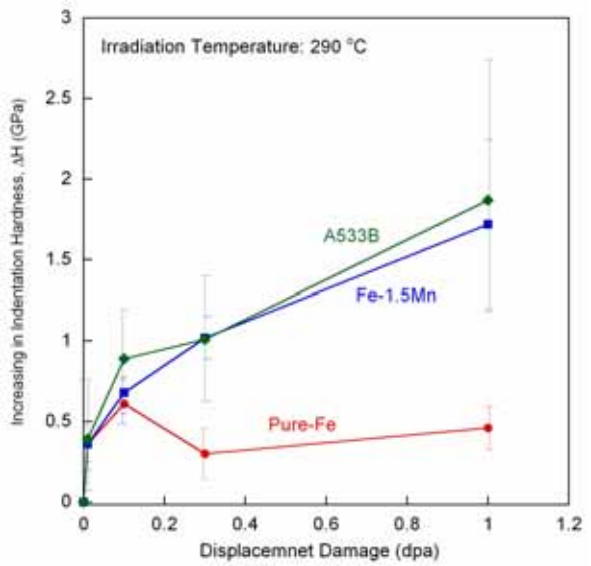


Fig.7: Dose dependence of irradiation hardening of Pure Fe, Fe-1.5Mn and A533B after Fe-ion irradiation estimated by nano-indentation hardness tests.

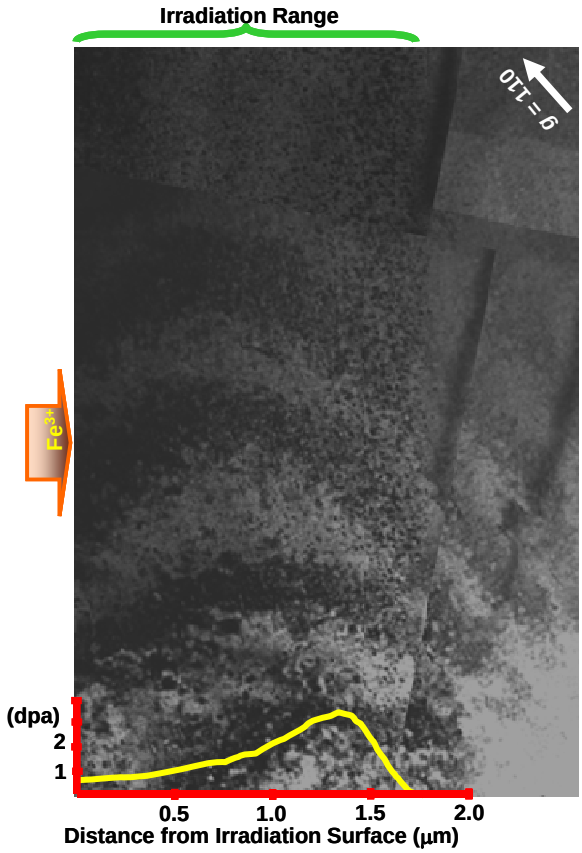


Fig.8: TEM bright field image of ion-irradiated area of Fe-1.5Mn model alloy.

5. R&D of nano-micro composite particle coating on structural materials for next generation reactors

In this fiscal year, our research group has begun a new MEXT project **"Nano- and Micro- Composite Particles Coating Repairable on Site of PBE-FR"**. The objective of this project is to develop nano- and micro- composite particles coating for protection of structural materials against lead-bismuth corrosion in the lead-bismuth eutectic fast reactor (PBE-FR) and to develop the on-site repairing methodology of the coating. The schematic of the anti-corrosion coating was given in the Fig. 9. In this fiscal year, we developed the coating methodology by using sol-gel processing to coat Al_2O_3 on stainless steels. Furthermore, rotating specimen corrosion testing system was newly developed as shown in Fig.10. installed in the glove box.

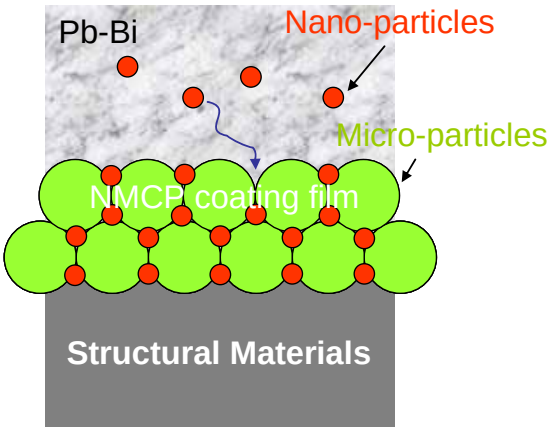


Fig.9: Schematic of the NMCP coating against LBE corrosion.

Fig.10: Rotating specimen corrosion testing system.

Advanced Energy Generation Division

Complex Plasma Systems Research Section

F.Sano, Professor
K.Hanatani, Associate Professor

1. Introduction

Magnetic fusion has some key features which make it an attractive option in a future energy mix: inherent safety features; waste which will not be a burden for future generations; no greenhouse gases; and the capacity for large scale energy production. The required raw materials for the fuel are abundantly and widely available in the Earth. The combination of these features provides magnetic fusion the potential to make a substantial contribution to satisfying world energy demand later this century and beyond. The development of magnetic fusion as a commercial reactor of electricity requires the solution to the physics problems of plasma transport and magneto-hydrodynamics. The goal of the fusion plasma research is the discovery of a magnetic configuration that can efficiently confine high density and temperature plasma for a sufficiently long confinement time to produce net thermonuclear power. The point is to deepen the understanding of fusion plasma dynamics and to create key innovative technologies to make magnetic fusion a practical energy source. This research section seeks to investigate the confinement optimization of high-temperature plasmas in the helical-axis heliotron line. For the experimental and theoretical investigation of this theme, the plasma device of Heliotron J has been operated to study the magnetic configuration effects of confinement in Heliotron J with special regard to the improved confinement regime, H-mode. With regard to these experimental studies, the related theoretical as well as computational studies of plasma transport and NBI/ICRF heating have also been carried out.

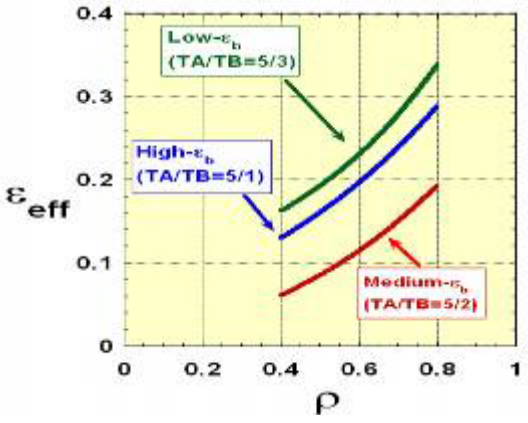


Fig.1 Calculated "effective" helical ripple ε_{eff} as a function of radius for high-ε_b, medium-ε_b and low-ε_b configurations.

2. Heliotron J Experiments

Experiments have progressed toward its research mission of the concept exploration of an optimized helical-axis heliotron. The main experimental results are concerned with thermal confinement, fast ion confinement, MHD, plasma current control, edge/SOL plasma properties and divertor plasma dynamics. Magnetic configuration control studies were performed with special regard to vacuum edge iota control and bumpiness control for low-β plasma confinement. With regard to edge iota control [1], L-H transition characteristics have been studied on the basis of their threshold (or boundary) conditions of density, power, plasma-wall interactions, etc. However, the observed H-mode still remains transient in a time scale of τ_E while the steady-state phase is not yet achieved. The experimental efforts toward this direction are necessary.

Bumpiness control studies have clarified the important role of bumpiness in the effective control of bulk plasma confinement, fast ion confinement, plasma current, and edge/SOL plasma characteristics. As for the bulk plasma confinement, the reduction of the neoclassical transport depends on the appropriate choice of the bumpiness ε_b [2,3]. Here, the "effective helical ripple", ε_{eff}, in the $1/\nu$ collisionless regime was calculated by Monte Carlo techniques for the three types of bumpiness, that is, high, medium, and low-bumpy configurations [3]. The results from the DCOM code showed that the medium-ε_b configuration provides a greater degree of neoclassical optimization in the $1/\nu$ collisionless regime as shown in Fig.1. Figure 2 shows the relationship between the ratio of the global energy confinement time τ_E^{exp} to the international stellarator scaling law (τ_E^{ISS04}) and the "effective helical ripple", ε_{eff}, calculated at r/a=2/3 for 0.3-MW, 70-GHz on-axis ECH plasmas, where R_{ax}~1.20 m, $\iota/2\pi$(a)~0.56 are nearly kept the same and $\tau_E^{exp}=W_p/(P_{abs}-dW_p/dt)$; W_p is the diamagnetic plasma energy; P_{abs} is the ECH absorption power estimated using TRECE code under the condition of single-pass absorption modified by the assumed 30% multi-reflection effects. It is suggested that the reduction of ε_{eff} introduces a favorable effect on the confinement of ECH in the L- and the transient H-mode phases. However, due to the large data scatter and inherent error bars, further studies are necessary to

understand the more detailed, statistical and physical trends of anomalous confinement by accumulating the sufficient data and by measuring the turbulence structure including the plasma electric field, plasma flow, etc.

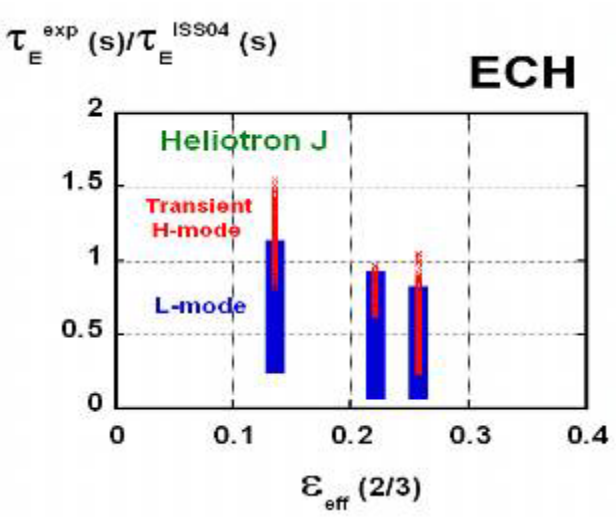


Fig.2 Confinement enhancement factor, H_{ISS04}, with regard to the ISS04 scaling as a function of ε_{eff} at r/a=2/3 for ECH plasmas with the bumpiness modified configurations.

Here it should be commented that the experimental comparison between the bumpiness dependence of thermal confinement and that of energetic ion confinement produces a question. As for NBI heating, an example of plasma parameters in the stage-injection mode of NBI is shown in Fig.3. In this case, the target deuterium plasma for NBI(H^0) was produced only by short-pulse ECH, and then NBI-only plasma was sustained in the stage-injection mode, where NBI power (P_{NB}) in the 1st stage was 340 kW(CO) and that in the 2nd stage was 990 kW(CO+CTR). In the 2nd stage, the ion temperature (T_i) measured with the neutral particle analyzer (NPA) reaches about 0.4 keV at $\bar{n}_e$ =2x10^{19}m^{-3}. To avoid the complicated NBI heating situations for the configuration control studies, the increase of T_i only for the CO injection mode was measured by changing the bumpiness under the conditions of the constant density of n_e =2.5x10^{19}m^{-3}, as shown in Fig.4. The results suggest that the high-ε_b configuration provides better ion heating efficiency as compared with that of the medium-ε_b or low-ε_b configuration. On the other hand, as shown in Ref. [3], flux of the charge-exchange flux (at the toroidal angle 12 degree of the NPA that views the passing orbits) just after the neutral beam (NB) turn-off revealed that the CX-flux decay time improves with an increase in bumpiness, indicating the effective confinement improvement of helically trapped or toroidally trapped fast ions in the high-ε_b case. By using ICRF minority (H) heating to the ECH target plasma (D), the formation and confinement of high energy ions were studied with

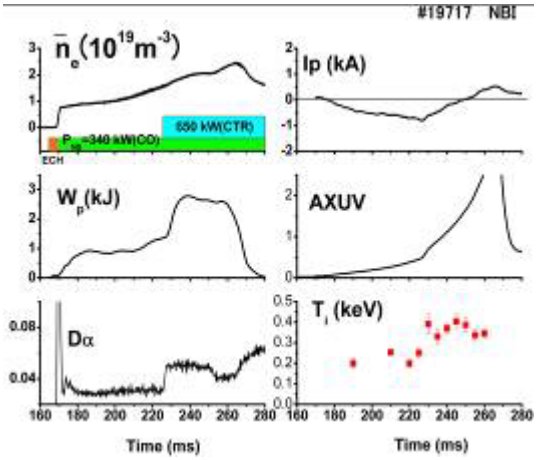


Fig.3 Time evolutions of plasma parameters in the stage-injection of NBI (CO and CO+CTR) in the medium- ε_b configuration.

special regard to the bumpiness modification under almost the same central resonance conditions by adjusting the ICRF frequency. The experiments suggested that the tail T_i increases with an increase in bumpiness ε_b under the same density ($\bar{n}_e$ =0.4x10^{19}m^{-3}) and RF power (200 kW) conditions [4].

Therefore, to determine what effect in the global energy confinement (with regard to electron-heating ECH and ion-heating NBI/ICRF plasmas)–ignored here, e.g. drift loss properties, electric field formation, turbulent flow shear characteristics, etc. –makes up this

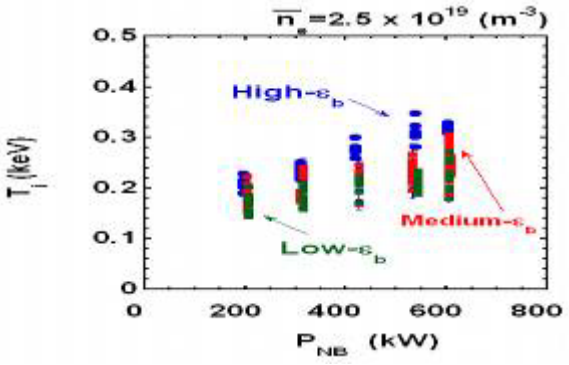


Fig.4 T_i increase as a function of NBI power under the constant density of $\bar{n}_e$=2.5 x 10^{19} m^{-3} for the high, medium and low-ε_b configurations.

apparent difference would shed an interesting light on the different properties of thermal and/or energetic ion confinement in the helical-axis heliotron. This is an important task that should be continued in the Heliotron J experiments.

3. Monte Carlo simulation of particle confinement in Heliotron J

Heliotron J device is designed to realize the configuration with compatibility between MHD stability and good particle confinement, using the l=1, m=4 continuous helical winding. Due to the limitation which comes from the used continuous helical winding, the toroidicity is larger than that of geometrically equivalent tokamak so that the unfavorable large equilibrium current changes the profile of rotational transform at high β value and also enhance the neoclassical diffusion. Here, we concentrated on the enhancement of diffusion and we pointed out that increasing bumpiness, the Fourier amplitude of which characterizes the strength of the mirror field in the toroidal direction, reduces the neoclassical diffusion in the collisional regime.

First of all, we investigated the toroidicity of configuration by solving the magnetic differential equation of the current stream function numerically. It is summarized as the Fourier expansion of $1/B^2$ on magnetic surfaces. Figure 5 shows the toroidicity of the three typical configurations, which characterized by the different bumpiness values (ε_b = 0.01, 0.06, 0.15 at r/a=2/3) and that of the tokamak geometrically equivalent to the Heliotron J configuration. The results suggest that the toroidicity of Heliotron J is larger than that of the equivalent tokamak. Toroidicity changes the properties of equilibrium drastically due to the large Pfirsch-Schlüter current in high β and give rise to the diffusion in collisional regime. This conflicts with our need to realize the configuration with good particle confinement, but the collisional diffusion in Heliotron J does not so large especially in the high bumpiness configuration.

We investigated the collisional diffusion in Heliotron J, using an orbit following Monte-Carlo code in Boozer coordinates. We used the three different bumpiness model fields of Heliotron J to study the effect of bumpiness. These models are characterized by the bumpiness (ε_b = 0.01, 0.06, 0.15 at r/a=2/3) and all the other components (e.g. the average B field strength, plasma volume, etc.) are exactly the same. This cannot be realized by the experimental situation due to the restriction of devices; but serves to illustrate the effect of bumpiness on transport properties. Figure 6 shows the inverse of the confinement time, S*, versus normalized mean-free-path for the above three models and the equivalent tokamak. The quantity S* can be interpreted as the magnitude of the ion transport. In Pfirsch-Schlüter regime (L* > 1), the ion transport of high bumpiness model is nearly equal to the equivalent tokamak in spite of the large toroidicity, and also in the plateau regime (1 < L* < 10) the ion transport of high bumpiness model is smaller than that of the other two models. These results suggest that the large bumpiness reduces the collisional diffusion.

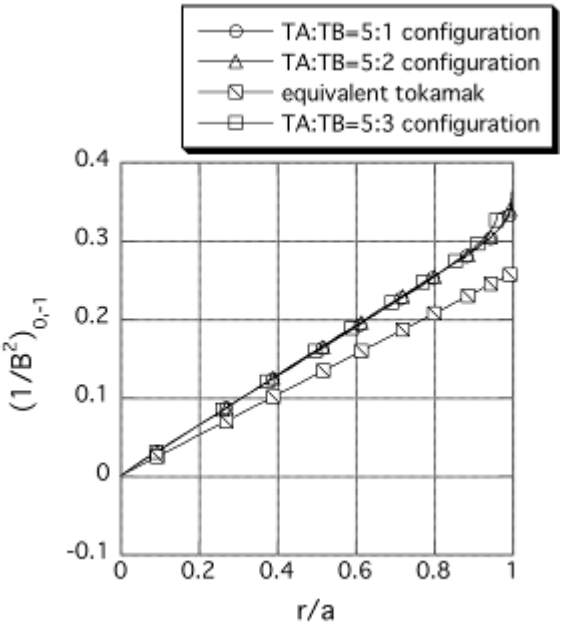


Fig.5 The toroidicity of Heliotron J and the geometrically equivalent tokamak. These values are calculated by the Fourier transformation of $1/B^2$ on the magnetic surfaces.

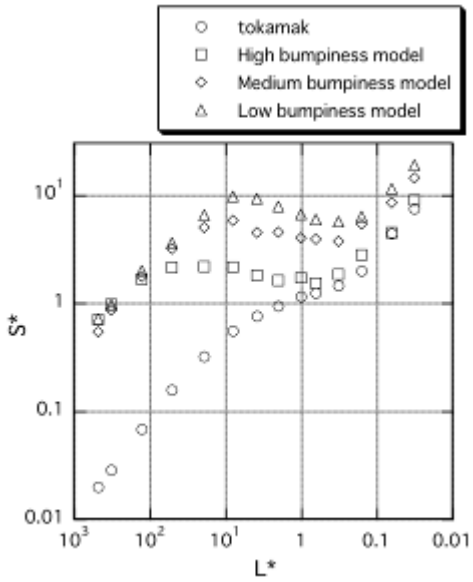


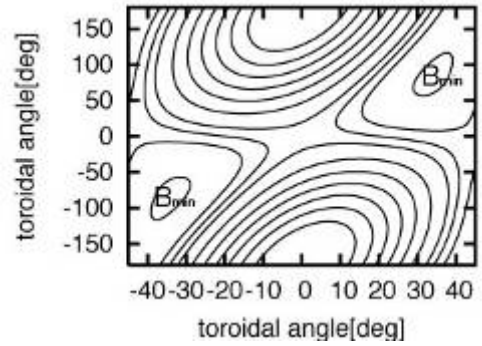
Fig. 6 The inverse of the confinement times S* in three model fields of Heliotron J. S*=1 denotes the tokamak plateau value and L*<1 represents the P.S.regime.

This result can be explained by the reduction of drift velocity of passing particle due to the bumpiness. We assume that the rotational transform per period so small that the magnetic field lines go straight in toroidal direction with constant ψ, θ. Here, ψ is the toroidal flux and θ is the poloidal angle variables in Boozer coordinates. The radial drift velocity is proportional to $B^{-1}\ \partial B/\partial\theta$. This term can be expressed by the Fourier expansion of the magnetic field strength on the magnetic

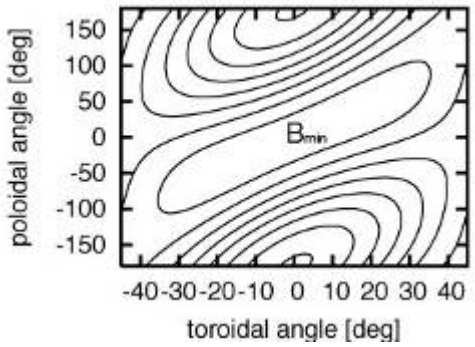
surfaces, $B=\sum B_{nm} \cos(4n\varphi - m\theta)$. In calculation, the term which depends on the toroidal angle gives no net drift in one toroidal period because the average of $\cos(4n\varphi)$, or $\sin(4n\varphi)$ term will be zero. But the superposition of the bumpiness, $\cos(4\varphi)$, and the helicity ,$\sin(4\varphi-\theta)$, cancels the toroidal dependence and produces the effective poloidal contribution. As a result, the shift of passing particles from the magnetic surface is given by

$$\Delta r = \frac{v_{\parallel}}{\iota R}\left(2 + \frac{\varepsilon_b \varepsilon_h}{\varepsilon_t}\right) + O(\varepsilon_t),$$

where $v_{\parallel}$ is the parallel velocity of the particles, ι is the rotational transform, Ω_0 is the Larmor frequency. The last term indicates the effects neglected in the approximation, $\iota/N << 1$. The first term comes from the toroidicity, and the second term represents the effective toroidal contribution due to the bumpiness and the helicity. The order of the second term is $O(\varepsilon_t)$. In helical configurations, the last term enhances orbit deviation from flux surfaces so that the collisional diffusion is generally larger than that of equivalent tokamak even when toroidicity is not so large.



(a) high bumpiness model



(b) medium-bumpiness model

Fig.7 The mod-B contours of high and medium bumpiness models of Heliotron J. Figure shows that toroidal localization of mod-B_{min} is realized in high bumpiness model

In Heliotron J, the bumpiness reduces the collisional diffusion up to the order $O(\varepsilon_t)$. Therefore, the collisional diffusion is nearly equal to that of equivalent tokamak, especially in the high bumpiness model. The reduction in plateau regime is also explained by the reduction of the drift velocity of trapped particles with large $v_{\parallel}$.

In this report, we mainly treat the problem of the collisional diffusion. The intrinsic problem about the neoclassical diffusion in helical configurations is the diffusion in the low collisionality regime. We previously pointed out the importance of the loss-cone effect on the ion confinement in this regime in Heliotron J [5]. We have calculated drift orbits in the three models used here, and investigate the loss region of trapped particles.

Figure 8 shows that the wide region of confined trapped particles with $v_{\parallel} \approx 0$ appears on outer side of the torus. This region is characterized by the toroidally localized closed mod-B_{min} [6]. The mod-B contours of three model fields are shown in Fig.7. In medium and low bumpiness models, the closed mod-B_{min} also exists but they are not localized toroidally. To confine trapped particles, the vertical drift must be cancelled. In conventional planar-axis heliotron, the deep-helical ripple compensates this vertical drift; on the other hand, the toroidal localization of trapped particles is key to good trapped particle confinement in Heliotron J.

The particle confinement studies in Heliotron J from various aspects are in progress. Especially, the numerical approach is very useful to investigate the complex 3D systems such as Heliotron J. We are now developing the several numerical codes, to calculate the Boozer coordinates, drift orbit, ion thermal diffusivity. These tools will allow us to analyze the particle confinement in Heliotron J configuration in more detail.

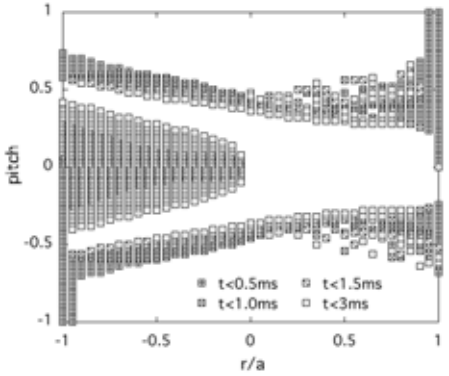


Fig.8 The loss region in high-bumpiness model. The drift-loss time is denoted by τ. The particles are injected from the straight section with various pitch $v_{\parallel}/v$

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Clean Energy Conversion Research Section

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(The University of Tokyo)

1. Introduction

An advanced nanofabrication technique is required that realizes high spatial resolution, high precision in controlling size and position, and is applicable to various materials. Many nanofabrication techniques have been proposed, such as self-organized growth and electron beam lithography [1,2]; however, they have problems, e.g., low spatial precision, limitation of the variation of materials. In order to solve these problems, I have proposed a novel technology, called nanophotonics [3]. Nanophotonics is defined as a technology that utilizes local electromagnetic interactions between a small nanometric element and an optical near field. Since an optical near field is free from the diffraction of light, nanophotonics brings us the unique nanofabrication techniques.

In this report, I review experimental results of the near-field optical chemical vapor deposition. Next, I discuss a unique photochemical reaction based on the spatial locality of the optical near field, which is called "nonadiabatic photochemical reaction". Finally, I apply this reaction to the photolithography.

2. Near-field Optical Chemical Vapor Deposition

For NFO-CVD(Near-field optical chemical vapor deposition), ultra-high purity argon (Ar) was used as a buffer gas and diethylzinc (DEZn) as a reacting molecular gas source. The second harmonic (λ = 244 nm; 5.08 eV) of an Ar^+ laser was used as a light source that resonates the absorption band (band edge E_{abs}=4.13 eV) of DEZn [4]. A He-Cd laser (λ=325 nm; 3.81 eV) was used as the light source that was nearly resonant. The fundamental frequencies of Ar^+ (λ= 488 nm: 2.54 eV) and diode (λ= 684 nm: 1.81 eV) lasers were used as nonresonant light sources. The fiber probe used for NFO-CVD was a high throughput single tapered fiber probe, which was fabricated by pulling and etching a pure silica core fiber [5]. The cone angle of the fabricated fiber probe was 30 degrees and its apex diameter was 30 nm. In order to investigate the deposition effect of nonresonant far-field light, a fiber probe without the usual metal coating, i.e., a bare fiber probe was used for the deposition. Therefore, the optical far-field was generated by light leaking through the circumference of the fiber probe, while the optical near-field was generated at the apex. The separation between the fiber probe and the sapphire substrate was controlled to within several nanometers by using a shear-force technique [5]. The laser output power from the fiber probe was measured with a photo-diode placed behind the sapphire substrate. The sizes of the deposited Zn dots were measured using a shear-force microscope. During deposition, the partial pressure of DEZn was 100 mTorr and the total pressure in the chamber was 3 Torr. It should be noted that the deposition of Zn on the fiber probe and the resultant decrease in the efficiency of optical near-field generation are negligible because the deposition time is sufficiently short.

Figure 1 shows the shear-force topographical images of the sapphire substrate after NFO-CVD using ONF with photon energies of 3.81 eV (λ=325 nm) (a), 2.54 eV (λ=488 nm) (b), and 1.81 eV (λ=684 nm) (c), respectively. The high purity quality of the deposited Zn was confirmed by X-ray photoelectron spectroscopy, and we observed luminescence from ZnO dots prepared by oxidizing the Zn dots fabricated by NFO-CVD [6]. Experimental results in Fig. 1 demonstrate that the unique photodissociation process using ONF. In order to discuss this novel photodissociation process quantitatively, I examine the relationship between the photon-flux I, and the deposition rate R of Zn, in Fig. 2. For $\hbar\omega = 3.81$ eV (◆), R is proportional to I. For $\hbar\omega = 2.54$ eV (■) and 1.81 eV(●), higher-order dependencies appear and are fitted by the third-order function $R = a \cdot I + b \cdot I^2 + c \cdot I^3$. The respective fitting values of a, b, and c agreed well with our theoretical exciton-phonon-polariton model[7].

3. Nonadiabatic Photolithography

The nonadiabatic photochemical reaction is also applicable to photolithography. Here, we call this novel method as "Nonadiabatic Photolithography" [8].

Figures 3 shows atomic force microscopy (AFM) images of the photoresist surface after exposure and development. Here I used the photoresist TDMR-AR87 (Tokyo-Ohka Kogyo Co.) and a g-line light. TDMR-AR87 is the photoresist for an i-line (365-nm) light source, whose sensitivity reacts for g-line is little. The conventional photolithography using a photomask with a periodically nanometric array strongly takes harmful effects on polarization of light and interference fringes. We confirmed difficulties due to these harmful effects experimentally. However, using nonadiabatic photolithography method, we succeeded in transfers of the 2D nanometric arrays of T-shapes and circles; as shown in Fig.3.The grooves on the photoresist appear

along the ridge lines of the Cr mask pattern. While the used light source was non-polarized, the harmful effects were drastically reduced. Thus, usefulness of the nonadiabatic photolithography was confirmed.

I also succeeded in patterning even the EB resist, while it never exposed by the propagating light. This result shows the possibility that the best material can be used without considering whether it is active or inactive to the light.

4. Summary

I demonstrated NFO-COV of nanometric Zn dots based on the photodissociation of gas-phase diethylzinc and zinc-bis(acetylacetonate) using an visible optical near field. To clarify the physical origin of this process, the optical power and photon energy dependencies of the deposition rates were measured. The dependencies were explained using multiple-step excitation process via the molecular vibration mode and the exciton-phonon polariton model. Such unique nonadiabatic photochemical process is applicable to the "nonadiabatic photolithography". In this technique, cheaper visible light source and optics can be used for nanometric photolithography overcoming the diffraction limit of light.

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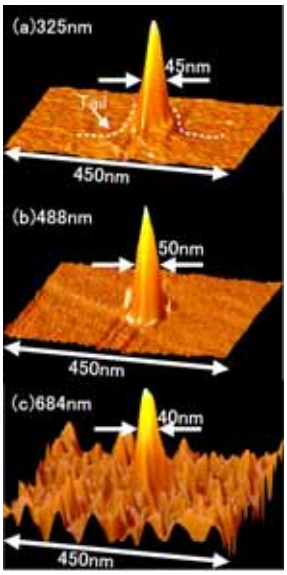

Fig. 1 . Shear-force topographical images after NFO-CVD at wavelengths of λ = 325 (a), 488 (b), and 684 (c) nm.

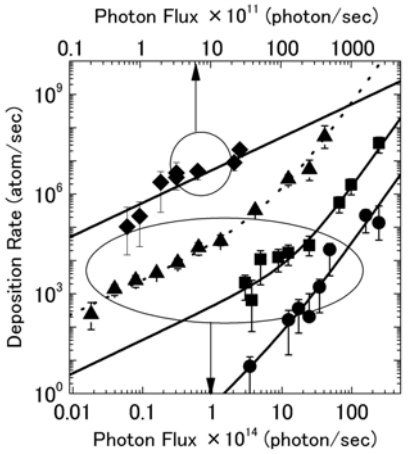

Fig.2. The optical power (photon-flux: I) dependency of the rate R of Zn deposition.

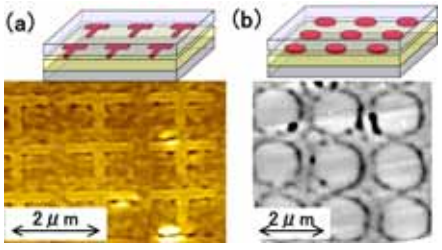

Fig. 3. (a) AFM images of photoresist TDMR-AR87 developed using a T-shaped array photomask. (b) AFM images of photoresist TDMR-AR87 using a circle-shaped array photomask.

Clean Energy Conversion Research Section

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1. Introduction

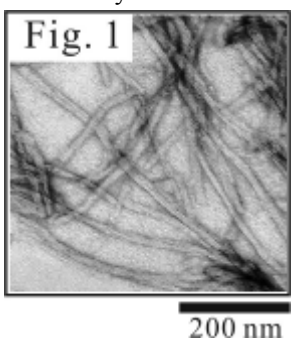
Assembly of organic molecules and their aggregate formation are found in a variety of phenomena ranging from life science to material engineering. Understanding the physico-chemical principle that governs the molecular assembly would lead us to effective production of medical drugs as well as artificial materials. Among such kinds of assembly phenomena, we are focusing upon the so-called "amyloid formation", that is, a fibrously ordered assembly of polypeptide chains.

The amyloid formation in human brains and peripherals is a hallmark lesion of human degenerative diseases. The aggregation of fibrillogenic polypeptides including β-peptide and tau of Alzheimer's disease and islet amyloid polypeptide (IAPP) of type 2 diabetes has been related to pathological events responsible for cell death and organ dysfunctions. Previous studies have elucidated some details of the fibrillation mechanism and the fibril structures, but many important problems including events occurring in the living body as well as artificial control of morphology of the aggregates are unresolved. Our studies have made some progress in these problems.

2. Synergistic action of polyanionic and non-polar cofactors in fibrillation of IAPP [1]

Physiological concentrations of amyloidgenic proteins are lower than the critical lower limit concentrations of the fibrillation *in vitro*. To explain this discrepancy, previous studies have identified a variety of fibrillation enhancers such as lipid membranes and polyanions. Many species of solutes in physiological media, some being ionic and others being non-polar, could always coexist at any sites of the living body. This consideration had led us to suppose that synergy of different solute species might play substantial roles in the amyloidgenesis. To support this proposition, experiments were conducted *in vitro* for demonstrating a synergistic action of polyanionic and non-polar cofactors upon amyloid fibril formation of IAPP. Heparin and alcohol were used for polyanion and non-polar cofactors, respectively.

Amyloid formation of IAPP was monitored by fluorescence and scattering methods in solutions containing heparin and alcohol. The concentration of IAPP was 0.5 μM throughout. At this low peptide concentration, no aggregate was generated without cofactors. Typical aggregation kinetic data were obtained at 4-8 % TFE and 0.5-5 μg/ml heparin, which exhibited an initial delay followed by evolution and final plateau phases, whose properties are typical for amyloid formation. Aggregates generated in these conditions were fibrous in shape (Fig. 1), typical for amyloid.



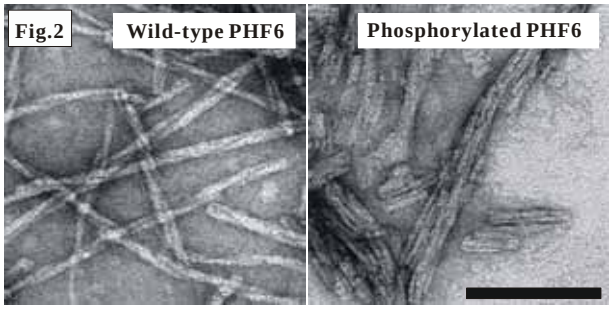
Notably, without TFE, heparin even at 100 μg/ml could not induce the fibrillation, whereas 0.5 μg/ml or less of heparin was enough to form fibrils in the presence of TFE. Similarly, TFE was ineffective up to 15 % in the absence of heparin, whereas 5 % or less of TFE induced the IAPP aggregation with a trace amount of heparin. These results indicate that the aggregation enhancement in the heparin-TFE mixture cannot be explained by a simple sum of the two independent cofactor's actions. The coexistence effect of the two is non-linearly strong.

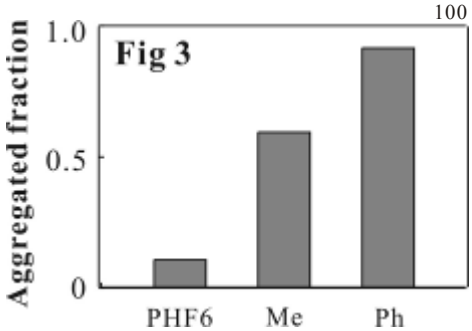
A variety of alcohol species could cooperate with heparin in the IAPP fibrillation. In the presence of 5 μg/ml heparin, HFIP induced the fibrillation at less than 1 %. In case of isopropanol (iPrOH) or ethanol (EtOH), higher alcohol concentrations are required for the fibrillation. The order of the efficiency was HFIP > TFE > iPrOH > EtOH. We also tested the effects of other polyanion species, N-acetylheparin and polyglutamate, which could also yield the IAPP fibrils only when the solution contained TFE.

Polyanionic molecules such as GAGs and nucleic acids are abundant in human tissues, and have been suggested to promote amyloidgenesis. However, the effects of polyanions must be weak in physiological media containing counter cations. The weakened polyanionic effects *in vivo* may require synergistic action with the non-polar milieu for promoting the amyloidgenesis. On the other hand, a surface of biomembrane is a plausible site of amyloid nucleation, where negative charges at head group of lipid molecules are essential for the fibril formation. It means that co-existence of anionic and non-polar parts of the lipid membrane is essential. These considerations agree well with the present observations in the polyanion-alcohol mixtures. Strong synergistic action of multiple cofactors might play important roles in amyloidgenesis in the living body.

3. Amyloid-forming propensity of the chemically modified fibril-forming core peptide of human tau [2]

Tau forms amyloid-type aggregates in brains of patients with the Alzheimer's disease progressively, and is a key molecule for diagnosis and therapy of the diseases. Previous studies have found that several small portions of tau can produce amyloid-type fibrous aggregates similar to that formed by full-length tau. We synthesized a variety of chemically modified peptides of these fragments, and extensively analyzed their aggregation properties and aggregate structures. By this approach, we are elucidating essential molecular components and mechanisms that lead to fibril formation. Here we briefly introduce two of our results which employed the peptide portion VQIVYK (PHF6) and its derivatives modified in the tyrosine (Y) residue. The left panel of Fig.2 shows a transmission electron microscopic image of the fibrils formed by wild-type PHF6.



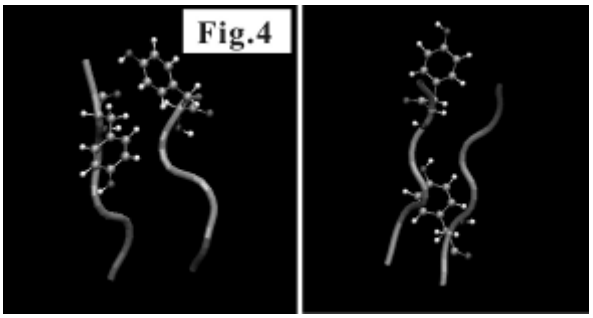


First, we studied the effect of phosphorylation of the Y residue. It is well known that tau phosphorylation is an essential step in pathology of the Alzheimer's disease. We found that this modification of PHF6 strongly enhanced the fibril-forming propensity of PHF6 and resulted in forming tight mass of fibrils as shown in the left panel of Fig. 2. We are now resolving some electrostatic mechanisms underlying this aggregation enhancement.

Next, some results obtained for "hydrophobic" derivatives of PHF6 are shown in Fig. 3. We produced the peptides that carry hydrophobic parts on the aromatic ring of the Y residues. "Me" and "Ph" in the figure indicate the derivatives that carry additional methyl and aromatic parts attached to Y of PHF6. The results have demonstrated that the hydrophobicity of the peptide strongly enhance the aggregation.

4. Molecular dynamics simulation of PHF6 and its derivatives.

For further understanding of the aggregation of tau peptides and its derivatives, we are performing computer simulation of the peptides. Typically, we constructed a system containing several peptides and thousands of water molecules and performed a full-atom molecular dynamic simulation. The calculation time required to obtain meaningful results is very long, and our studies are still under progress. We would only show some simulated structures composed of two assembled PHF6 molecules in Fig. 4.



5. Closing

By changing peptide structures and solution environments, we are approaching detailed mechanisms and artificial control of the amyloid-type peptide assembly. The events occurring in the human body, especially in pathological condition, are very complex and are hard to be understood. Combination of empirical and rational approaches undoubtedly contributes to human welfare in medicine. On the other hand, development of the method producing nano-structures such as well ordered fibers is achieved only via a cross-talk between experimental and theoretical results. We expect that our studies employing chemical synthesis, physico-chemical analysis and computer simulation methods would find a reasonable way to these difficult problems.

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Chemical Reaction Complex Processes Research Section

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1. Introduction

The results obtained in Chemical Reaction Complex Processes Research Section during the fiscal year of 2006 are described in the following sections 2 to 7. In section 2 the study of laser ablation aiming at surface elemental analysis *in situ* in liquid is described, especially emphasizing the low destructive nature when a long nanosecond pulse is used. In section 3 the effects of pulse duration upon the plume-formation mechanism is discussed on the basis of time-resolved plume emission imaging. In section 4 the mechanism of ordered-macropore formation in p-Si is studied. In section 5 the electrochemical filling of metals into Si macropores is studied especially focusing on whether the deposited metal has tubular or rod structure. In section 6 the progress obtained on the subject of photo-assisted control of metal deposition onto Si is described. Finally in section 7 the application of the Si rugate filter to sensors and its stabilization by oxidation are demonstrated.

2. Quasi Non-destructive Elemental Analysis of Solid Surface in Liquid by Laser Ablation Plume Spectroscopy

Emission spectroscopy of laser ablation plume can be used for surface elemental analysis. The method is generally called "Laser induced breakdown spectroscopy" or LIBS and is promising, since it does not require any bulk sample preparation. The sampling is done merely by pulsed laser irradiation of the surface to be analyzed. Since there is not any established method for *in situ* elemental analysis of solid surface in liquid, this method would be useful for a wide variety of applications such as monitoring of electrodeposited films or corrosion of the inner wall of piping, environmental monitoring of the bottom of a lake or sea. However, emission spectra from the plume in liquid usually show broadened and deformed spectra due to a high density and steep temperature gradient in the plume. Such broadening and deformation cause difficulties in the application to elemental analysis of the solid surfaces in liquid.

In our previous study we reported that the irradiation of long nanosecond pulses, such as pulse width of 150 ns, gives sharp and narrow line spectra applicable to the surface analysis. It was hard to obtain such clear spectra by using short pulses such as 20-ns pulses, even though we optimized irradiation conditions, such as laser focusing condition.

In this section we report that the use of long nanosecond pulse gives not only the sharp clear line spectra but also very limited damage to the analyte surface, and the method can be regarded as a quasi non-destructive method.

Fig. 2-1 shows the spectra obtained by consecutive irradiations of 150-ns pulses to the same spot on an electrodeposited copper film on a platinum plate. The average thickness of the original Cu film estimated by coulometry during the electrodeposition was 164 nm. The pulse energy was adjusted to 1.7 mJ and 100-mm focal length lens was used to focus the laser pulse down to the target surface. The gate of the ICCD detector was set to be open from 800 ns from the ablation pulse and the gate width was set to be 5 ms. The first pulse shot gives clear intense Cu lines with very low intensity of the lines originated from Pt atoms. In the spectra obtained by the following consecutive irradiations to the same spot, the emission lines assigned to Pt atoms appear in addition to the Cu lines. By continuing the irradiation to the same spot the intensity of the Cu lines decreases and finally the spectrum is dominated by the emission lines from Pt atoms, suggesting that the Cu film

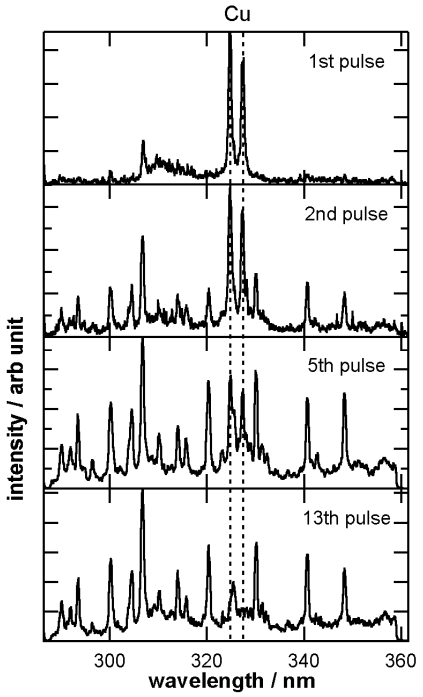
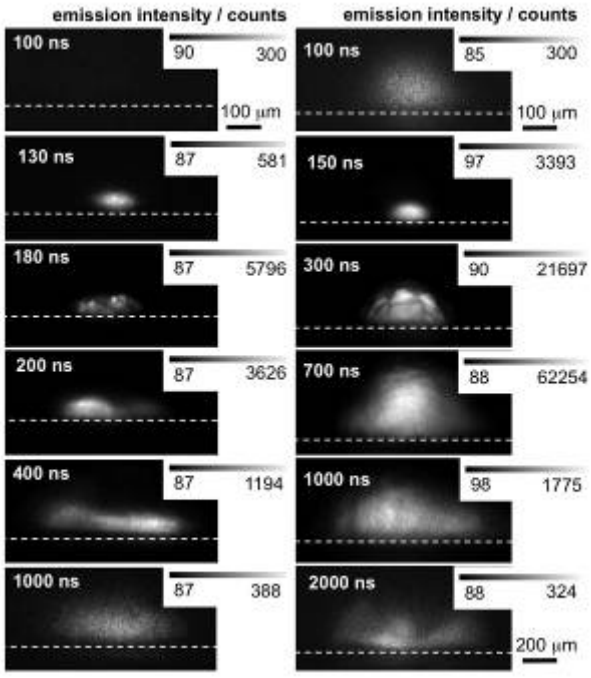


Fig. 2-1. Spectrum obtained by consecutive irradiation of the same spot on the Cu thin film electrodeposited on a Pt plate. The intensity is normalized to the highest peak in the spectrum. The spectral lines other than 324.75 and 327.40 nm are all assigned to atomic Pt.

was penetrated by the hole drilled by the laser pulse irradiation. If we assume that the disappearance of the Cu lines corresponds to the complete Cu film removal at the irradiation spot, the material removal rate is estimated to be ca. 13 nm/pulse in the present experimental condition. The damages of 2–10 nm/pulse have been reported, depending on the experimental condition, for minimized damages in LIBS studies in gas phase or in vacuum. The present results are comparable to these results, and promising for "quasi non-destructive" analysis in liquid.

3. Effects of pulse duration upon the plume formation by the laser ablation in liquid

As mentioned in the previous section, a 150 ns pulse gives a narrow emission line profile at the delay time over around 500 ns, although emission lines are broadened and merged at the delay time earlier than 400 ns. It is known that a short pulse brings about an efficient ablation. However, the pulse as short as 20 ns gives very weak emission intensity, as well as broadened lines superposed on a continuous spectral profile. The result that a longer pulse gives an intense emission, while showing inefficient ablation, is seemingly contradicted. In the present work, time-resolved images of the ablation plume were taken by a high speed camera based on an intensified charge coupled device (ICCD), and the plume size and shape have been discussed to verify the effect of the pulse duration.



(A) (B)

Fig. 3-1. Images of the plume obtained by the irradiation of a Cu plate immersed in pure water by the laser with the pulse duration of (A) 20 ns and (B) 150 ns. The delay time of 130 ns means that the image is taken right at the start of the irradiation by the pulse. The intensity scale of each image is adjusted for clarity, and the gradation bar is shown in each image. The white broken line indicates the approximate position of the target surface. A 95-%-cut ND filter was used for the images of 180-ns delay when 20-ns pulse was used and 300, 400, and 500-ns delays for the 150-ns pulse.

Figures 3-1(A) and (B) show images of the plume obtained by the irradiation of a Cu plate immersed in pure water by the laser with the pulse duration of 20 ns and 150 ns, respectively. Delay time from the laser oscillation is noted at each image. In our experimental setup the laser pulse arrives at the target surface at the delay time of 130 ns.

By the irradiation with a 20 ns pulse the emission appeared at 130 ns, and the intensity increased for a while. The most intense emission was observed at the delay time of 180 ns. In most of the images obtained by the irradiation with 20 ns pulse, several spots with bright centers are clearly seen. One of the reasons of the broadened and continuous spectra observed throughout the delay time by the 20-ns pulse irradiation may be due to the emission from the high density bright spots.

In the case of the irradiation with a 150-ns pulse, a weak stray light is observed at the delay time of 100 ns (Fig. 3-1(B)). The emission from the ablation plume appears at the delay time of 150 ns, and then the intensity increases gradually with time. The highest intensity was obtained at ca. 400 ns, and the emission lasted till 2000 ns. In the images obtained at the delay time of ca. 300 ns, bright spots were observed as in the case of 20-ns pulse. At the delay time of ca. 400 ns and later, however, the bright spots were not observed anymore and the emission is rather homogeneously distributed with the brightest region at the center of the ablation plume. Also, the shape of the emission region looks hemispherical. This noticeable difference in the appearance of the bright spots in the plume images suggests the further excitation of the plume directly by a 150-ns pulse, which is less important in the case of 20-ns pulse irradiation. The front part of a 150 ns pulse triggers an ablation, resulting in the formation of the ablation plume which contains the high density spots. The later part of the pulse, in the case of 150-ns pulse, keeps exciting the plume directly, leading to the fractionation of the high density spots to a comparatively lower density gaseous state while keeping the atoms excited. At the delay time of ca. 400 ns or later, therefore, the atoms in the plume still emit light efficiently. The timing of the transition from the highly broadened spectra to narrow and sharp spectral lines corresponds to the timing of the disappearance of the bright spots in the plume images. These results are explained by the direct excitation of the plume by the later part of the pulse, when the pulse duration is long enough, such as 150 ns.

4. Macropore Fomation in *p*-Type Silicon

Macroporous Si is now expected to contribute in promising fields of applications such as solar cells, chemical sensors and photonic crystals. To date, we have investigated metal electrodeposition into ordered macropores prepared from p-type silicon, focusing on its novel application to a template for microfabrication. From the viewpoint of the practical application, it is important to understand the suitable formation condition of the template and to control its

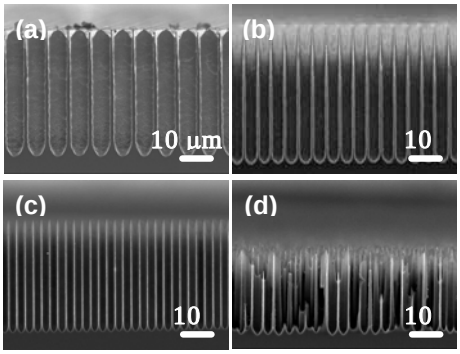


Fig. 4-1 Cross-sectional FE-SEM images of prepatterned silicon wafers after anodization in HF solution at 13 mA/cm^2 for 2 hours. The spacing of etch pits is (a) 8, (b) 5 , (c) 3 , and (d) 2 μm.

configuration. We performed an observational investigation on the early stage of the macropore formation using a prepatterned silicon wafer, aiming to understand the formation process of ordered macropores. Then, the effect of the spacing of prepared etch pits on the shape of macropores was investigated.

A macropore array was fabricated in HF solution by anodic oxidation of a prepatterned p-type silicon (100) wafer with a resistivity of 10-20 Ωcm on which four types of etch-pit arrays were prepared. Etch pits having 2-, 3-, 5-, and 8-μm intervals were created on the respective silicon wafers by photolithographic prepatterning and subsequent alkaline etching. The pre-etched surface was then anodized at 13 mA/cm^2 in a mixture solution of HF, deionized water, and 2-propanol. The diameter and the depth proportionally increase with anodization time at the early stage. When the neighboring pores sufficiently get close each other, the lateral growth ceases, and then the pores grow only in the depth direction at a constant rate. On the 5 μm-interval sample, the diameter settles at around 4.5 μm. The vertical growth continues with keeping the constant pore diameter: 4-hour anodization forms an array of ordered macropores of around 90 μm in depth. It implies that silicon dissolution proceeds only at the bottoms of the pores. Their diameter and wall thickness depend on the initial spacing of the etch pits, showing a tendency to decrease with decreasing the interval (Fig. 4-1). The 2 μm-interval sample finally results in the collapse of the wall. The wall thicknesses obtained are smaller than the double widths of the respective space-charge regions (SCR). The macropore formation model based on the depletion of carriers in the SCR, which has been extensively accepted, cannot explain these results. Another model, which can interpret the formation process of macropores shown here, is awaited.

5. Pore-Filling with Metal in Macroporous Silicon

It is of great interest to use well-ordered macroporous silicon as templates for fabricating microstructures of metal. However, studies of metal deposition into macropores are quite few in number. In particular, to our knowledge, there is no report using p-type silicon as a template for metal

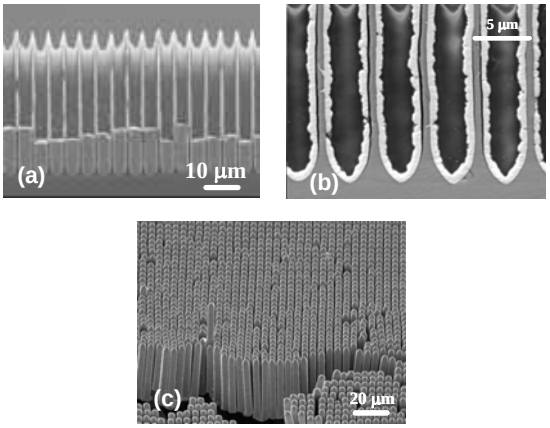


Fig. 5-1 Metal deposition into macropores. (a) copper deposition in the dark, (b) nickel deposition under illumination, and (c) after dissolution of the silicon template.

deposition although the good work was reported using n-type silicon. When a silicon template is perfectly dissolved by alkaline etching solution after metal deposition, micro-metal products copying the initial template structure of macroporous Si can be obtained.

Copper and nickel electrodeposition into ordered macropores prepared in p-type silicon were studied in aqueous solutions containing cupric and nickel ions, respectively (Fig. 5-1). When a macroporous silicon template is cathodically polarized in 0.1 M cupric sulfate solution, copper is deposited preferentially at the pore bottom in the dark. The deposition takes place densely and the surface of the deposits is smooth. No electrodeposition of Cu is observed on the pore wall. In contrast, the deposition of nickel in 0.1 M nickel sulfate solution is not possible in the dark, while deposition occurs uniformly on the entire surface of the pore wall under the backside illumination. The deposits uniformly grow on the pore wall and cover the inner surface of the macropore, which results in a tubular structure of Ni deposits. Dissolution of silicon templates by alkaline etching process leads to the formation of copper microrods and nickel microtubes. The different deposition behavior of both metals is attributed to different paths supplying charge carriers. Cu is a noble metal and hence the redox potential level overlaps with the valence band of silicon. It enables the reduction of cupric ions even in the dark. The favored site is the pore bottom judging from the potential distribution. This charge transfer process produces microrods. On the other hand, Ni is a less-noble metal, and charge transfer via the valence band cannot be expected. Metal deposition is possible only under illumination. Photo-generated electrons are consumed for metal deposition, and the sites can be where illuminated. Microtubular morphology is thus produced.

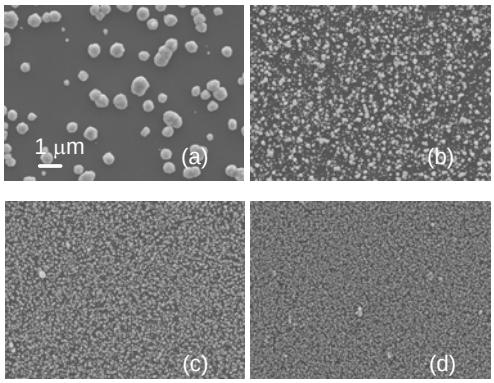


Fig. 6-1. SEM images of Cu-deposited p-type silicon. Electrodeposition was conducted in aqueous solution containing 4 mM $CuSO_4$ (a) in the dark, under illumination of (b) 12.5, (c) 25, and (d) 50 mW/cm^2.

6. Photo-Assisted Control of Metal Electrodeposition on *p*-Type Silicon

Photoelectrochemical solar cells are expected as a way of direct energy conversion like from solar to hydrogen. Control of size and distribution of metal particles in surface modification of semiconductor plays a vital role in the enhancement of electrocatalysis of semiconductor electrodes for a practical use of semiconductor as the photoelectrochemical solar cells. We have succeeded in controlling the size and distribution of Pt electrodeposits on p-type silicon by utilizing the band structure of silicon electrode (Annual Reports 2005). In electrodeposition of noble metals like Pt, nucleation is predominant under illumination due to charge transfer of photoexcited electrons via the conduction band. On the other hand, the growth of nuclei is predominant in the dark due to hole injection via the valence band. We obtained different particle density and size of the electrodeposits on p-type silicon by modulating illumination condition during potentiostatic electrolysis.

This method was applied to noble metals other than Pt. Cu deposition can be controlled by the modulation of illumination. Partcle density of Cu deposits increases with light intensity (Fig. 6-1). On the contrary, it is difficult to control the morphology of electrodepsits in Au and Pd systems, because these metals are spontaneously deposited even in the dark by immersion plating with high deposition rate, which takes place in parallel with the oxidation of silicon. This makes it difficult to control the electrodeposition by illumination or even by the potential step method. In contrast, Pt is also deposited by immersion but the rate of the deposition is low. Controlling the deposition of these two metals with modulation of illumination may be possible. It is necessary to inhibit the immersion plating in the Pd or Au system for the purpose. The modification of the redox level using complexation may be a solution. One question to be solved arises here. Although the redox level of Pt is more positive than that of Pd, the rate of immersion plating is lower than that of the Pd system.

7. Rugate-Type Porous Silicon Multilayer Formation and Its Application to Sensing

A porous silicon multilayer prepared by sinusoidally modulating current density during anodization of silicon produces a kind of 1-D photonic structure. This so-called rugate filter exhibits a characteristic spectral peak in the reflectance spectrum and shows better filter characteristics as compared to conventional porous silicon multilayers based on the Bragg stack. In contrast to porous silicon Bragg reflectors, in which the current density varies in a discrete way during the anodization process, the rugate filter gives a very clean spectrum without strong sidelobes around the reflectance peak.

Porous silicon multilayers were prepared by electrochemical anodization of p^+-type Si wafer, (100) and 0.01-0.02 Ωcm, in 22 wt.% HF ethanolic solution. The current density was sinusoidally varied between 68 and 94 mA/cm^2. A unique reflection peak appears in the rugate filter and the peak position varies with periodicity and refractive index of multilayer (Fig. 7-1). When the filter is exposed to saturated vapor of alcohol, the resonant peak red-shifts due to capillary condensation of the vapor into pores, the average size of which is around 20 nm, and the subsequent increase in the average refractive index. The repeated use results in oxidation of the pore surface leading to a blue-shift of the resonant peak.

In order to stabilize the filter, electrochemical oxidation was performed in H_2SO_4 solution at galvanostatic condition of 2 mA/cm^2. As the oxidation time increases, the degree of oxidation becomes higher and the peak position shifts toward the blue direction. The oxidation replaces silicon nanocrystallites by silicon dioxide which has a refractive index lower than that of silicon. No further blue-shift was observed at oxidation time longer than 20 min. It was found that the oxidized structure endures more than 100 adsorption-desorption cycles of ethanol vapor without degradation. It is concluded that electrochemical oxidation improves the durability of the filter

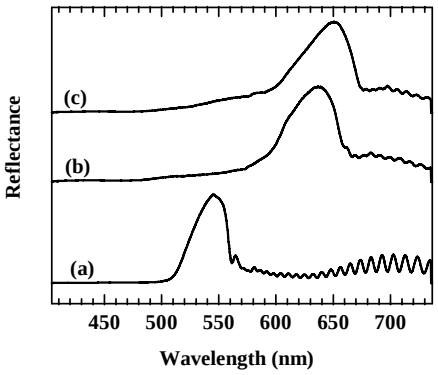


Fig. 7-1 Reflectance spectra of rugate filters before (a) and after exposure to saturated vapors of methanol (b) and (c) ethanol for 15 min.

Molecular Assemblies Design Research Section

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1. Introduction

Solar energy is widely accepted as being the most abundant and accessible renewable energy source. In contrast to the other sources such as hydropower, wind, and geothermal, solar energy is easily accessible to small, large, low-tech and high-tech systems. Even in the countries with relatively low irradiation intensity it is still high enough to make solar energy profitable. The main challenges associated with the use of solar energy are the development of more cost-effective systems with improved photon conversion efficiency and the ability to convert the captured energy into chemical energy such as hydrogen fuels.

A broad range of organisms have developed complex molecular machinery for the efficient conversion of sunlight to chemical energy over the past 3 billion years, which to the present day has not been matched by any man-made technologies. In this context, in order to build such kinds of efficient system mimicking living system, utilization of self-organized molecular assembly is a quite essential approach. It provides a breakthrough for new energy systems of high performance with minimum energy consumption. This research section focuses on the development of novel one- or two-dimensional nanomaterials of metal oxide and/or conductive polymer, such as nanotubes, nanowires, and/or nanosheets. Furthermore, we are developing highly efficient organic solar cells, such as organic thin film solar cell and dye-sensitized solar cell (DSC), as well as highly active photocatalyst to realize sustainable energy systems based on next-generation solar technologies.

2. Organic Thin Film Solar Cells

Mechanisms for generation of photocurrent of organic solar cells are (1) absorption of photons by dye and generation of excitons, (2) diffusion of exciton to donor-acceptor interface, (3) dissociation of exciton into electron and hole (viz. charge separation), and (4) transport and collection of charges. Therefore, elongation of lifetime of the excitons and restraint of charge recombination is essential for the sake of development of highly efficient solar cell. We design novel materials for electrode, electron transporting layer (ETL), light-absorption layer (LAL), and hole transporting layer (HTL) and construct novel cells and evaluate their performances. Particularly, we succeeded to develop highly efficient and stable solar cell with glass-ITO/PEDOT:PSS/P3HT:PCBM/TiO_2/Al structure (Fig. 1).

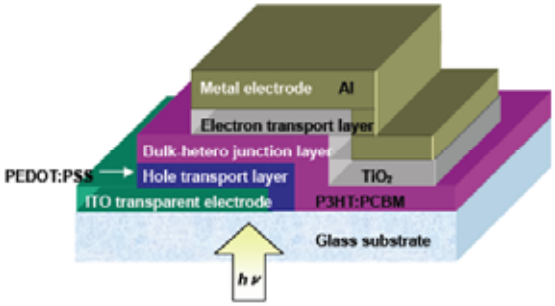


Fig. 1 Structure of organic thin film solar cell.

The TiO_2 layer plays an important role for preventing the electron recombination and cell degradation. The efficiency of the novel cell attained 4.05% with short circuit current J_{sc} of 9.72 mA/cm^2, open circuit voltage V_{oc} of 0.60 V. In particular, 0.694 as fill factor (*FF*) was the world best record among polymer solar cells composed of P3HT: PCBM system to the best of our knowledge (Fig. 2). Furthermore, this organic solar cell including TiO_2 layer showed an excellent durability under an atmospheric illumination at light intensity of 100 mW/cm^2, AM 1.5. The current density decreased no more than 6% even after the illumination for 100 h (Fig. 3). We introduced TiO_2 into the intermediates of the tandem cell as ITO/PEDOT: PSS/P3HT-PCBM/TiO_2/Pt/PEDOT: PSS/P3HT-PCBM/TiO_2/Al. Such components of the structure enabled to increase the V_{oc} and the *FF* of the tandem cell efficiently, though the J_{sc} was

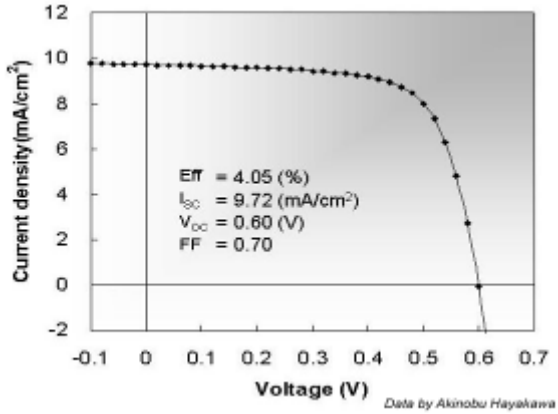


Fig. 2 I-V curve and cell efficiencies of ITO/PEDOT:PSS/P3HT:PCBM/TiO_2/Al.

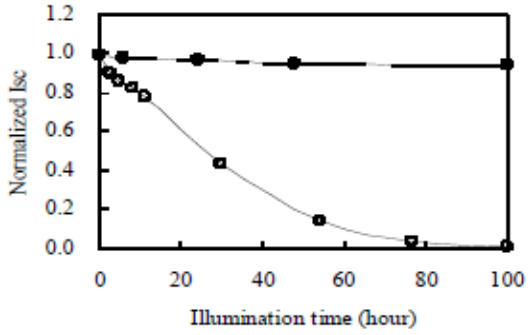


Fig. 3 Durability of ITO/PEDOT:PSS/P3HT:PCBM/TiO_2/Al under an atmospheric illumination at light intensity of 100 mW/cm^2, AM 1.5.

decreased compared with that of the single one. Further improvement and optimization of the multi-layered organic solar cells by using other kinds of metals and/or metal oxides such as Au, ZnO, and so on, in terms of higher cell efficiencies were examined underway.

This research was supported by New Energy and Industrial Technology Development Organization (NEDO) from the Ministry of Economy, Trade and Industry (METI) to S.Y.

3. Dye-sensitized solar cells (DSCs)

As a prospective candidate of next-generation solar cells, we have eagerly studied on DSC. DSC, one of the most promising candidates of next-generation solar cells, absorbs the visible light at various wavelengths via organic dyes adsorbing on the porous TiO_2 electrode, as well as the UV light directly by the porous TiO_2. In DSC, efficient charge separation and carrier transfer are achieved by the electron injection into the conduction band in TiO_2 semiconductor, and thus, the ideal efficiency of DSC is expected to be very high, 33 % of the incident sunlight. However, the real efficiency up to now is ~ 10 %, which is caused by e.g., the grain boundary resistance of porous TiO_2 film. To circumvent this problem, the nanostructural design should be a key technology to achieve the more efficient electron transfer.

Another serious problem of DSC is lack of the durability against heat, light, oxygen, moisture, and so on. Such mechanisms on the decomposition of

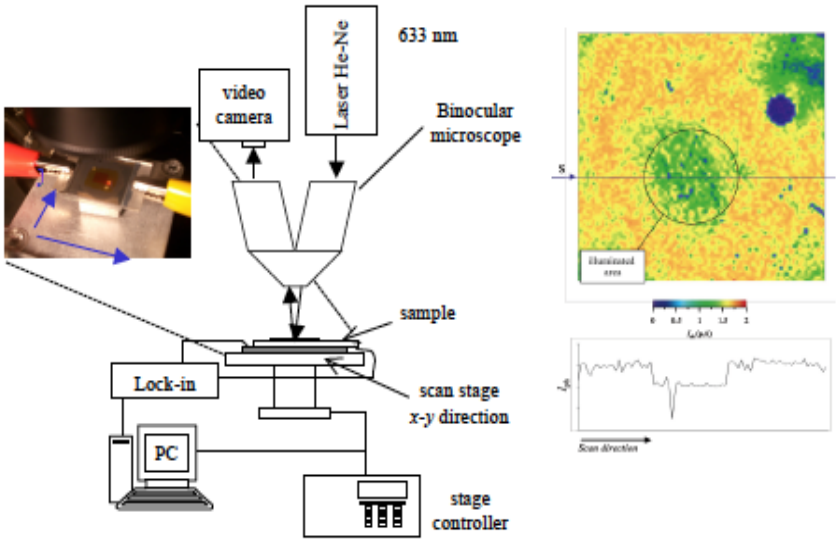


Fig. 4 Instrument (left) of Laser Beam Induced Current (LBIC) and photocurrent image (right) of DSC after illumination of fluorescence light through the circular mask for 3 week.

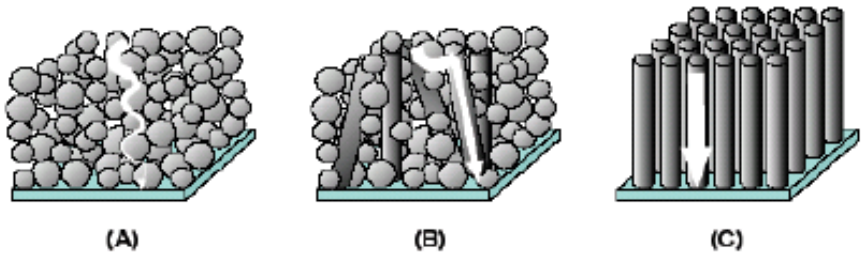


Fig. 5 "Electron expressway concept" by using 1D or 2D nanosized metal oxides as electron transport layer or electrode for organic solar cell; (A) Conventional nanosized grains, (B) 1D nanowires with grains, (C) 2D arrays of nanorods..

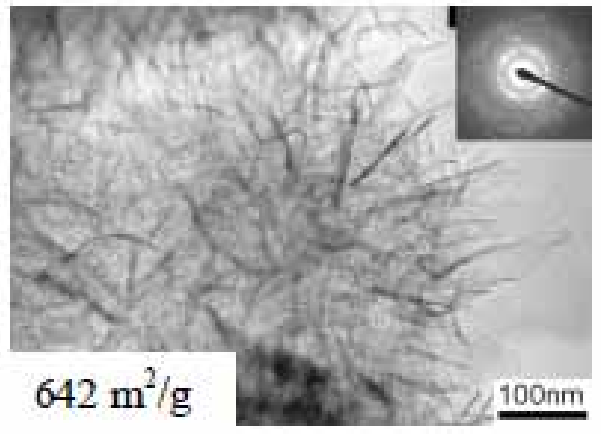


Fig. 6 TiO_2 nanosheet..

the cell are still obscure and must be clarified. For the sake of elongation of stability in terms of cell performance, we are engaged in encapsulation of the cell and monitoring the device through high-throughput analysis of laser beam induced current as shown in Fig. 4.

Applications of 1D- or 2D-nanomaterials of organic- and/or inorganic-compound as electrode for DSC are promising strategies to develop highly efficient solar cells. We have developed various kinds of nanotubes, nanowires, or nanosheets of 1D-materials, and 2D-array of nanobrushes through hydrothermal synthesis (Fig. 5). In particular, we succeeded to control the microstructures of TiO_2 and titanate materials as rods, tubes, wires, and sheets (Fig. 6).

One important limiting factor in the DSC performance is electron diffusion. During the diffusion of electron to the electrode, the electron is estimated to traverse the 10^3-10^6 of nanoparticles. Disordered structures of the nanoparticles of film led to the enhancement of scattering of free electrons, caused reduction of the electron mobility with promoting of charge recombination especially at the grain boundaries. Films made with an array of oriented single-crystalline nanorods instead of the nanoparticles offer the improvement of the electron diffusion leading to higher photoelectric effects. The pathways provided by the nanorods ensure the rapid collection of photoelectrons generated throughout the device at the interface of conducting substrate. Fewer grain boundaries of the nanorod arrays are also effective to suppress the charge recombination. Moreover, electron diffusion in the crystalline rod is expected to be faster with several orders of magnitude than percolation through a random polycrystalline network.

In this sense, DSCs were fabricated with ZnO nanorod arrays on the fluorine-doped SnO_2

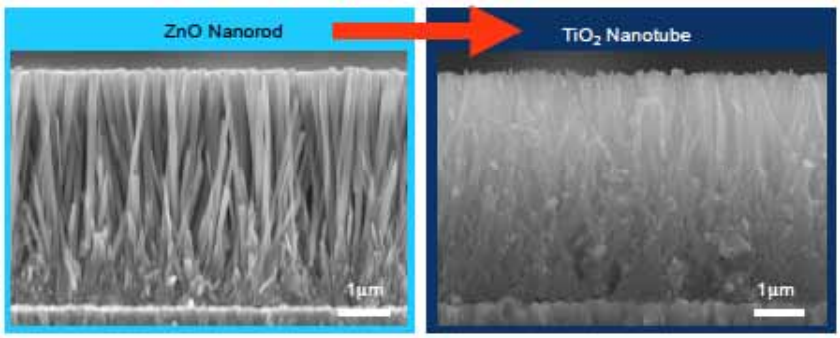


Fig. 7 TiO_2 nanotube array from ZnO template.

transparent conducting oxide (FTO) glass substrates. These hybrid nanostructured cells based on nanorod arrays can be tailored to take advantage of the improved electron diffusion along the aligned nanorods. The DSC performances of the composite nanostructures were compared with various lengths of nanorod arrays. These composite nanostructures showed a remarkable enhancement in the shot circuit photocurrent and thereby in its efficiency compared with those prepared in the different length of nanorods. We also developed TiO_2 nanotube array from ZnO template as shown in Fig. 7. Further improvement of such TiO_2 nanotube array for solar cell is underway.

This research was supported by Kyoto University 21COE program "Establishment of COE on Sustainable Energy System."

4. Construction of Exciton Path of Bacterial Photosynthesis

Bacteriochlorophyll c (BChl *c*) and Bacteriochlorophyll e (BChl *e*) were obtained from *Chlorobium tepidum* and *Chlorobium phaeobacteroides*, respectively. Both of BChls were aggregated through the treatment with acetone, which were confirmed by their uv-vis spectroscopic analysis. SEM images of the thin-films of BChl *c* and BChl *e* also showed the formation of aggregated fibers as shown in Fig. 8. Further application of these fibrous thin films for organic thin-film solar cell is now under investigation.

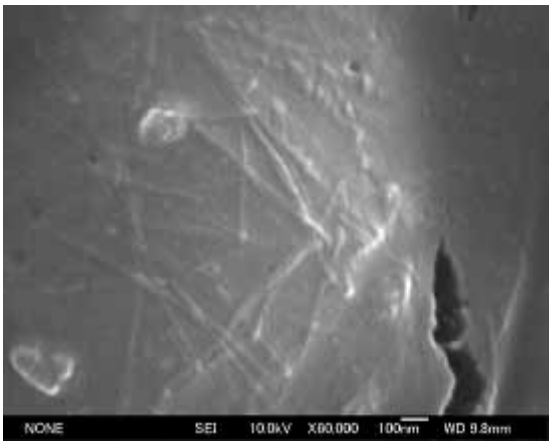


Fig. 8 SEM image of BChl *e* film.

5. Photocatalytic Evolution of Hydrogen

The utilization of mesoporous TiO_2 photocatalyst with platinum loading was investigated towards the photocatalytic H_2 evolution. A surfactant-assisted templating sol–gel process was used to obtain the mesoporous TiO_2 with uniform and narrow pore size distribution. Various platinum contents (0.1–0.9 wt%) were supported on the synthesized mesoporous TiO_2 by single step sol–gel (SSSG), incipient wetness impregnation (IWI), and photo-chemical deposition (PCD) methods. The SSSG method, in which Pt precursor was introduced into the completely hydrolyzed TiO_2 sol prepared with a mesopore-directing surfactant template, was revealed to be a helpful candidate, exhibiting the highest photocatalytic activity (optimum loading of 0.6 wt%) as well as the broadest photocatalytic activity window. This method also proposes a great prospect to the development of highly active photocatalysts.

TiO_2 NT was also prepared by hydrothermal treatment in NaOH (aq.) by using commercially available TiO_2 (Degussa P-25) as starting material. Produced TiO_2 NTs were characterized by thermogravimetry-differential thermal analysis (TG-DTA), X-ray diffraction (XRD) measurement, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and N_2-adsorption/desorption analysis. SEM and XRD observations of the product revealed the formation of titanate nanotube structure with its diameter of about 10 nm. Post-heat-treatment over 300 ^oC began to break some parts of the nanotubes into particles of anatase phase. Moreover, the particles changed into rutile phase through the post-heat-treatment at higher temperatures over 800 ^oC. Photocatalytic activity of the TiO_2 NTs for H_2 evolution from from aqueous methanol solution was evaluated. The physical properties such as crystal structure and specific surface area of the TiO_2 NTs were thoroughly studied in relating to its photocatalytic activity. It was found that the TiO_2 NTs through the calcination at appropriate temperature exhibited higher yield of H_2 than that of the commercially available TiO_2 such as Ishihara ST-01 and Degussa P-25.

Advanced Energy Utilization Division

Biofunctional Science Research Section

T. Morii, Professor
T. Sugimoto, Assistant Professor

1. Introduction

Functional materials enabling highly efficient energy utilization and chemical transformation processes play key roles in a sustainable energy system. The work in our research group takes synthetic, organic chemical, biochemical and biophysical approaches to understand the biological molecular recognition and chemical reactions. We are exploring the design and application of biomaterial-based (proteins, RNA, and DNA) functional small domains to assemble advanced functional materials that enable highly efficient energy utilization in water, a solvent of life. The strategy developed here would afford functional small proteins essential for nano-biotechnology tools such as biosensors and protein chips. Followings are main research achievments in the year of 2006.

2. A new strategy for tailoring fluorescent biosensors

The RNA—protein complex serves as a novel framework for design of receptors and enzymes. The marvelous functions of RNA-protein complexes in the cell are exemplified by the action of ribosomes, which catalyze peptide-bond formation. Three-dimensional structures of RNA-protein complexes solved by X-ray crystal analysis or NMR spectroscopy provide a sense of the remarkable diversity of RNA—protein complexes. We have reported on a ribonucleopeptide (RNP) that binds ATP[3] by employing a structure-based design that provides a stable RNP scaffold of a Rev-RRE (Rev Responsive Element) complex, and successive in vitro selection steps. The structural characteristics of the RNP are suitable for molding of a ligand-binding pocket of the RNP in a step-wise manner.

Fluorescent biosensors that facilitate reagentless sensitive detection of small molecules are crucial tools in the areas of therapeutics and diagnostics. However, construction of fluorescent biosensors with desired characteristics, i.e., detection wavelengths and concentration ranges for ligand detection, from macromolecular receptors is not a straightforward task. An ATP-binding ribonucleopeptide (RNP) receptor was converted to a fluorescent ATP sensor without chemically modifying the nucleotide in the ATP-binding RNA. The RNA subunit of the ATP-binding RNP and a peptide modified with a pyrenyl group formed a stable fluorescent RNP complex that showed an increase in the fluorescence intensity upon binding to ATP. The strategy to convert the ATP-binding RNP receptor to a fluorescent ATP sensor was applied to generate fluorescent ATP-binding RNP libraries by using a pool of RNA subunits obtained from the in vitro selection of ATP-binding RNPs and a series of fluorophore-modified peptide subunits. Simple screening of the fluorescent RNP library based on the fluorescence emission intensity changes in the absence and presence of the ligand afforded fluorescent ATP or GTP sensors with emission wavelengths varying from 390 to 670 nm. Screening of the fluorescence emission intensity changes in the presence of increasing concentrations of ATP allowed titration analysis of the fluorescent RNP library, which provided ATP sensors responding at wide concentration ranges of ATP. The combinatorial strategy using the modular RNP receptor reported here enables tailoring of a fluorescent sensor for a specific ligand without knowledge of detailed structural information for the macromolecular receptor.

We first tested whether simple replacement of the Rev peptide of an ATP-binding RNP receptor with a fluorophore-labeled Rev peptide could afford a fluorescent

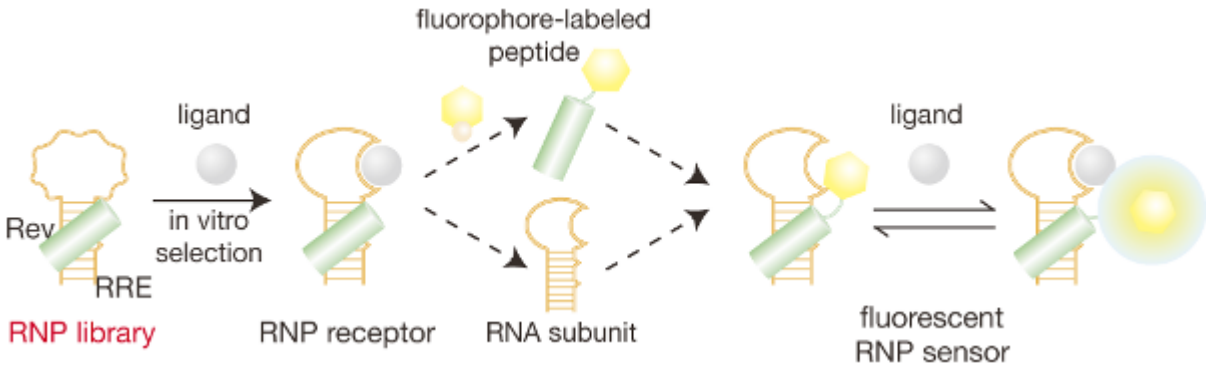


Figure 1. A scheme illustrates a direct conversion of a ribonucleopeptide (RNP) receptor to a fluorescent RNP sensor. A complex of the Rev peptide and RRE RNA was used as a framework for the RNP receptor and RNP sensor.

ATP sensor (Figure 1). The ATP-binding RNP was obtained by in vitro selection as previously reported. The size of random nucleotides within the RNA subunit was increased to 30 nucleotides (RRE30N) from the previously reported 20 nucleotides to accomplish greater divergences in the RNA sequences of ATP-binding RNP at the first in vitro selection.

The RNP receptors obtained by the in vitro selection against the ATP-agarose resin were tested for the ATP-binding characteristics. An RNP complex A23/Rev with a consensus 5'-GUAGUGG-UGUG-3' sequence bound ATP with a dissociation constant (K_D) of 21.0 μM and discriminated ATP over other ribonucleotides GTP, CTP, and UTP efficiently. Another RNP complex A28/Rev not sharing the consensus sequence in the RNA subunit also bound ATP efficiently with a K_D of 15.2 μM. The A23/Rev RNP receptor was converted to a fluorescent ATP sensor by complexation of pyrene-labeled Rev (Pyr-Rev) and A23 RNA. This process was essentially the same as that described for the chemical modification of the macromolecular receptor by a fluorophore. In the present case, the N-terminal of the Rev peptide in the RNP receptor was chemically modified with a pyrene group. Fluorescence responses of RNP A23/Pyr-Rev were evaluated in the absence or presence of ATP. Addition of ATP resulted in a 2-fold increase of the fluorescence intensity of A23/Pyr-Rev. A significant change in the fluorescence intensity of A23/Pyr-Rev was elicited only with ATP, not with other NTPs, indicating that the specificity of A23/Pyr-Rev to ATP is parallel to that of the parent A23/Rev receptor. Titration of the changes in fluorescence intensities of A23/Pyr-Rev by ATP gave a K_D value of 19.5 μM for the A23/Pyr-Rev—ATP complex, which was in good agreement with the K_D value for the complex of parent A23/Rev and ATP (Figure 3B). In a similar manner, complexation of A28 RNA with Pyr-Rev afforded a fluorescent ATP sensor A28/Pyr-Rev with an affinity (K_D = 6.6 μM) comparable to the parent A28/Rev RNP receptor (K_D = 18.1 μM). The results indicate that reconstitution of the ATP-binding RNP receptor with a fluorophore-labeled Rev peptide simply and effectively converts ATP receptors into fluorescent ATP sensors without diminishing the affinity and selectivity of the parent ATP receptors.

In vitro selection of the ATP-binding RNP receptors generated a series of RNA sequences varying in the location of the consensus sequence within the randomized nucleotide region, affording a library of RNA subunits. Each RNA subunit forms a ligand-binding pocket that has a unique geometry to the N-terminal of the Rev peptide and a defined affinity to the ligand in the RNP complex. Combination of the RNA subunit library and a fluorophore-labeled Rev peptide generates a library of fluorescent RNP receptors with a range of affinities and emission properties. Such a fluorescent RNP library would be ideal for obtaining a fluorescent sensor tailor-made for a given target. Previous approaches, such as in vitro selection of fluorescently labeled aptamers and the rational modular design of aptamer sensors, could also be applicable to construct such sensor libraries.

The feasibility of the screening scheme of fluorescent RNP sensors was demonstrated by using libraries of fluorescent RNP receptors constructed from the 29 different RRE30N RNAs obtained from the selection of ATP-binding RNP and Rev peptides modified with different fluorophores, 7-methoxycoumarin-3-carboxylic acid (7mC-Rev), 4-fluoro-7-nitrobenz-2-oxa-1,3-diazole (NBD-Rev), and Cy5 mono NHS ester (Cy5-Rev) at the N-terminal.

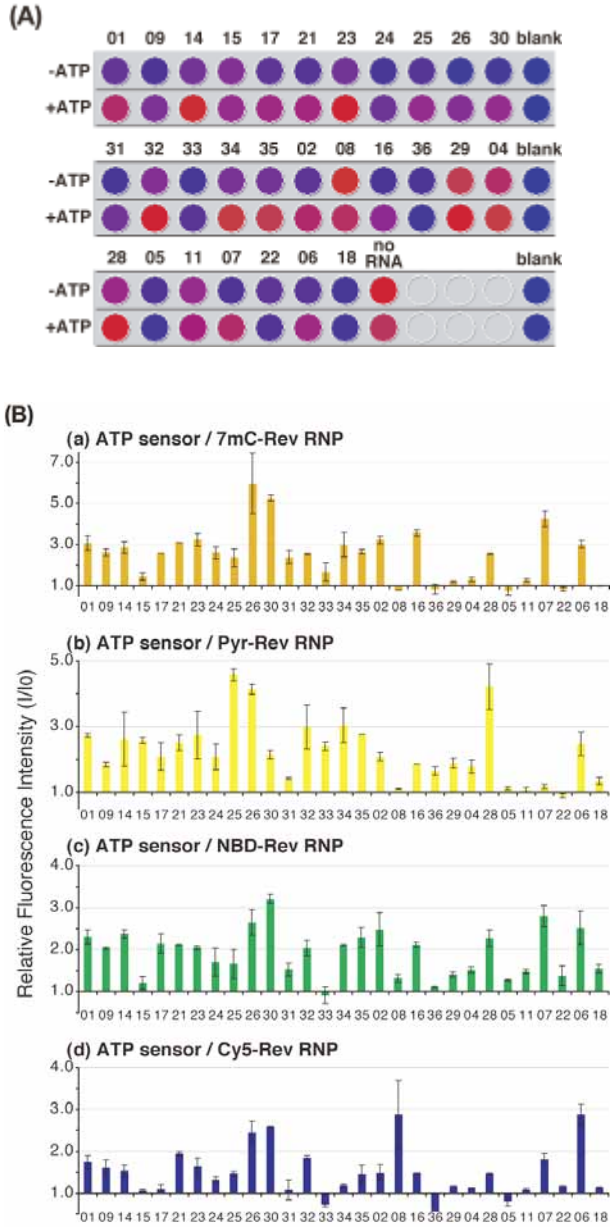


Figure 2. (A) A scanned image showing the microplate assay for the combinatorial screening of the fluorescent RNP library. Fluorescence intensities of 7mC-Rev derived RNPs (1 μM) were evaluated in the absence or presence of 1 mM of ATP with excitation at 355 nm and emission 390 nm with intensities being weak in blue color and strong in red.. (B) Relative fluorescence intensity changes (I/I_0) of RNPs upon ATP binding are shown in the bar graphs for (a) 7mC-Rev RNP, (b) Pyr-Rev RNP, (c) NBD-Rev RNP, and (d) Cy5-Rev RNP.

Each 7-methoxycoumarin-3-carboxylic acid-labeled Rev (7mC-Rev) and RNA complex was placed individually on a

multi-well plate, and was evaluated by the change of fluorescence intensities in the absence or presence of ATP (1 mM) by using a microplate reader. Figure 5A shows a scanned image of multi-well plate assay of a fluorescent ATP-binding RNP library constructed from the RNA subunits of the ATP-binding RNP (Figure 2A) and 7mC-Rev. In most of the cases, the fluorescence emission of 7mC-Rev was quenched upon formation of RNP complexes as compared to that of 7mC-Rev alone (the lane marked "no RNA"). As typically shown in lanes 14, 23, 32, 34, 35, 02, 28, 07, and 06, the fluorescence emission increased in the intensity upon addition of ATP, indicating that these fluorescent RNPs could serve as ATP sensors.

The fluorescence intensities in the absence and presence of ATP were evaluated in the similar manner for fluorescent RNP libraries obtained by combination of the RNA subunits of the ATP-binding RNP and Pyr-Rev, NBD-Rev and Cy5-Rev (Figure 2B). Relative ratios of fluorescence intensity (I/I_0) in the absence (I_0) and the presence (I) of ATP for fluorescent RNPs with 7mC-Rev, Pyr-Rev, NBD-Rev, and Cy5-Rev monitored at 390, 390, 535, and 670 nm, respectively, were summarized in Figure 2B. The I/I_0 ratio of each sensor varied from 0.8 to 6. Considerable numbers of fluorescent ATP sensors responded with the I/I_0 ratio over 2 in all the cases of fluorophores. The fluorescent RNP library with Cy5-Rev provided several ATP sensors with an emission at long wavelength (670 nm) and with I/I_0 ratios of over 2 (Figure 2B, panel d). Together, the above simple approach efficiently provided fluorescent ATP sensors emitting from 390 to 670 nm with excitation wavelengths ranging from 340 to 650 nm.

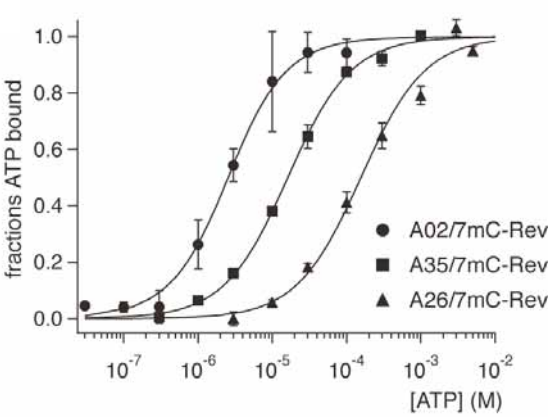


Figure 3. Saturation curves of 7mC-Rev RNPs A02/7mC-Rev (filles circles), A35/7mC-Rev (filled squares), and A26/7mC-Rev (filled triangles) in the presence of 10 nM to 10 mM ATP were determined by titrations of fluorescence intensity changes.

The above simple screening scheme based on the relative changes in emission intensities of fluorescent RNPs with or without the ligand ATP (I/I_0) is quite useful for the screen of RNP sensors with desired emission wavelength and with high I/I_0 ratio. On the other hand, screening of the fluorescence emission intensities in the presence of increasing concentrations of ATP (10 nM to 10 mM) allowed titration analysis of the fluorescent RNP library, which enabled screening of ATP sensors responding within certain concentration ranges of ATP (Figure 3). Evaluation of the fluorescence emission pattern versus the added ATP concentration instantly pointed a concentration range at which each fluorescent RNP responses. For example, saturation midpoints of three sensors, A02/7mC-Rev, A35/7mC-Rev, and A26/7mC-Rev, were spaced at approximately one order of magnitude intervals (Figure3), with K_D values being 2.2, 15.7, and 156 μM, respectively. A fourth sensor, A31/7mC-Rev, began to show fluorescence response at the ATP concentration of 1-10 mM. Simultaneous application of these four sensors covers ATP concentration ranges from ~10^{-7} to ~10^{-2} M.

This research was supported by a Grant-in-aid for Scientific Research from Ministry of Education, Science, Sports and Culture, Japan to T.M (17310125, 17026019), and by SORST from Japan Science and Technology Agency (JST) to T.M.

3. Fibril formation by short peptides

Proteins that form the amyloidal aggregates, such as microtubule-associated protein tau and islet amyloid polypeptide (IAPP), contain short peptide segments that play critical roles in the fibril formation. It has been shown that certain defined sequences nucleate amyloid formation of proteins. Aromatic amino acid residues tyrosine (Tyr) and phenylalanine (Phe) in the short peptide segments have been shown to stabilize the amyloid fibrils of pathogenic polypeptides, as has been demonstrated for tau, IAPP and beta-peptide.[5] A short peptide segment VQIVYK (PHF6) corresponding to the core part of tau fibril formation is one of such sequences capable of forming paired-helical filaments.[6] The N-terminal hydrophobic and the C-terminal charged residues of the PHF6 peptide are important to the fibril formation. PHF6 derivative peptides substituted at the Tyr position by natural amino acid residues with aromatic or large hydrophobic side chains showed high amyloidogenic propensities. Mutants of the PHF6 peptide formed twisted filaments, flat and rolled sheets, or spherical or annular particles.[7] In order to get further insights on the role of aromatic side chains on the amyloid fibrils by short peptides, PHF6 derivative pepitdes, in which the Tyr position of PHF6 was substituted with hydrophobic non-natural amino acids, were synthesized and were tested their fibril-forming property. The hydrophobic non-natural amino acids influence the fibril-forming property of a peptide derived from core part of tau fibril formation.

PHF6 derivatives substituted at the Tyr-310 residue of PHF6 were synthesized to represent a variety of aromatic side chains. Non-natural amino acids, 4-phenylphenylalanine (PHF6FPh), 4-fluorophenylalanine (PHF6FF) and 4-methylphenylalanine (PHF6FMe) were incorporated at the Tyr-310 position of PHF6 (Figure 4).

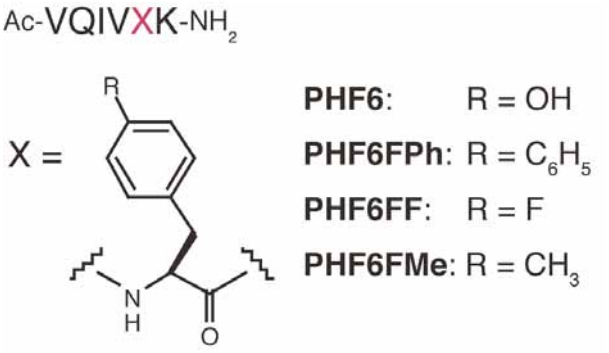


Figure 4. Structures of PHF6 peptide derivatives used in this study. Tyr at the position X corresponds to the Tyr-310 residue of native tau.

PHF6 formed amyloid-type paired-helical fibers (Figure 5A) as reported previously.[8] PHF6FPh formed tightly segregated mass of fibers (Figure 5B). Fluorine substitution at the 4-position of phenyl ring (PHF6FF) caused formation of helical filaments with wider radius than that of PHF6 (Figure 5C). Abundant straight filaments were observed when the 4-position of phenyl group was substituted with a methyl group in PHF6FMe (Figure 5D). Thus even sharing the same aromatic phenyl group at the position Tyr-310, substitution at the phenyl ring with different groups caused formation of fibrils with different morphologies.

In the amide I region of the IR spectra for the aggregate of PHF6 exhibited strong maximum of absorbance around 1625 cm^{-1}, indicating a very high content of the β-sheet secondary structure as previously reported. Each aggregate of PHF6FPh, PHF6FF, and PHF6FMe also exhibited the strong maximum of absorbance around 1630 cm^{-1}, indicating that the amyloid type fibers of PHF6FPh, PHF6FF, and PHF6FMe contained the β-sheet secondary structure as assessed by FT-IR.

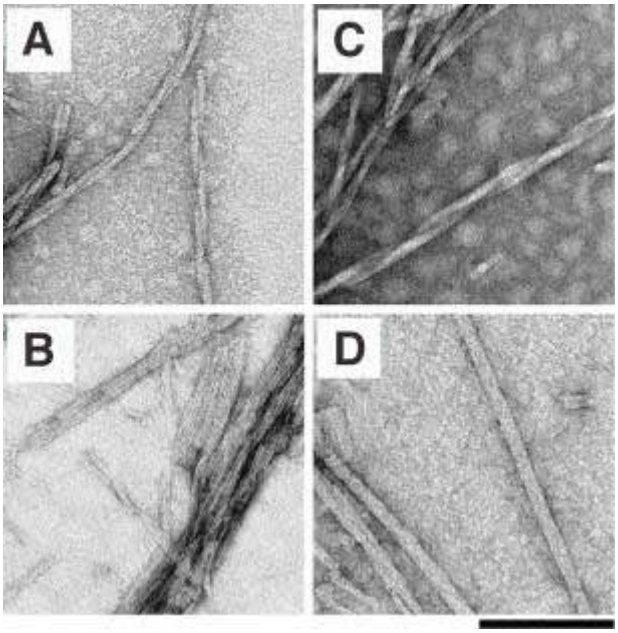


Figure 5. TEM images of amyloid-type fibers formed from (A) PHF6 and (B) 4-phenyl derivative PHF6FPh, (C) 4-fluoro dervative PHF6FF, (D) 4-methyl derivative PHF6FMe. Samples were negatively stained with 2% uranyl acetate. Scale bar: 100 nm.

We next performed time-course analyses of the aggregates formation by the Tyr-310 mutants of PHF6 in 20 mM MOPS (pH 7.5) containing HFIP to assess the effect of substitution at the 4-position of phenyl group on the fibril formation. Fibril formation of these peptides were monitored by thioflavin T (ThT) fluorescence in the presence of 0.1 M NaCl. The time-course analyses of the aggregates formation revealed no induction time for PHF6FF, PHF6FMe and PHF6FPh. PHF6FPh revealed constant ThT fluorescence intensities immediately after the beginning of the aggregates formation experiment, indicating rapid formation of amyloid-type fibers by PHF6FPh. It is likely that the formation of fibrils by PHF6FPh reached to a plateau right after the beginning of the aggregates-forming experiment. Aggregates formation kinetics for PHF6FMe and PHF6FF followed a single exponential approach to equilibrium. On the other hand, PHF6 aggregation kinetics showed an initial retardation of the fluorescence evolution followed by the faster change in the later phase, indicating that the fibril formation of PHF6 is a nucleation-dependent process, as is widely known for amyloid-type aggregations. PHF6FPh had the fastest aggregation kinetics, and PHF6FMe and PHF6FF had faster aggregation rates than PHF6. The hydrophobic group substituted at the 4-position generally accelerated the aggregation rate of PHF6 derivatives.

All the findings above demonstrated that the aromatic and hydrophobic non-natural amino acids substituted at the Tyr residue of the fibril-forming core peptide of human tau play important roles in enhancing the amyloid-forming propensity of the peptide. PHF6FPh, PHF6FMe and PHF6FF showed faster amyloid-forming kinetics than PHF6. It is likely that PHF6FPh accelerates association of peptides by interaction between the hydrophobic and aromatic side chains. Because the modification at the 4-position of phenyl group was accommodated in the fibrils of PHF6 derivatives, it would be possible to control the amyloid-forming propensity of short peptides by using non-natural amino acids. Such a strategy would afford novel biomaterials with defined size and shape.

This research was supported by a Grant-in-aid for Scientific Research from Ministry of Education, Science, Sports and Culture, Japan to T.M.(16651108, 17310125), and by SORST from Japan Science and Technology Corporation (JST) to T.M.

Bioenergy Research Section

K. Makino, Professor
T. Kodaki, Associate Professor

1. Introduction

Our research section seeks to develop environmentally clean and efficient reaction systems by means of chemically or biologically manipulated systems suitable for energy production. For the development of such a process by learning from biological systems, it is essential to understand complex network of biological signal transductions and mechanism of chemical transformations in the system. Following aspects have been investigated to establish the fundamental basis that would emerge a new technology for the energy-efficient utilization of ubiquitous environmental resources.

2. Enhancing Surface Amine Functionality for DNA Microarray Fabrication: Effect of Alkylsilane Structure

DNA microarrays are very important tools for comprehensive and systematic study of genome. In many cases, aminosilane treated molecular layers on glass surfaces are used for fabrication of DNA microarrays. However, the presence of surface silanol groups on silica surface after aminosilanization reduce the chemical immobilization efficiency for biomolecules on the array surface affecting the performance of DNA microarrays. To improve the immobilization efficiency, we developed additional surface modification with alkylsilane to convert the remaining silanol groups in to silylether linkages thereby liberating the amino groups from non-specific interaction (Fig. 1). In this fiscal year, we explored the silanol capping effect with regard to alkylsilane types to enhance the amino functionality on the array surface.

Capped amine functionalized glass slides were prepared as described elsewhere. Several types of alkylsilanes having different numbers of alkoxy groups and different types of non-alkoxy alkylchains (butyltrimethoxysilane (BMS), trimethoxymethylsilane (TMS), methoxytrimethylsilane (MTMS), octadecyltriethoxysilane (ODTES)) were used to cap surface silanols on amine functionalized glass slides (APS). The silanol capping performance was evaluated by measuring contact angles of sessile water droplets (1μL) using goniometer. The capped amine functionalized glass slides possess increased contact angles compared with control APS surface.

To evaluate amine functionality regarding alkylsilane types capped on APS glass slides, the chemical immobilization efficiency of a fluorescent label, Cy3-NHS (50 pmol/μL) was evaluated by spotting on each glass slide with inkjet spotter, washing and analyzing Cy3 intensity on the slide. All the capped glass slides showed enhanced immobilization efficiency of Cy3-NHS dye compared to control APS glass slides (Fig. 2). Trialkoxy-type alkylsilanes with high silanization chance were found to be more effective capping regents for obtaining high efficiency of Cy3-NHS immobilization compared with monoalkoxy-type alkylsilanes. On the other hand, an exceptional tendency was also observed, that is, APS+MTMS glass slide (monoalkoxy type) was found to show higher efficiency than APS+TMS glass slide (trialkoxy types), as shown in Fig. 2. Considering that less than two equivalents of alkoxy groups per one silane molecule react with the silanols to form Si-O-Si-R linkage, there is a large chance for one silanol to be left in the molecular layers. Therefore, in the case of APS+TMS glass slide, some of liberated amines on the surface have chance to interact again with the silanol groups lowering the amine-functionality on the surface. In contrast, unlike TMS, MTMS has a very low chance to leave one silanol group in the molecular layers, which could enhance the chemical immobilization. Although similar low-immobilization efficiency could be expected in the case of APS+BMS or APS+ODTES glass slides, the presence of long alkylchains may provide a kind of steric hindrance to keep amino group away from interacting with the silanol groups. These results suggests that, as well as capping performance of remaining silanol groups, the structure of alkylsilane is also an important factor influencing the enhancement of surface amine functionality. Therefore, we should consider alkylsilane type when the capping strategy is employed for obtaining high surface amine-functionality.

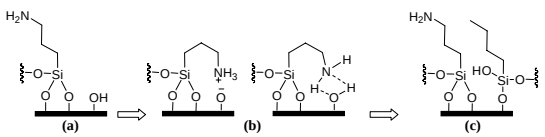


Figure 1. Schematic illustration of (a) APS glass slide (b) non-specific interactions of amino groups with surface silanol groups on the modified surface and (c) capped amine glass

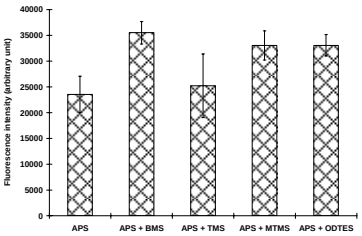


Figure 2. Comparison of Cy3 fluorescence intensity on APS (Control), APS+BMS, APS+TMS, APS+TMS and APS+ODTES glass slides.

3. Reactive Oxygen Species Generation Through NADH Oxidation by 6-Formylpterin Derivatives in the Dark

6-Formylpterin (6FP, Fig. 3), one of the common derivatives of folic acid abundant in nature, has unique physiological and pharmacological activities and chemical natures: It has been demonstrated that 6FP has strong neuroprotective effects against transient ischemia-reperfusion injury (IRI), events caused by lack of oxygen supply, and that *in vitro*, 6FP converts molecular oxygen to reactive oxygen species (ROS) such as superoxide anion radical ($\cdot O_2^-$) and hydrogen peroxide (H_2O_2) in the presence of NADH or NADPH under light illumination, with the oxidation of NADH to NAD^+. Since ROS are not only involved in cell death but also modulate a variety of cell functions, the mechanism and biological implications of this unique property of 6FP remain to be revealed.

In this fiscal year, it is demonstrated that some 6FP derivatives in which the 3-position of 6FP is modified have such unique activities even in the dark where the majority of biological events occur *in vivo*. NADH was converted to NAD^+ (Fig. 5) and O_2 to H_2O_2 (Fig. 4) in the dark by 2-(N,N-dimethylaminomethyleneamino)-6-formyl-3-pivaloylpteridin-4-one (DFP, Fig. 3) and 2-(N,N-dimethylaminomethyleneamino)-6-formyl-3-methylpteridin-4-one (DFM, Fig. 3) in which the 2-amino group is modified by dimethylaminomethylene group and the 3- positions are modified by pivaloyl and methyl groups, respectively and 2-amino-6-formyl-3-methylpteridin-4-one (FM, Fig. 3) in which the amino group at the 2-position is free and the 3- position is modified by a methyl group. However, intact 6FP and 2-(N,N-dimethylaminomethyleneamino)-6-formylpteridin-4-one (FM, Fig. 3) in which only the 2-position amino group is modified by a dimethylaminomethylene group did not show such effects. When a PBS solution containing 2-(N,N-dimethylaminomethyleneamino)-3-pivaloylpteridin-4-one (DP, Fig. 3) in which the formyl group on 6-position of 6FP is removed and NADH was stirred, NADH was not converted to NAD^+. These results indicate that modification of the 3-position of 6FP is essential to make the activities of 6FP available in the dark, and that the electron-withdrawing or donating nature of the modifiers on the 3-position has little influencing. The present findings would be the key for elucidating the mechanism of the unique activity of 6FP *in vivo* and in designing pharmaceutical compounds that generate appropriate and controllable amounts of ROS *in vivo*.

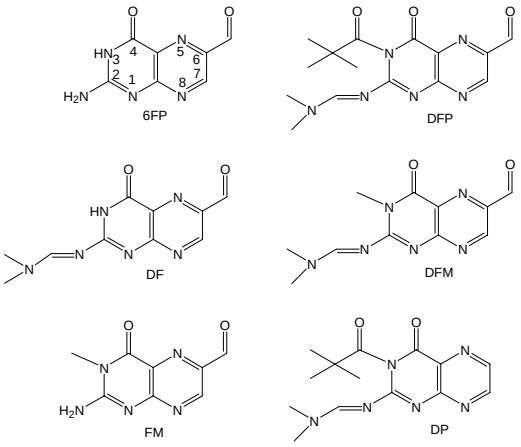


Figure 3. 6FP, 6FP derivatives, and pterin derivative studied in the present studies

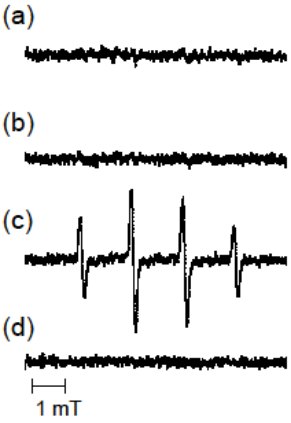


Figure 4. H_2O_2 generation in the PBS solution containing DFP and NADH. EPR spectra obtained for PBS (pH 7.4) containing (a) 2 mM NADH, (b) 2 mM DFP, (c) 2 mM DFP and 2 mM NADH, and (d) 2 mM DFP and 2 mM NADH.

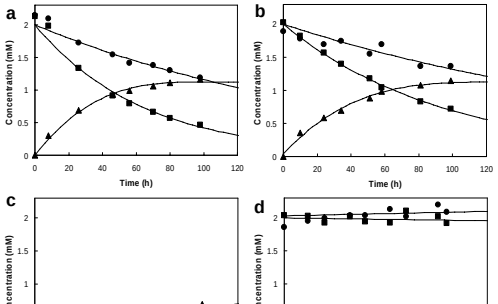


Figure 5. Oxidation reaction of NADH by (a) DFP, (b) DFM, (c) FM, (d) 6FP, (e) DF, or (f) DP in the dark. The time course of the change in DFP, DFM, 6FP, DF, DP, NADH, and NAD^+ concentrations in the dark in open system was measured by RP-HPLC. PBS solutions (pH 7.4, except for (d) and (e)) containing (a) 2 mM DFP and 2 mM NADH (●, DFP; ■, NADH; and ▲, NAD^+), (b) 2 mM DFM and 2 mM NADH (●, DFM; ■, NADH; and ▲, NAD^+), (c) 2 mM FM and 2 mM NADH (▲, NAD^+), (d) 2 mM 6FP and 2 mM NADH (●, 6FP; ■, NADH; and ▲, NAD^+), (e) 1 mM DF and 1 mM NADH (●, DF; ■, NADH; and ▲, NAD^+), and (f) 2 mM DP and 2 mM NADH (●, DP; ■, NADH; and ▲, NAD^+) were stirred in the dark. The pH of the solutions (d) and (e) were 9.7 and 7.6, respectively.

4. Efficient Bioethanol Production from Woody Biomass by Yeast Transformed with Protein Engineered $NADP^+$-dependent Enzyme

Xylose is one of the major fermentable sugars present in woody biomass, the second most abundant carbohydrate polymer in nature. *Saccharomyces cerevisiae* is used widely for industrial ethanol production because of the ability to produce high concentrations of ethanol and high inherent tolerance. Since the native *S. cerevisiae* can not ferment xylose, molecular engineering of *S. cerevisiae* for xylose utilization has been focused on adapting the xylose metabolic pathway from the xylose-utilizing yeast *Pichia stipitis*. *S. cerevisiae* transformed with the native genes encoding XR and XDH from *P. stipitis* ferments xylose to ethanol but has not yet been applied to the industrial bio-process due to the unfavorable excretion of xylitol. Intercellular redox imbalance caused by the different coenzyme specificity of XR (using NADPH/NADH with preference for NADPH) and XDH (exclusively using NAD^+) has been thought to be one of the main factors of xylitol excretion. In this fiscal year, we constructed recombinant yeasts that were transformed with the genes encoding the wild type XR and the protein engineered XDH of *P. stipitis*. These recombinant yeasts were characterized based on the enzyme activity and fermentation ability of xylose to ethanol.

XR and XDH from *P. stipitis* are necessary for *S. cerevisiae* to ferment xylose to ethanol because of a lack of genes encoding these enzymes in native *S. cerevisiae*. In our previous study, site-directed mutagenesis for complete reversal of coenzyme specificity was performed on NAD^+-dependent XDH from *P. stipitis* to generate $NADP^+$ dependent XDH. In this fiscal year, we constructed recombinant yeasts that were transformed with the genes encoding a wild type XR and the protein engineered XDH of *P. stipitis* and characterized those recombinant yeasts based on the enzyme activity and fermentation ability of xylose to ethanol. The protein engineered enzymes were expressed significantly in *S. cerevisiae* as judged by the enzyme activity *in vitro* (data not shown). Introduction of $NADP^+$-dependent XDH was shown to prevent the xylitol excretion probably because of maintaining the intercellular redox balance. Ethanol accumulation in the medium was measured and the best recombinant yeast strain Y-ARSdR was shown to produce much more ethanol compared to the strain tranformed with the wild type enzyme (Fig. 6). Since Y-ARSdR produced the highest ethanol and excreted the lowest xylitol, it was further investigated in a high performance bioreactor under oxygen-limited conditions. Y-ARSdR produced ethanol at 7.02 g/l with a yield of 0.46 g of ethanol/ g of total consumed sugars (Fig. 7) from 5 g/l glucose plus 15 g/l xylose.

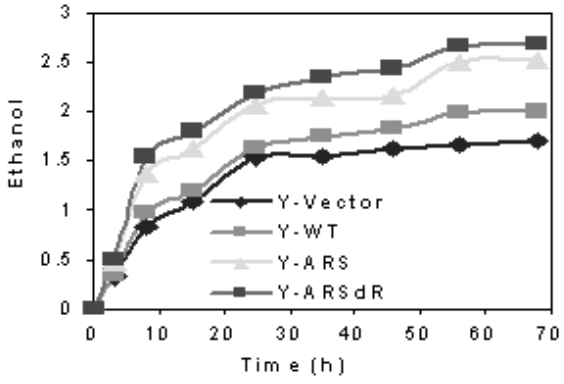


Figure 6. Ethanol accumulation in minimal medium

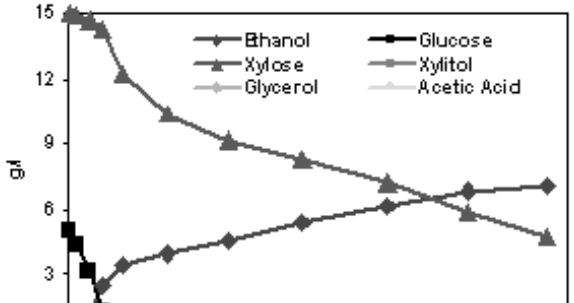


Figure 7. Fermentation performance in bioreactor by Y-ARSdR

5. Engineering of *Pichia stipitis* Xylitol Dehydrogenase towards Improved Thermostability

Heterologous expression of the *P. stipitis* enzymes xylose reductase (XR) and xylitol dehydrogenase (XDH) in *S. cerevisiae* has been extensively studied with respect to xylose fermentation in lignocellulose-based bioethanol production. During this process, the problems are low yields of ethanol and xylitol excretion. Generation of the thermostable XDH mutants may able to solve these problems. However, the present protein engineering approaches have difficulties when using XDH. That is, the random mutagenesis method demands an appropriate selection system, lack of three-dimensional (3D) structure of XDH precludes rational design, and without any reports on XDHs from thermophilic microorganisms, we cannot employ the consensus method. XDH belongs to the polyol dehydrogenase (PDH) subfamily which comes under medium-chain dehydrogenase/reductase (MDR) super family. This family classified based on the similarities of amino-acid sequences and substrate structures. Many MDRs have one zinc atom at the catalytic site, which is essential for enzyme activity, and some of the enzymes have an additional second zinc atom which is playing a prominent conformational role, probably by stabilizing the tertiary structure of the enzyme. However, the functional significance of structural zinc is still unclear.

In a recent report, we constructed XDH with structural zinc (C4 mutant) by site-directed substitution of Ser96, Ser99, and Tyr102 with cysteine based on the fact that some members of the PDH family contain structural zinc, which is bound tetrahedrally to four sulfur atoms of cysteine in the loop. The C4 mutant showed a 4.5 °C higher transition temperature (T_{CD}) than wild-type XDH, indicating that the mutation of the structural zinc binding loop could be effective in increasing the thermostability of XDH. In this fiscal year, with a vision that refinement of the zinc binding loop may be involved in XDH thermostabilization, we carried out subsequent site-directed mutagenesis around the structural zinc loop. Based on the sequence alignment within the other PDH family members, we designed the mutagenesis strategy and constructed four mutants at first.

Thermostabilities of the four mutants were analyzed by measuring the remaining activities at 35 °C after heat treatment at various temperatures. Among the four mutants, C4/F98R, C4/E101F were found to possess higher thermostability than the C4 mutant, whereas C4/P95S and C4/H112D showed lower thermostability than C4. The $T_{1/2}$ (Half denaturation temperature) values of mutants C4/F98R and C4/E101F were 7.0 ºC and 4.8 °C higher than C4 mutant, respectively. On the other hand, C4/P95S and C4/H112D mutants were showed lower $T_{1/2}$ than C4 mutant by 8.7ºC and 2.1 °C, respectively (Table. 1). Thermostability of mutated XDH was also estimated by CD measurements. When compared with the C4 mutant, the T_{CD} (Thermal transition temperature) values of C4/F98R and C4/E101F mutants increased by 4.2 °C and 3.0 °C, respectively, while the TCD values of C4/P95S and C4/H112D mutants decreased by 4 °C and 0.5 °C, respectively (Table. 1). Based on the results, we also constructed the C4/F98R/E101F mutant to examine the synergic effect of combination of two successive mutations on XDH thermostabilization. The obtained XDH mutant (C4/F98R/E101F) is the best in thermostability, in which T_{CD} was 6.3 °C higher than the C4 mutant. In the case of $T_{1/2}$, the C4/F98R/E101F mutant was also found to possess higher thermostability than C4 mutant by 9.9 °C (Table. 1).

Table 1. Thermostability of P. *stitpis* XDH mutants

Protein	$T_{1/2}$ (°C)	T_{CD} (°C)
C4	46.1 ± 0.31	47.5 ± 0.09
C4/P95S	37.4 ± 0.24	43.5 ± 0.08
C4/F98R	53.1 ± 0.15	51.7 ± 0.09
C4/E101F	50.9 ± 0.14	50.5 ± 0.06
C4/H112D	44.0 ± 0.26	47.0 ± 0.08
C4/F98R/E101F	56.0 ± 0.31	53.8 ± 0.05

These works were supported by the Center of Excellence (COE) program for the "Establishment of COE on Sustainable Energy System", a Grant-in-Aid for Scientific Research, and "Kyoto Nanotechnology Cluster Project", a Grants for Regional Science and Technology Promotion from the Ministry of Education, Science, Sports and Culture, Japan. These works were also supported by CREST of the Japan Science and Technology Agency.

Laboratory for Complex Energy Processes Section

H. Okada, Associate Professor

1. Introduction

The major subjects in this section are to study fast-ion confinement in plasma confinement devices and to investigate interactions between fast-ions and materials, such as a first wall and a vacuum vessel. The fast-ion confinement is a critical issue for the fusion reactor since the alpha particles produced in the D-T reaction should be utilized to heat plasma efficiently. The interactions between fast-ions and materials cause the impurity problem for the plasma confinement and the damage for the vessel or the first wall materials.

The fast-ion confinement and heating efficiency are investigated by using RF wave heating with a special emphasis on the dependence on the magnetic field configuration. The minority heating scheme is used for this purpose since the fast ion is easily generated in this heating scheme. The dependence of the fast ions on the one of the magnetic field component, the bumpiness, was reported in the last report. The resultant heating efficiency is discussed in this report. For the analysis of the minority heating experiment, we develop Monte Carlo code for simulating fast ions in the ICRF heating. The loss cone regions and energy spectra of fast ions for three configurations are discussed.

2. Dependence of the Bulk-Ion Temperature on the Bumpy Field Component

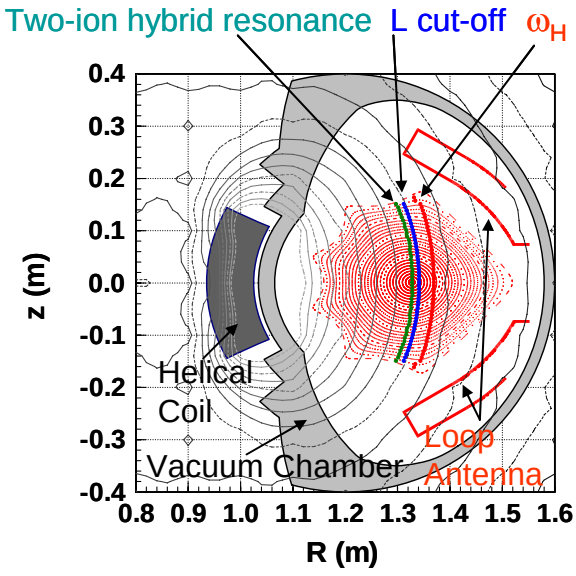
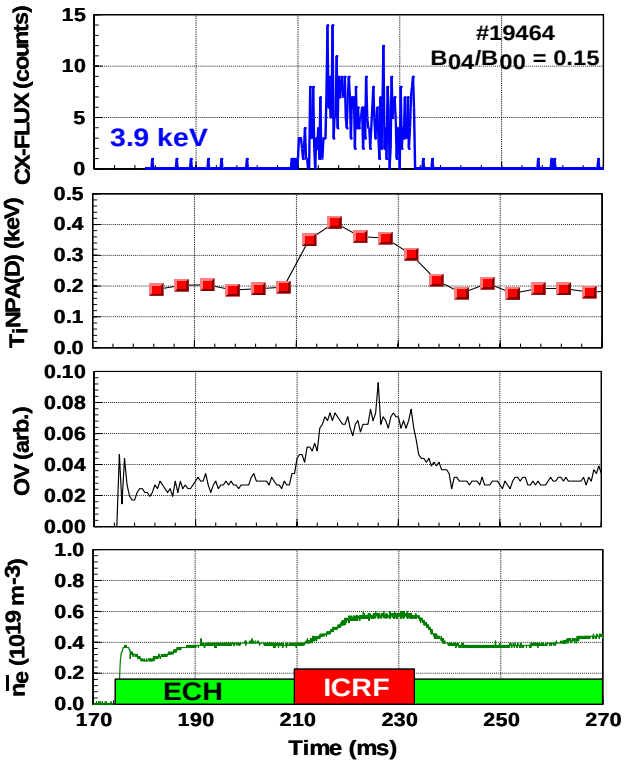


Fig. 1 Two ICRF antennas in the corner section of Heliotron J.

The formation and confinement experiment for fast ions is performed using the ICRF minority heating scheme with a proton minority and a deuteron majority in Heliotron J, a low-shear helical-axis heliotron (R_0 = 1.2 m, a = 0.1-0.2 m, $B_0 \leq$ 1.5 T). The effect of the magnetic configuration on the fast ion confinement is one of the most important issues in helical devices. The effect of the bumpiness on the trapped fast ion confinement and the heating efficiency are discussed by using ICRF minority-heating. The role of one of the Fourier components, the bumpiness, is a key issue for the design principle of the magnetic filed of Heliotron J, where the particle confinement is controlled by the bumpiness. The proper bumpiness causes deeply trapped particles to be confined in the small grad-B region. For the study of the configuration dependence on the fast particle confinement, three configurations are selected; the bumpy ripples (B_{04}/B_{00}, where B_{04} is the bumpy component and B_{00} is the averaged magnetic field strength) are 0.01, 0.06 and 0.15 at ρ = 0.67. The configuration of B_{04}/B_{00} = 0.06 corresponds to the standard configuration in Heliotron J.

The ICRF loop antennas are installed on the low-field side of the corner section of the Helitoron J as shown in Fig. 1. The high energy ions are produced up to 10 keV by injecting an ICRF pulse into an ECH target plasma where $T_i(0)$ = 0.2 keV, $T_e(0)$ = 0.8 keV and $\overline{n}_e$ = 0.4 x 10^{19} m^{-3}.

The bulk-deuteron temperature is evaluated from the deuterium flux observed by the CX-NPA. The two antenna loops are used for heating and the phase between the two-antenna currents is controlled in order to maximize the observed CX fluxes. The RF frequency is 23.2 MHz in the cases of B_{04}/B_{00} = 0.15 and 19 MHz for 0.06 and 0.01 as in the previous section. The line-averaged density before the ICRF pulse is about 0.4 x 10^{19} m^{-3} in all cases. The ion temperature before turning on the ICRF-pulse is in the range from 0.15 to 0.2 keV in an ECH plasma as shown in Fig. 2. The ion temperature is evaluated every 5 ms, and the bumpy component is 0.15 in this case. The ion temperature increases from 0.2 to 0.4 keV just after the ICRF pulse injection. The density is also raised during the ICRF pulse in this case. However, the density increase is negligible in most discharges. The line-emission from light impurities such as carbon or oxygen and metal impurities such as iron or titanium increases during the ICRF pulse.



The ion temperature increases with P_{ICRF} in the power range from 0.07 to 0.34 MW for three cases as shown in Fig. 3. Here, P_{ICRF} is the injected ICRF power at the position of the vacuum feedthrough. The increment of the ion temperature reaches 0.2 keV at the power of 0.3 MW in the high bumpy case. In the other cases, the temperature increase is lower than that in the high bumpy case. In the low bumpy case, it is less than 0.1 keV over this power range. The bulk-ion heating efficiency is also higher in the high bumpy case as well as the high-energy ion confinement. The bulk-ion heating in this heating scheme is performed through the Coulomb collisions with the high-energy minority ions produced by the ICRF heating. Therefore, the heating efficiency depends on the confinement of the high-energy ions as well as the bulk ions. It is considered that the energy transfer from the minority ions is larger in the high bumpy case since the high-energy tail is larger as mentioned in the previous section. In target ECH plasmas, the global energy confinement time is almost same for three configurations except the improved confinement mode. Quantitative estimation of the energy transfer from the high-energy tail to bulk particles and the bulk-ion confinement for the various the bumpy components must be performed to understand this change of the heating efficiency.

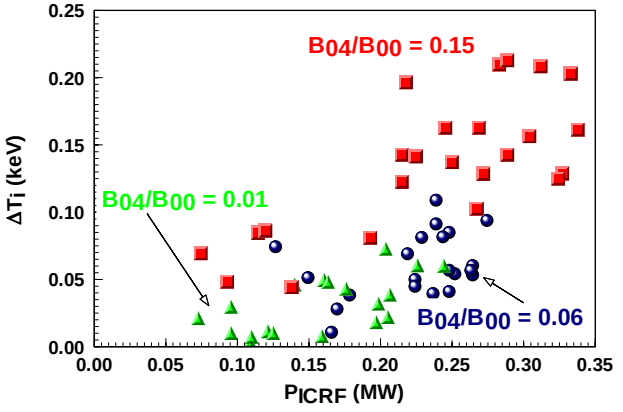


Fig. 3 Increase of the bulk ion temperature as a function of the injected ICRF power for three bumpy cases.

3. Monte Carlo Analysis for ICRF Heating

A Monte-Carlo calculation is performed to understand the bumpy dependence of the fast-ions and bulk heating. The calculation model contains orbit tracing in the real space and pitch-angle scattering and energy scattering in the velocity space as in Refs. 1 and 2. The basic equations of the orbit calculation are given as follows;

where $2\pi\psi$ is the toroidal flux, $\rho_c = mv_{//}/eB$ and θ and ϕ are the periodic poloidal and toroidal angles,

Fig. 2 Time traces of the charge exchange flux (Hydrogen), T_i,,the oxytgen OV line emission and the density.

$$\dot{\psi} = (\dot{P}_\theta g - \dot{P}_\phi I)/\gamma,$$

$$\dot{\rho}_c = [-(\rho_c g' - \iota)\dot{P}_\theta + (\rho_c I' + 1)\dot{P}_\phi]/\gamma,$$

$$\dot{\theta} = \left(\delta\frac{\partial B}{\partial \psi} + q\frac{\partial \Phi}{\partial \psi}\right)\frac{\partial \psi}{\partial P_\theta} + \frac{q^2B^2}{m}\rho_c\frac{\partial \rho_c}{\partial P_\theta},$$

$$\dot{\phi} = \left(\delta\frac{\partial B}{\partial \psi} + q\frac{\partial \Phi}{\partial \psi}\right)\frac{\partial \psi}{\partial P_\phi} + \frac{q^2B^2}{m}\rho_c\frac{\partial \rho_c}{\partial P_\phi},$$

respectively. q, m and b are the electric charge of a paticle, the mass and the magnetic field strength, respectively. The toroidal current within a flux surface is $I(\psi)/(2\text{x}10^{-7})$ A, and the poloidal current outside a flux surface is $g(\psi)/(2\text{x}10^{-7})$ A, respectively. The electrostatic potential is assumed to be the form

$$\Phi = \Phi_0(1 - \psi/\psi_e),$$

where ψ_e specifies the plasma edge.

The functions γ, δ and the canonical moments are

$$\gamma = q[g(\rho_c I' + 1) - I(\rho_c g' - \iota)],$$

$$\delta = q^2\rho_c^2 B/m + \mu,$$

$$\dot{P}_\theta = -\delta\frac{\partial B}{\partial \theta},\ \dot{P}_\phi = -\delta\frac{\partial B}{\partial \phi}.$$

defined by

The derivatives of ψ and ρ_c with respect to the moments

$$\frac{\partial \psi}{\partial P_\theta} = \frac{g}{\gamma},\ \frac{\partial \rho_c}{\partial P_\theta} = -\frac{(\rho_c g' - \iota)}{\gamma},\ \frac{\partial \psi}{\partial P_\phi} = -\frac{I}{\gamma},\ \frac{\partial \rho_c}{\partial P_\phi} = \frac{(I'\rho_c + 1)}{\gamma}.$$

are

Pitch angle (λ) scattering and energy (E) scattering are expressed as follows [2];

$$\lambda_n = \lambda_0\left(1-\nu_d\tau\right)\pm\left[\left(1-\lambda_0^2\right)\nu_d\tau\right]^{1/2},$$

$$E_n = E_0 - \left(2\nu_E\tau\right)\left[E_0 - \left(\frac{3}{2}+\frac{E}{\nu_E}\frac{d\nu_E}{dE}\right)T\right] \pm 2\left[TE_0\left(\nu_E\tau\right)\right]^{1/2}.$$

The suffix 0 means the initial value. ν_d, τ, ν_E, T are the deflection collision frequency, the calculation time step, the energy scattering frequency and the temperature, respectively.

Minority protons are regarded as test particles in this model. An ICRF heating term is expressed by the velocity "kick" in the perpendicular direction when ions cross the cyclotron resonance layer.

$$\Delta v_\perp = \frac{qE_{RF}}{2m}\left(\frac{2\pi}{n\left|\dot{\Omega}\right|}\right)^{1/2} J_{n-1}\left(k_\perp\rho_\perp\right)\exp\left(-in\phi_0\right),$$

$$E_{RF} = E_{RF0}\,(1 - \psi/\psi_e).$$

Here, $v_\perp$, Ω, J_{n-1}, $k_\perp$, $\rho_\perp$, n, ϕ_0 and E_{RF} are the perpendicular velocity to the magnetic field, the cyclotron angular frequency, Bessel Function, the perpendicular wave number, the Larmor radius, the harmonic number, the random phase and the electric field amplitude of ICRF wave, respectively.

The electric field amplitude of the ICRF wave and its spatial distribution are given as input parameters. The field amplitude is used to determine the input power. The angular distribution of test ions is uniform in the velocity space and the energy distribution is initially determined due to the bulk ion temperature. For the real space, the starting point of a test particle is distributed parabolically in the radial direction and uniformly in the poloidal and toroidal directions.

The loss region of the proton starting at the point of (ρ, θ, ϕ) = (0.3, 0.0, 0.0) where ρ is the normalized minor radius, θ is the poloidal angle and ϕ is the toroidal angle is shown in Fig.4. The origin of the toroidal angle is where the L=1 helical coil is placed at the innermost position and the origin of the poloidal angle is the outermost position of the torus. The high bumpy case, the medium bumpy case and the low bumpy case correspond to Fig. 4(a), 4 (b) and 4 (c), respectively. The maximum energy is 20 keV. Although there is loss region along the perpendicular direction for all cases, the loss region for the high bumpy case is smallest among three cases.

Using 5000 particles, the energy spectra for three cases are calculated. The plasma parameters are: $T_e(0)$ = 0.7 keV, $T_i(0)$ = 0.3 keV, $n_e(0)$ = 0.5 x 10^{19} m^{-3} and Z_{eff} =

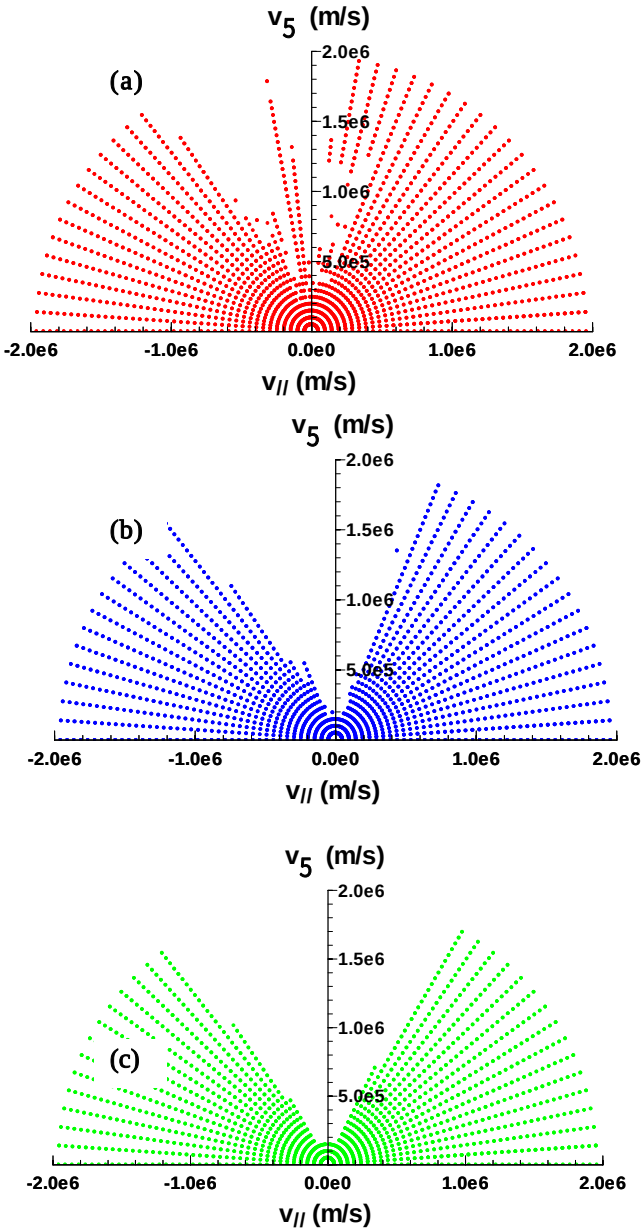


Fig. 4 Loss cone region for (a) the high bumpy case, (b) the medium bumpy case and (c) the low bumpy case.

3.0. The input power is about 150 kW. The calculated energy spectra are shown in Fig. 5. The particle loss ratios are 0.43, 0.60 and 0.57 for the high bumpy case, medium bumpy case and the low bumpy case, respectively. The tail temperatures estimated between 1 to 6 keV are in the same range as the experimental data. The tail formation above 6 keV is largest in the high bumpy case as shown in Fig. 5(a) although the difference is not as large as the experimental data in Ref. 4. The bulk heat source, which is delivered mainly to ions in three cases, is also largest in the high bumpy case. The bulk ion heating power in the high bumpy case is 10 % larger than two other cases. However, the tail temperature determined from the energy spectra

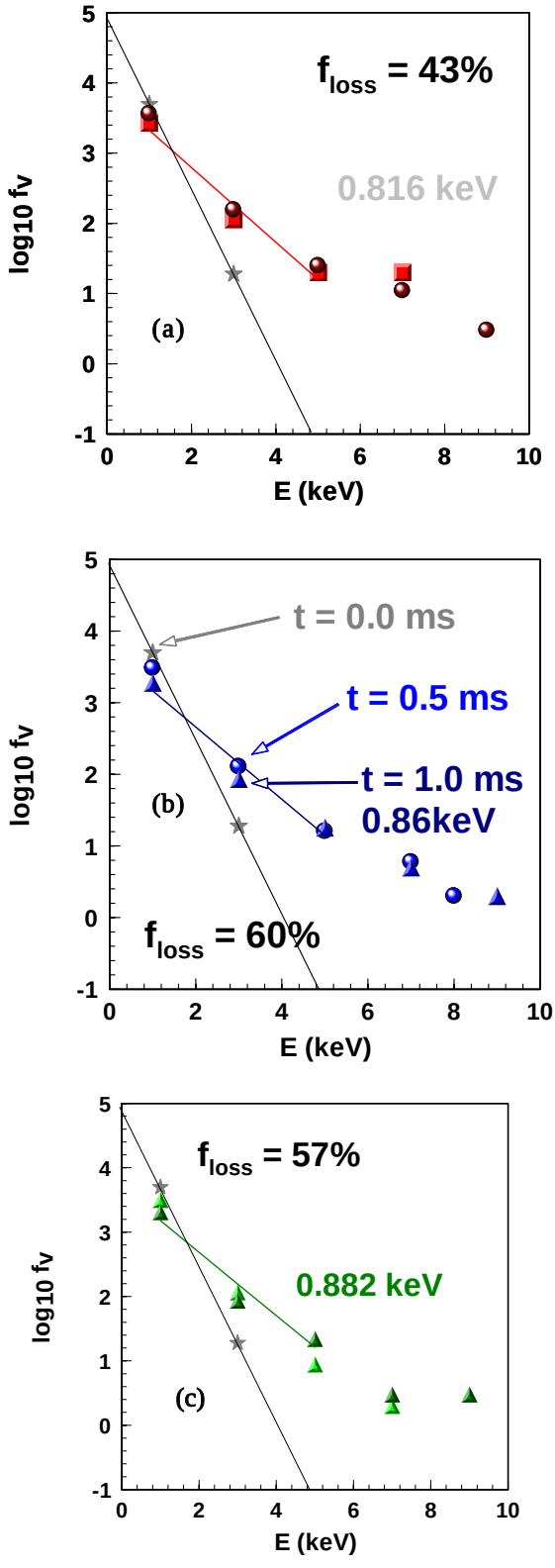


Fig. 5 Energy spectra calculated by Monte Carlo method for (a) the high bumpy case, (b) medium bumpy case and (c) the low bumpy case.
bumpy case and (c) the low bumpy case.

between 2 to 6 keV has deferent dependence from the experimental data and the deference of the input power to bulk ions for three cases is very small. Additional consideration is required in order to explain the experimental data.

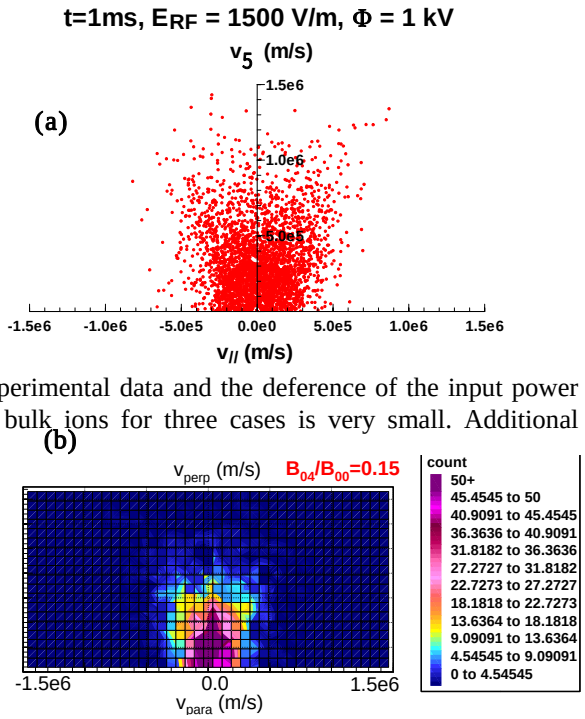


Fig. 6 Velocity distribution for the fast ions in the high bumpy case; (a) dot plot and (b) contour plot.

The calculated velocity distribution for protons in the high bumpy case is indicated in Fig. 6(a) as an example. It is not prolonged in the perpendicular direction, but in the direction of about 20-30 deg from the perpendicular. The contour plot is shown in Fig. 6(b) in order to clarify the distribution. This deviation is consistent with the experimental observation in the pitch angle scan experiment [4]. This calculation explains experimental data qualitatively; however, more discussion is needed taking account of the effects not included in this calculation, such as radial electric field, finite beta and so on.

Acknowledgements

This work is performed with the support and under the auspices of the Collaboration Program of the Laboratory for Complex Energy Processes, Institute of Advanced Energy, Kyoto University, Kyoto University 21st Century COE Program, and the National Institute of Fusion Science Collaborative Research Program of NIFS04KUHL002.

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COLLABORATION WORKS IN THE LABORATORY FOR COMPLEX ENERGY PROCESSES

1. Introduction

The laboratory was established in 1996 simultaneously with the Institute as an attached facility for research on advanced processes of energy production, conversion and application. In order to perform the research objectives of the Institute of Advanced Energy, it is essentially necessary to organize the cooperative research program with much close connection between related research fields in the Institute. The laboratory takes charge of organizing and promoting the cooperative research project as a center of research activity in the Institute. The research staffs in the Institute participate in specific projects to carry out their subjects. The scientists of other faculties in Kyoto University can also participate the cooperative project to enhance the progress of research and educational activities. The laboratory also manages various functions such as symposium and seminar for related topics on energy field.

The cooperative research activities will be published in a publication edited in the laboratory at the end of the year.

Research activities have been directed mainly toward the following cooperative projects as the principle research subject of the Institute.

A1. Interdisciplinary Field of Plasma Energy

The scientific and technological researches on advanced plasma energy system aim at the development of a frontier field "complex plasma energy systems research" based on plasma, hydrogen and material sciences. This field includes the basic research on advanced plasma energy related to the plasma confinement improvement, the effective transport of heat and particle fluxes, the system construction for hydrogen fuel cycle, the basic study on POP of advanced divertor, the control of plasma surface interaction and the development of materials under extremely severe environment.

A2. Interdisciplinary Field of Bioenergy

Researches in this field include development of highly efficient material/energy-transformation systems on basis of bio-nano-technologies and biomimetic approaches and elucidation, improvement, and utilization of the biological processes. The environmental aspects associated with the energy utilization are also studied in this field.

A3. Interdisciplinary Field of Photon and Quantum Energy

This specially-promoted field includes researches for extending advanced functions peculiar to photon, quantum and related materials, studies of fundamentals and /or technology for generating new functions of the energy, and interdisciplinary studies using the energy functions aiming at the creation of a new field of science and technology.

B. Cooperative use of facilities and equipments

Facilities and equipments of the laboratory are provided to cooperated researches for the scientists in the university.

2. The cooperative research project consists of (a) a specific program for "Promotion of a priority project" and (b) a standard program.

(a) A specific program was not planned in this year.

(b) Summary of the standard cooperative research subjects carried out in the year of 2006.

A public collection of cooperative research application was carried out, in this year, for a program which consists of 3 group of "Kiban" , "Syorei" and "Kikaku-chosa" cooperative research. The "Kiban " cooperative research means a program to promote leading research themes of the Institute projects. The "Syorei" cooperative research means a program to promote general research themes with respect to the Institute projects. The "Kikaku-chosa" cooperative research means a program to promote the cooperative research through a seminar or symposium.

As a result, the research themes of 46 were applied and applications of 43 were accepted after the approval by a steering committee of the laboratory. The number of research subjects are listed in Table 1 according to the project categories.

Table 1 Number of the accepted research subjects according to the standard project theme

The whole sum 43

		category A			B	total
		A1	A2	A3		
Kibann *1	inside	1	1	1	0	3
	outside	0	0	0	0	0
Syorei *2	inside	11	4	5	0	20
	outside	11	3	2	1	17
Kikaku -chosa *3	inside	1	0	0	0	1
	outside	0	1	1	0	2

"inside" or "outside" : Numbers applied by the inside or outside of the Institute

The individual research subjects are as follows, *1, *2 and *3 mean the "Kiban", "Syorei" and "Kikaku-chosa' cooperative research theme, respectively,

The individual Research subjects are as follows.

A1

"Confinement Study for the Effect of Magnetic Field Fourier Components in Heliotron J Plasmas Using RF Heating"

(1) H.OKada, S.Kobayashi, T.Mizuuchi, K.Nagasaki, F.Sano, K.Hanatani
(2) Y.Torii
(3) K.Kondo, Y.Nakamura
(4) T.Mutoh, S.Yamamoto
(5) Y.Nakashima
(6) N.Nishino
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Frontier Sciences, The University of Tokyo
(3) Graduate School of Energy Science, Kyoto University
(4) National Institute for Fusion Science
(5) Plasma Research Center, University of Tsukuba
(6) Graduate School of Engineering , Hiroshima University

"Experimental Studies of the Cylindrical Inertial Electrostatic Confinement Neutron Source —Effects of Titanium Coating on the Electrode—"

(1) Y.Yamamoto, Y.Takeuchi, S.Konishi
(2) Y.Ueno, K.Noborio
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University

"Hydrogen Production from Biomass Using Nuclear Heat"

(1) Y.Takeuchi, S.Konishi, Y.Yamamoto
(1) Institute of Advanced Energy, Kyoto University

"Optimization Studies of Helical System Concept"

(1) F.Sano, T.Mizuuchi, K.Nagasaki, K.Hanatani, H.Okada, S.Kobayashi
(2) K.Kondo, Y.Nakamura, G.Motojima, H.Arimoto, Y.Kishimoto
(3) S.Okamura, K.Ida, K.Toi, Y.Suzuki, H.Iguchi, A.Fujisawa, T.Minami, S.Nishimura, Y.Yoshimura, M.Isobe, C.Suzuki, K.Nagaoka, M.Yokoyama, T.Akiyama, O.Yamagishi
(1) *Institute of Advanced Energy, Kyoto University*
(2) *Graduate School of Energy Science, Kyoto University*
(3) *National Institute for Fusion Science*

"Dynamic Change of Edge Field Topology during a Plasma Discharge"

(1) T.Mizuuchi
(2) Feng Zhen
(1) Institute of Advanced Energy, Kyoto University
(2) South Western Institute of Physics

"Physics of Non-Inductive Current Drive and Its Control in Toroidal Plasmas"

(1) K.Nagasaki, T.Mizuuchi, S.Kobayashi, K.Sakamoto, F.Sano, K.Hanatani, H.Okada
(2) K.Kondo, Y.Nakamura
(3) Y.Yoshimura
(4) A.Fernandez, A.Cappa
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto

University
(3) National Institute for Fusion Science
(4) Laboratorio Nacional de Fusión por Confinamiento Magnético Asociación EURATOM-Ciemat

"Development of Multi-Channel Beam Emission Spectroscopy and Its Application to Simultaneous Measurements of Density Gradient and Fluctuations"
(1) S.Kobayashi, T.Mizuuchi, K.Nagasaki, F.Sano, H.Okada
(2) K.Kondo, H.Arimoto, Y.Nakamura, S.Matsuoka
(3) S.Yamamoto
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University
(3) National Institute for Fusion Science

"Study of Stress Corrosion Cracking in Boiling Water Reactor Power Plants Made of L-Grade Stainless Steel"
(1) A.Kohyama, H.Kishimoto
(2) Y.Sueishi
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University

"Improvement of Joining Technique for SiC and SiC/SiC Composites"
(1) T.Hinoki
(2) Jung Hun Chea
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University

"Irradiation Effects of Ceramics Oxides under Fusion and Fast Neutron Fission Reactor Environments"
(1) H.Kishimoto, A.Kohyama, T.Hinoki
(2) K.Shimoda
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University

"A Modeling Study of the Response of Fusion Materials to Irradiation"
(1) K.Morishita, A.Kohyama
(2) Y.Watanabe
(3) H.Iwakiri
(4) Y.Kaneta, Chen Ying
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University
(3) Research Institute for Applied Mechanics, Kyushu University
(4) Graduate School of Engineering, The University of Tokyo

"EAC Behavior of Dissimilar Joint Part of Reduced-Activation Ferritic Steel F82H and Austenitic Stainless Steel SUS316**"**
(1) R.Kasada, A.Kimura, A.Kohyama
(2) H.Tanigawa, H.Ogiwara
(1) Institute of Advanced Energy, Kyoto University
(2) Japan Atomic Energy Agency

"Confinement Improvement in Helical Systems"
(1) T.Mizuuchi
(2) S.Murakami
(3) A.Fujisawa
(4) Y.Kamada
(5) S.Kitajima
(6) Jeffrey H.Harris
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Engineering, Kyoto University
(3) National Institute for Fusion Science
(4) Japan Atomic Energy Agency
(5) School of Engineering, Tohoku University
(6) Oak Ridge National Laboratory

"Study of Ion Behavior in Heliotron J"
(1) K.Kondo, S.Matsuoka, H.Arimoto, G.Motojima, S.Watanabe, T.Tomokiyo, M.Nosaku, D.Katayama
(2) T.Mizuuchi, K.Nagasaki, H.Okada, S.Kobayashi, F.Sano
(1) Graduate School of Energy Science, Kyoto University
(2) Institute of Advanced Energy, Kyoto University

"Measurement of Heliotron J Peripheral Plasma by a Fast Camera"
(1) N.Nishino, Y.Fukuyama, T.Abe, K.Kaga, S.Sakurada, S.Honda
(2) K.Kondo
(3) F.Sano, T.Mizuuchi, H.Okada, K.Nagasaki, S.Kobayashi
(1) Graduate School of Engineering , Hiroshima University
(2) Graduate School of Energy Science, Kyoto

University
(3) Institute of Advanced Energy, Kyoto University

"Electron Bernstein Wave Heating in Helical Systems"
(1) Y.Yoshimura, S.Okamura, S.Kubo, T.Shimozuma, H.Igami, T.Notake
(2) K.Nagasaki, T.Mizuuchi, S.Kobayashi, F.Sano, K.Hanatani, H.Okada
(3) K.Kondo, Y.Nakamura
(1) National Institute for Fusion Science
(2) Institute of Advanced Energy, Kyoto University
(3) Graduate School of Energy Science, Kyoto University

"Study of Particle Transport in Three Dimensional Non-Axisymmetric System"
(1) Y.Nakashima, M.Ichimura
(2) S.Kobayashi, T.Mizuuchi, F.Sano, K.Nagasaki, H.Okada
(3) K.Kondo, Y.Nakamura, H.Arimoto, S.Matsuoka
(4) S.Yamamoto
(1) Plasma Research Center, University of Tsukuba
(2) Institute of Advanced Energy, Kyoto University
(3) Graduate School of Energy Science, Kyoto University
(4) National Institute for Fusion Science

"Precipitation Mechanism of Oxide Particles in 9Cr-ODS Steel"
(1) M.Inoue, H.Sakasegawa, S.Ohtsuka, T.Kaito
(2) A.Kohyama, T.Hinoki
(3) S.Ukai
(1) Japan Atomic Energy Agency
(2) Institute of Advanced Energy, Kyoto University
(3) Graduate School of Engineering, Hokkaido University

"High-Fluence Irradiation Behavior of Reduced Activation Fusion Reactor Materials"
「Evaluation of Dual Beam Irradiation Behavior in Reduced Activation ODS Steels at High Temperature」
(1) H.Tanigawa, H.Ogiwara, H.Sakasegawa
(2) A.Kohyama, T.Hinoki, H.Kishimoto
(3) T.Mizui
(1) Japan Atomic Energy Agency
(2) Institute of Advanced Energy, Kyoto University
(3) Graduate School of Energy Science, Kyoto University

"Theoretical Simulations for Irradiated Materials Based on First Principles Method"
(1) Y.Kaneta, Chen Ying
(2) A.Kohyama, K.Morishita
(3) Y.Watanabe
(1) Graduate School of Engineering, The University of Tokyo
(2) Institute of Advanced Energy, Kyoto University
(3) Graduate School of Energy Science, Kyoto University

"Fundamental Study of Solid Materials Irradiated with Helium Ions"
(1) H.Iwakiri, N.Yoshida
(2) K.Morishita
(1) Research Institute for Applied Mechanics, Kyushu University
(2) Institute of Advanced Energy, Kyoto University

"Dynamical Behavior and Segregation of Helium in Austenitic and Ferritic Steels"
(1) M.Miyamoto, K.Ono
(2) K.Moroshita
(1) Interdisciplinary Faculty of Science and Engineering, Shimane University
(2) Institute of Advanced Energy, Kyoto University

"Energetic Ion Driven MHD Instabilities and Their Effects on Ion Transport in the Heliotron J Plasmas"
(1) K.Toi, Y.Suzuki, M.Osakabe, S.Yamamoto
(2) K.Nagasaki, F.Sano, T.Mizuuchi, H.Okada, S.Kobayashi
(3) K.Kondo, Y.Nakamura
(4) B.Blackwell
(1) National Institute for Fusion Science
(2) Institute of Advanced Energy, Kyoto University
(3) Graduate School of Energy Science, Kyoto University
(4) The Australian National University

"Nano-Mechanics of SiC/SiC Composites by High Energetic Multi-Ion Irradiation"
(1) T.Shibayama, S.Watanabe
(2) T.Hinoki, H.Kishimoto, A.Kohyama
(1) Center for Advanced Research of Energy Conversion Materials, Hokkaido University
(2) Institute of Advanced Energy, Kyoto University

University

A2

"Construction of a Miniature Enzyme from Native Methane Monooxygenase"

(1) T.Morii, T.Sagawa, K.Sugimoto, K.Mokino
(2) M.Kinoshita
(1) Institute of Advanced Energy, Kyoto University
(2) International Innovation Center, Kyoto University

"Fabrication of Materials for Photon-Electron Transfer by Using Functional Peptide"

(1) T.Sagawa, T.Morii, K.Sugimoto
(2) N.Fujimoto
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University

"Construction of a Conductive Nano-Wire Using Amyloid Fibril Template"

(1) K.Sugimoto, T.Morii
(1) Institute of Advanced Energy, Kyoto University

"Development of Energy- and Material-Recycling Systems by Use of Supercritical Fluid and Biological Functions"

(1) K.Makino, Pack Seung Pil, T.Kodaki
(2) S.Watanabe
(3) K.Tajima
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Engineering, Kyoto University
(3) Kyoto Institute of Technology

"Development of Highly Efficient Biomass Conversion System by Identification of Novel Metabolic Pathway of Sugar"

(1) T.Kodaki, K.Makino
(2) S.Watanabe
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Engineering, Kyoto University

"Energies of Si [001] Small Angle Grain Boundaries"

(1) K.N.Ishihara
(2) A.Otsuki
(1) Graduate School of Energy Science, Kyoto University
(2) Institute of Advanced Energy, Kyoto University

"Gene Analysis by Electrochemical DNA Chip"

(1) K.Yamana
(2) T.Morii
(1) Graduate School of Engineering, University of Hyogo
(2) Institute of Advanced Energy, Kyoto University

"Formation of Nano-Scale Structures and Molecular Recognition by Biomolecules"

(1) T.Konno
(2) T.Morii
(1) Faculty of Medical Sciences, University of Fukui
(2) Institute of Advanced Energy, Kyoto University

"Mechanistic Investigation for Oxidative Radical Reaction of Biological Molecules Occurring on UV-Irradiated TiO_2 Surface"

(1) K.Tajima, K.Kanaori
(2) K.Makino
(1) Kyoto Institute of Technology
(2) Institute of Advanced Energy, Kyoto University

A3

"Nano-Scale Control and New Function Generation of Materials with Femtosecond Laser Pulses"

(1) K.Miyazaki, G.Miyaji
(2) N.Yasumaru
(3) M.Ohtsu
(4) Alexander E.Kaplan
(1) Institute of Advanced Energy, Kyoto University
(2) Fukui National College of Technology
(3) Graduate School of Engineering, The University of Tokyo
(4) Johns Hopkins University

"Stabilization of Electron Gun Operation Using Current Feedback System"

(1) H.Ohgaki, T.Yamazaki, K.Yoshikawa, K.Masuda, T.Kii
(2) H.Zen
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University

"Performance Improvement of KU-FEL RF

Gun by Use of RF Triode Structure"

(1) K.Masuda, T.Yamazaki, H.Ohgaki, T.Kii, K.Yoshikawa
(2) T.Shiiyama
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University

"Spin-Polarization Induced by Femtosecond Laser Pulses"

(1) T.Nakajima, T.Sakka
(2) Y.Matsuo, T.Kobayashi
(1) Institute of Advanced Energy, Kyoto University
(2) The Institute of Physical and Chemical Research

"Generation and Control of Intense UV Pulses with Laser-Aligned Molecules"

(1) G.Miyaji, K.Miyazaki
(2) K.Yoshii
(3) Farhad H.M.Faisal
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University
(3) Bielefeld University

"In Situ Elemental Analysis of Solid Surfaces in Liquid by Laser Ablation Plume Spectroscopy"

(1) T.Sakka, Y.H.Ogata, T.Nakajima
(2) H.Oguchi
(3) Y.Suzuki
(1) Institute of Advanced Energy, Kyoto University
(2) Graduate School of Energy Science, Kyoto University
(3) Uyemura &Co.,Ltd.

"Promotion of Selective Synthetic Organic Reaction by Means of Infrared Pulse Laser Irradiation"

(1) K.Fugami
(2) T.Sakka
(1) Faculty of Engineering, Gunma University
(2) Institute of Advanced Energy, Kyoto Universit

"Fabrication of Nanostructures Using Laser Ablation in Liquid Media"

(1) T.Sasaki
(2) T.sakka
(1) National Institute of Advanced Industrial Science and Technology
(2) Institute of Advanced Energy, Kyoto University

"Feasibility Study on Exploring New Frontier Physics Using Fast Heavy Ions and Intense Free Electron Laser"

(1) A.Itoh, H.Tsuchida
(2) T.Yamazaki, H.Ohgaki, T.Kii, K.Masuda
(1) Graduate School of Engineering, Kyoto University
(2) Institute of Advanced Energy, Kyoto University

B

"Development of a New Bending Test Using the Microsamples"

(1) N.Nita, S.Fujita, H.Matsui
(2) R.Kasada, A.Kimura
(1) Institute for Materials Research, Tohoku University
(2) Institute of Advanced Energy, Kyoto University

SYMPOSIUM IN THE LABORATORY

Symposium
The Symposium has been arranged in order to introduce the research activities in sections and to enhance the mutual cooperation among different fields. In 2006 four regular meetings and the annual meeting for the cooperative research results were held with following theme.

1. The regular meeting

The First Meeting, June 29, 2006
Il-Soon Hwan「核廃棄物転換システム PEACER 及び鉛ビスマステストループ」
Il-Soon Hwan, "A Sustainable Regional Waste Transmutation System: PEACER and LBE Loop Tests", *Seoul National University*

The 2nd. Meeting, July 14, 2006
Thomas J. Dolan「静電的プラズマ閉じ込め」
Thomas J. Dolan, "Electrostatic Plasma Confinement", *Idaho National Laboratory*

The 3rd. Meeting, July 21, 2006
Alexander E. Kaplan「相対論的ポンデロモーティブ力：レーザー・電子散乱における新しい展望」
Alexander E. Kaplan, "Relativistic Ponderomotive Force -New Landscapes in Laser-Electron Scattering- ", *Johns Hopkins University*

The 4th. Meeting, September 28, 2006
大津元一「近接場光を介した微細パターン形成と加工」
M.Ohtsu, "Micro-Pattern Formation and Processing with Optical Near Filed", *Graduate School of Engineering, The University of Tokyo*

2. The Annual Meeting for the Cooperative Research Results, April 6, 2007

岡田浩之「高周波加熱を用いたトーラス磁場のフーリエ成分に対するヘリオトロン J プラズマの閉じ込め研究」
H.Okada, "Confinement Study for the Effect of Magnetic Field Fourier Components in Heliotron J Plasmas Using RF Heating", *Institute of Advanced Energy, Kyoto University*

作花哲夫「液中個体表面のレーザーアブレーションプルーム分光によるその場元素分析」
T.Sakka, "In Situ Elemental Analysis of Solid Surfaces in Liquid by Laser Ablation Plume Spectroscopy", *Institute of Advanced Energy, Kyoto University*

森井　孝「ミニチュアメタン酸化酵素の創製」
T.Morii, "Construction of a Miniature Enzyme from Native Methane Monooxygenase", *Institute of Advanced Energy, Kyoto University*

山本　靖「円筒形静電慣性閉じ込め中性子源の実験」
Y.Yamamoto, "Experimental Studies of the Cylindrical Inertial Electrostatic Confinement Neutron Source –Effects of Titanium Coating on the Electrode- ", *Institute of Advanced Energy, Kyoto University*

森下和功「核融合炉材料の照射下挙動モデリング」
K.Morishita, "A Modeling Study of the Response of Fusion Materials to Irradiation", *Institute of Advanced Energy, Kyoto University*

宮崎健創「フェムト秒レーザーによるナノ物質制御と新機能創出」
K.Miyazaki, "Nano-Scale Control and New Function Generation of Materials with Femtosecond Laser Pulses", *Institute of Advanced Energy, Kyoto University*

佐川　尚「機能性ペプチドを利用した光電変換材料の創製」
T.Sagawa, "Fabrication of Materials for Photon-Electron Transfer by Using Functional Peptide", *Institute of Advanced Energy, Kyoto University*

増田　開「高周波三極管構造による KU-FEL 用高周波電子銃の高性能化」
K.Masuda, "Performance Improvement of KU-FEL RF Gun by Use of RF Triode Structure", *Institute of Advanced Energy, Kyoto University*

杉本健二「アミロイド繊維構造を鋳型とした

導電性ナノ配線の構築」
K.Sugimoto, “Construction of a Conductive Nano-Wire Using Amyloid Fibril Template”, *Institute of Advanced Energy, Kyoto University*

大垣英明「電子銃ヒーター電流のフィーバッ
ク制御による出力電流の安定化」
H.Ohgaki, “Stabilization of Electron Gun Operation Using Current Feedback System”, *Institute of Advanced Energy, Kyoto University*

21st Century COE Program
Establishment of COE on Sustainable Energy System

Graduate School of Energy Science
Institute of Advanced Energy
Research Institute for Sustainable Humanosphere

1. Succession and Extension of 21COE program

Under the 21COE program of Ministry of Education, Culture, Sports, Science and Technology (MEXT) which started in FY2001 and completed in FY2006, Institute of Advanced Energy, Graduate School of Energy Science, and Research Institute for Sustainable Humanosphere jointly promote a research and educational project, entitled as "Establishment of COE on Sustainable Energy System."

The COE program aims to contribute the Kyoto Protocol by the new energy development. Our institute takes the initiative for the Next Generation Solar Cell task, and Artificial Sun (Plasma Fusion) task, as well as the activities of the International Sustainable-Energy Information Center. As an activity of the international sustainable energy information center of 21COE program, Bangkok office and collaborative research laboratory were established in November 2003, in the center of Bangkok city and Rajamangala University of Technology (RMUT, former RIT), respectively. They are widely utilized for collaborative researches. While, as one of the activities for cooperative education of new energy of 21COE program, Prof. K. Yoshikawa, Prof. Saka, Assoc. Prof. Nagasaki, Assoc. Prof. Masuda, Prof. Tezuka, and Prof. S. Yoshikawa went to RMUT one after another and gave lectures on new energies as special intensive class (12 times).

At the moment, extension of the COE program, International New Energy Cooperative Organization (tentative) is going to be established. This organization consists of 5 research units, one education unit, and cooperation unit. The 5 research units include i) unit of solar cells for next generation, ii) solar power station/satellite (SPS) unit, iii) nuclear fusion unit, iv) unit of hydrogen energy for next generation, v) unit of bioenergy for next generation, and iv) new energy system unit. The cooperation unit is going to consist of following two forums; New Energy Forum including domestic universities and Sustainable Energy and Environment (SEE) Forum with the cooperation of ASEAN University Network (AUN) of 17 universities from ASEAN countries.

2. The 3rd International Symposium on Sustainable Energy System

The 3rd international symposium on sustainable energy system was held at Kyoto University Clock Tower Centennial Hall from August 30 to September 1, 2006.

2.1 Program

August 30, 2006 (Wednesday)

Opening remarks

Kazuo Oike (President, Kyoto University)

Susumu Yoshikawa (Program Leader, Kyoto University 21COE Program)

Numyoot Songthanapitak (President, RMUT, Thailand)

Progress in the Research of the 21COE Program

・ *Solar Cell*

Susumu Yoshikawa (Institute of Advanced Energy, Kyoto University)

・ *Solar Power Satellite Staition*

Kozo Hashimoto (Research Institute for Sustainable Humanosphere, Kyoto University)

・ *Nuclear Fusion*

Takashi Maekawa (Graduate School of Energy Science, Kyoto University)

・ *Hydrogen Energy*

Rika Hagiwara (Graduate School of Energy Science, Kyoto University)

・ *Bioenergy*

Shiro Saka (Graduate School of Energy Science, Kyoto University)

・ *Evaluation of Sustainable Energy System*

Tetsuo Tezuka (Graduate School of Energy Science, Kyoto University)

Plenary Lectures on Sustainable Energy Sytem

"Renewable Communities - An Answer To Our Energy Crisis"

Terry Penny (National Renewable Energy Laboratory, USA)

"Present Situation and Prospects of Biodiesel in Europe"

Martin Mittelbach (Karl-Franzes-University, Austria)

"Harmonious Coexistence within Human and Ecological Community on This Planet"

Hiroshi Matsumoto (Executive Vice- President, Kyoto University)

August 31, 2006 (Thursday)

Plenary Lectures on Sustainable Energy Sytem

"The Global Overview and Future of Biothanol"

Plinio Mârio Nastari (DATAGRO, Brazil)

"Advancing Spherical Tokamak Database for Practical Fusion Energy"

Martin Peng (Oak Ridge National Laboratory, USA)

"Power Generation and Conversion in a Hydrogen Economy"

Fritz Prinz (Stanford University, USA)

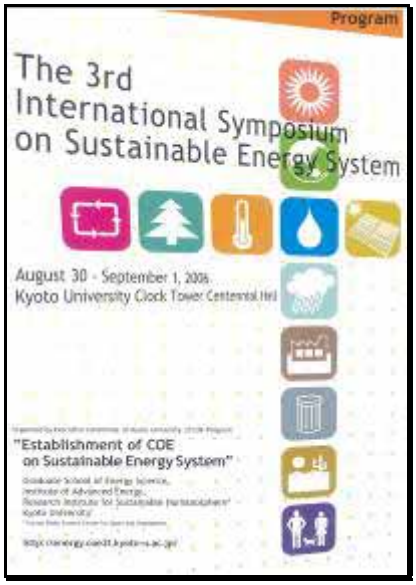
"A Clean, Safe and Reliable Baseload Power"

Darel Preble (Space Solar Power Workshop, USA)

"Economy, Energy, and the Environment in China: An Integrated Policy Framework"

Ji Zou (Renmin University of China, China)

Poster Session was held on August 30, and ***Parallel Sessions*** were held on August 31 and September 1.



3. JGSEE and Kyoto University 2nd Joint International Conference on "Sustainable Energy and Environment"

Sustainable Energy and Environment was held at Bangkok, Thailand from November 21 to November 23, 2006.

3.1 Program

November 21, 2006 (Tuesday)

Opening Ceremony and Special Presentation by Minister of Energy, Thailand

Keynote Lecture "Energy Mix Policy" Professor Dr. **Prida Wibulsawas** (Chairman of the Policy Board, Thailand Research Fund (TRF))

Keynote Lecture "Assessment of Technologies for Mitigating Climate Change"

Prof. Yoichi Kaya (Director General RITE, Professor Emeritus University of Tokyo, Japan)

Parallel Sessions were held on November 22 and November 23.

4. SEE Forum International Symposium "Challenges for Sustainable Energy System" and 21COE Summary Meeting

The SEE forum international symposium and 21COE summary meeting was held at Kyoto University Clock Tower Centennial Hall from March 11 to March 13, 2007.

4.1 Program

March 11, 2007 (Sunday)

Opening Speech

"New Energy Initiative – Message from 21COE on Sustainable Energy System"

Prof. Susumu Yoshikawa (Program Leader, 21COE on Sustainable Energy, Kyoto University)

SEE Forum International Symposium

"Sustainable EnergyDevelopment in Asia"

Prof. Hari Prakash Garg (Executive Director, ASEAN University Network, Chulalongkorn University)

"New Energy Policy in Thailand"

Prof. Bundit Fungtammasan (Director, The Joint Graduate School of Energy and Environment)

Invited Speakers

"New Energy Researches in Korea"

Dr. Chang-Soo Kim (Korea Institute of Energy Research in Daejeon)

"Solar Power Generation"

Dr. T. Takamoto (Sharp Corporation)

"Li Battery Research and New Energy, Science and Technology Trends in LBL"

Dr. Robert Kostecki (Lawrence Berkeley Laboratory)

"Superconducting Technology and Sustainable Energy System"

Dr. R. Hata (Sumitomo Electric Industries, Ltd.)

Closing Remarks

Prof. Hiroshi Matsumoto (Executive Vice-President, Kyoto University)

March 12, 2007 (Monday)

21 COE Symposium "Possibility of the Next Energy Technology"

Opening Speech

Prof. Susumu Yoshikawa (Program Leader, 21COE on Sustainable Energy, Kyoto University)

Prof. Hiroshi Matsumoto (Executive Vice-President, Kyoto University)

Prof. Takeshi Yao (Dean, Graduate School of Energy Science, Kyoto University)

Plenary Lectures

"Supercomputing and the Science & Engineering of Sustainable Energy System"

Prof. R. Alkire (UIUC, USA)

"Irreversible Thermodynamics in Biological System"

Prof. Signe Kelstrup (UTNU, Norway)

"Global Energy Perspectives"

Prof. N. Lewis (Caltech., USA)

Panel Discussion

"Expectations to New Energy Resources"

March 12, 2007 (Monday)

Poster Presentations

Graduate School Students

Presentations of Research Summary during 21COE Program

Task Members in 21COE Program

COLLABORATION WORKS WITH OTHER UNIVERSITIES AND ORGANIZATIONS

1. Core University Program between Seoul National University and Kyoto University on Energy Science and Engineering from 1998 to 2007

This Core University Program (hereinafter referred as "CUP"), started in 1998 between the Kyoto University and the Seoul National University is actively implemented and completed the 9th year. The circumstances of the energy problem in both countries are similar, and we share our expectations and interests on the advanced energy technology as our motivation for cooperation. However the previous collaborations have not been active despite of the distance, because both emphasized exchanges with US or European countries. The direct exchanges under the CUP had to begin with mutual understanding, and establishing the network between researchers followed.

With the progress of the activities, exchanges have been expanded to involve active research groups in each fields, and the member universities and institutes increased as many as some 70. Particularly in Korea side, nuclear technology and fusion technology are mainly pursued in research institutes such as Korea Advanced Institute of Science and Technology (KAIST), Korea Atomic Energy Research Institute (KAERI), and Korean Basic Science Institute (KBSI) and now newly formed Nuclear Fusion Research Center (NFRC) that joined as major contributors in the program.

Table 1 summarizes the numbers of the exchanges and its trend. As seen in the figure, personnel exchanges took place in the early stage, and as approaching to the completion of the program, most of the activities are now collaboration, and seminars are increasing. Approximately 110-130 exchanges were implemented in each year, that may be the largest number among the similar programs under JSPS. Accomplishments of the collaboration have been published in the form of joint papers or conference proceedings of exceeding 1200 to date.

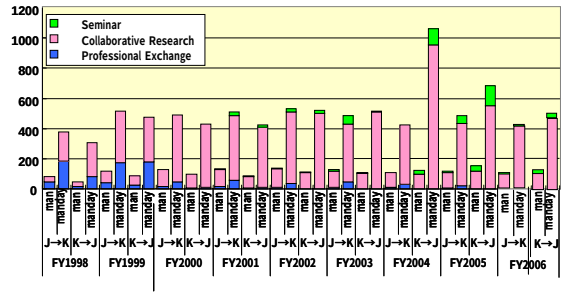


Table 1 personnel exchanges under the Japan-Korea Core University Program.

From the administrative aspects, some important changes have been implemented in the year 2006. Due to the change of the status of the Kyoto university from a part of the governmental organization to an independent legal entity, this collaborative activity is operated under a contract between JSPS and Kyoto university with more freedom and responsibility in the implementation by Kyoto university. This change caused some operational difficulty in the administrative procedure, but the system is now completely reformed to accommodate the new rule. Another change was a retirement of the Japan side program representative, Prof. Kiyoshi Yoshikawa, to be replaced with Prof. Akira Kohyama in the FY 2007.

As one of the consequence of the change, we are encouraged to report the achievements under this proram, that is now evaluated from the percentage of the accomplishment of planned exchanges. Our Japan-Korea exchanges have handled the largest number of short trips to both sides among the entire Core University Programs under JSPS and had completed at very high rate, in the fiscal year 2006, it was 93% for Japan to Korea visit. In this fiscal year, difficulty was encountered due to the higher air fare. This program maintained the activity by the almost same amount of budget, and the efforts and cooperation of the exchanging researchers.

Research subjects are of 4 categories; Highly qualified energy sources, Advanced energy materials, Renewable energy production, and advanced nuclear energy.

The brief summaries of the major tasks are as follows.

Task1: Physics:
CR-06-1-1: Highly Brilliant Relativistic Electron Beams and Their Advanced Applications.
Korean Host Leader: Yong-Seok Hwang (Seoul University)
Japanese Host Leader: Tetsuo Yamazaki (Kyoto University)

Collaboration was performed on; infrared free-electron laser, high-brightness electron beam, coherent transition radiation, and SASE S-free electron

laser. Prof. Yamazaki is retiring.

CR-06-1-2: Elementary Processes in Plasma and the Applications.

Korean Host Leader: Young-Dae JUNG *(POSTECH)*

Japanese Host Leader: Izumi Murakami (NIFS)

This project has been organized to study atomic and molecular processes and radiation processes in various kind of plasma with special focus on high density plasma. Establishment of data base is another important subject of this task.

This year exchanges on Atomic and Molecular Database on basic process in the plasma was carried out.. Title of the task and key persons in both side were changed. Research are being performed in following subjects :

(1) plasma polarization spectroscopy, (2) basic atomic processes for X-ray lasers, (3) collision processes for molecules, (4) nonlinear optics and X-ray interaction with ions, (5) spectroscopic diagnostics for magnetically confined plasma, (6) X-ray properties of molecules, (7) atomic database for dielectronic satellite lines, (8) Ionization, recombination and line emissions of high Z ions, (9) electron correlation in molecular polymers and copper oxide layers. Change of the task leader is anticipated.

CR-06-1-3: Fusion and Plasma Science

Korean Host Leader: Gon-Ho Kim (Seoul University)

Japanese Host Leader: Yasuaki Kishimoto (Kyoto University)

In this task, a new plan "Plasma Science and Technology" started on simulation study of fusion plasma. Several research groups are identified as future collaborative research partners in the area of plasma applications such as plasma processing and pulsed plasma applications. In the fusion area, the collaboration will be connected to the international fusion research such as International Thermonuclear Experimental Reactor (ITER) program in which Korea and Japan join as parties. Tokamak confinement, transport model and the structure of the pedestal are of one of the subjects studied. ECR system for KSTAR is also studied.

Task2: Engineering

CR-06-2-1Large scale application of superconductivity materials

Korean Host Leader: Sang-Im Yoo (Seoul National University)

Japanese Host Leader: Taketsune Nakamura (Kyoto University)

Seminars were held in both Japan and Korea in order to exchange scientific information to discuss deeply about updated scientific problems in the superconducting magnet technology field. Energy storage (SMES), materials, cable and conduit technology, high temperature superconducting materials were discussed..

CR-06-2-2: Advanced Infrastructure of Operation and Maintenance Technologies for Nuclear Power Plant

Korean Host Leader: Poong Hyun Seong, (Korea Advanced Institute of Science and Technology)

Japanese Host Leader: Poong Hyun Seong, Korea Advanced Institute of Science and Technology (Kyoto University)

Collaboration on the review and mutual discussion for the exploitation of advanced operation & maintenance technologies (monitoring, diagnosis & trend prediction: non-examination testing, fracture mechanics: advanced human interface devices, software V&V & software for network technologies, etc.) and their effective applications for future NPP Operation and Maintenance were discussed. Operation of nuclear power plants in both countries were observed and compared by workshops. Advanced maintenance technology, robotics, and human factor are also subjects discussed.

CR-06-2-3:Structural Observation and Analysis of Advanced and Energy Nano-materials

Korean Host Leader: Hu-Chul Lee (Seoul National University)

Japanese Host Leader: Somei Ohnuki (Hokkaido University)

Exchanges conducted on Experiment for investigating GMR mechanism of magnetic tunnel junction device using holography in TEM, and analyses of microstructure using TEM. Japan-Korea Electron Microscopy Tutorial for Resent Progress of Electron Microscopy for Materials Research was held. Dong-Eui university, POSTEC, KBSI, and Tohoku university were planned for further collaboration. This task is also expected as a major organizer of the summer school planned in 2007.

CR-06-2-4: Mechanisms of Environmentally Induced Plant Aging (EIPA)

Korean Host Leader: Il Soon Hwang (Seoul National University)

Japanese Host Leader: Tetsuo Shoji (Tohoku University)

Raman Spectroscopy was applied in-situ to characterize the oxides and measured the stress in the oxide film formed on the surface of 304L stainless steel during the scratching electrode test and the slow strain rate test (SSRT). In-situ observation of crack initiation and propagation in stainless steel in high temperature water for on-line monitoring of crack growth is underway. Magnetic for Non Destructive Evaluation method was discussed as a NDE method for SCC. On-line monitoring by high temperature UT monitoring of wall-thinning phenomena was discussed.

It has been agreed that ECP Measurement Campaign

will be conducted using both Stainless Steel and Alloy 600 specimens in both BWR and PWR environments. It was confirmed that methodology and standardized condition for the experiments are important to compare the results effectively.

CR-06-2-5:Fusion Science and Engineering

Korean Host Leader: Han-Ki Yoon (Dongeui University)

Japanese Host Leader: Tatsuya Hinoki (Kyoto University)

Following research activities were conducted:

- Effects of precipitation on high temperature mechanical properties of RAFs were investigate and Its Database was established.

-Porous SiC materials with various sizes and shapes of pores were developed.

- Based on NITE process, W coated SiC materials were developed.

Oxide dispersion strengthened steel (JLF-ODS) and NITE SiC/SiC composites were strongly studied for the applicability to the advanced fusion blankets .

Task3: Environment

CR-06-3-1: Research and Development for Environmentally Clean Renewable Energy Production Systems

Korean Host Leader: Tai Hyun Park (Seoul University)

Japanese Host Leader: Keisuke Makino (Kyoto University)

In FY2006, similarly to that in FY2005, the both sides aimed together the establishment of the novel method by which biomass is converted to ethanol by recombinant Saccharomyces cerevisiae efficiently. Saccharomyces cerevisiae, which lacks the enzymic systems to ferment pentoses, was transformed with genes of xylose reductase (XR) and xylitol dehydrogenase (XDH) of Pichia stipitis successfully by the aid of recombinant plasmid. In this study, Japan side is mainly in charge of development of new enzymes, and Korea side focuses on the biochemical technology. Many of the accomplishments were reported in academic meetings. We succeeded in producing this enzyme and will continued this work in FY2007.

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Task4: Innovative Nuclear Technology

CR-06-4-1: Advanced Fuel Cycle Initiative

Korean Host Leader: K.J. Lee (Seoul University)

Japanese Host Leader: H.Moriyama (Kyoto University)

Research cooperation aims for the initiation and development of new and innovative scientific and engineering techniques affecting the future of nuclear fuel cycle. The following outcomes are resulted through the cooperative program.

Recent progress of the conceptual and experimental studies on advanced fuel cycle are presented.

Results of the conceptual studies on proliferation-resistant, inherent safe, economic fast reactors are discussed. Particular interests are on dry process of the spent nuclear fuels. For this purpose, liquid metal and molten salts are studied as a fundamental research.

Experimental results of electrorefining process and pyrochemical reprocessing are discussed.

Physicochemical properties of molten salts and liquid metals are also discussed.

Achievements and current Issues for pyroprocess developments are discussed.

CR-06-4-2: Material and Engineering Validation for Innovative Nuclear Technology

Korean Host Leader: In Sup Kim (KAIST)

Japanese Host Leader: A. Kimura (Kyoto University)

This cooperative program have made the following outcomes

i) The information of environmental effects on creep-fatigue properties of nickel-based super alloys was exchanged.

ii) Fatigue behavior of 316 and 316LN stainless steels at various temperature and strain rates were discussed.

iii) Thermal aging embrittlement of ODS steels was significantly affected by the content of chromium. 14 Cr ODS steels showed the most promising mechanical properties to thermal aging embrittlement.

iv) Fracture characteristics of neutron irradiated Zr-2.5Nb were characterized depending on the irradiation temperature and fluence.

Irradiation experiments on reactor pressure vessel steels (RPVS) and claddings utilizing JMTR have been performed, and the obtained main results are:

1) The irradiation embrittlement of A533B cl.1 steel became remarkable beyond a neutron fluence of 2 x 10^{19}n/cm^2.

2) Among iron-based binary alloys, Fe-Mn alloy showed a rather big irradiation hardening which is as large as that of Fe-Cu alloy. It is considered that the large irradiation hardening is due to formation of extremely high density of small dislocation loops.

3) The Mn effect appeared above a neutron fluence of 2 x 10^{19}n/cm^2.

4) Aging embrittlement of high Cr-ODS steels was retarded by dispersion of oxide particles, which can be interpreted in terms of suppression of atomic diffusion.

Advanced ferritic steels, such as reduced activation ferritic steels and ODS steels were irradiated in HANARO to investigate irradiation effects on the materials performance at T(irr)=290°Cand Fluence=10^{20}n/cm^2.

CR-06-4-3: Hydrogen Production and Energy Conversion/ Storage

Korean Host Leader: Joo Han-Gyu (Seoul National University)

Japanese Host Leader: S. Konishi (Kyoto University)

Activities are ongoing in 3 fields. A newly proposed collaborative item is high temperature energy conversion with liquid metal for advanced nuclear energy systems. Hydrogen energy conversion and storage is also studied. Study on the electrochemical energy conversion process restarted with the newly assigned personnel.

Since the international efforts to develop ITER Test Blanket Modules have now being started, this collaboration will more emphasize blanket technology.

The following subjects were studied with particular interests :

1) Liquid metal technology for advanced nuclear energy: High temperature energy conversion with liquid metal based on Lead and its alloy attracts interests in both countries. Material compatibility, nuclear performance and heat transfer are studied. For fusion application, blanket concepts are pursued with ITER TBM program in mind.

2) Tritium technology issue for fusion energy conversion and hydrogen production: It is one of the critical issue and of interest for both. Korea has valuable experience and information related to heavy water technology, and Japan with fusion technology. Technical exchange was started on tritium processing technology such as metal hydride storage and environmental study.

3)Electrochemical energy technology:

CR-06-4-4: Advanced Reactor Concept

Korean Host Leader: M.H.Kim(Kyung Hee University)
Japanese Host Leader: S. Shiroya (Kyoto University)

The coperative works were investigated between both sides on advanced technology, specially in liquid metal fast neutron reactor concept PEACER in KAERI and accelerator driven subcritical reactor ADSR in Kyoto. Technical meetings were hald on various topics .in advanced nuclear technology.

This exchange program emphasizes education of graduate school students and young researchers in the both country. For the short term activity, no major event was held in 2006, but a plan for the 2007 joint summer school is in late August at the Seoul National University is being made. This will be a continuationof the first one in SNU, second in Busan in 2005.

For longer term exchange, Korean students visited Japanese graduate schools where young researchers are needed. Some of them returned to Korea, lead research teams, and send students of next generation. Such a cycle takes long time to benefit both sides, but this is one of the significant accomplishment of the program. Such a contribution will eventually enhance the research standard and globalization of academic society in the Asia area.

Toward the completion of this 10 year term, we have started to plan and discuss the possible next phase of activity. Particular interest is on including China as a collaborator. China has a strong research and education in energy field, particularly nuclear energy science and technology requires international coordination with Korea and Japan. Current possible framework under JSPS to be applied is an “Asian Core” program that is for multi-lateral exchanges for 5 years. So far this program has been successful due to the cooperation of many people concerned, and as a result, activity requires further expansion to enhance the close coordinationin the joint research works in energy field. Based on the accomplishment and Collaborative efforts of this CUP, preparation for the future application and propowal was started to be made in the fiscal year 2006.

2. Other Collaboration Works

Advanced Energy Generation Division

Advanced Atomic Energy Research Section

野村技工、「過熱蒸気発生装置に関する解析全般」、竹内右人

Advanced Particle Beam Energy Research Section

核融合科学研究所、「放電型核融合中性子源における熱中性子束密度の向上」、吉川潔

Advanced Plasma Energy Research Section

Univ. Wisconsin（米国）、Univ. Wisconsin（米国）、ORNL（米国）、Max Planck Institute（ドイツ）、Provence Univ.（フランス）、CIEMAT(スペイン)、ANU（オーストラリア）、Kharkov Institute（ウクライナ）、SWIP（中華人民共和国）、「先進ヘリカルにおける改善閉じ込めの研究」、佐野史道、水内亨、長崎百伸、岡田浩之、小林進二、花谷清、D. Anderson、F.S.B. Anderson (Univ. Wisconsin), J.H. Harris (ORNL)、F. Wagner (Max Planck Institute), S. Benkadda (Provence Univ.), E. Ascasibar, C. Hidalgo, A. Baciero, B. Zurro, A. Cappa, A. Fernandez, V. Tribaldos (CIEMAT), B. Blackwell, H. Punzmann (ANU), V. Chechkin (Kharkov Institute), Q. Yang (SWIP)

ハリコフ研究所（ウクライナ）、マックスプランク・プラズマ物理研究所（ドイツ）、CIEMAT（スペイン）、「ヘリカル型装置における SOL/ダイバータプラズマに関する研究」、水内亨、小林進二、大引得弘、V.V.Chechkin，P.Grigull，F.Tabares 他

CIEMAT（スペイン）、「ヘリオトロン J における ECH、ECE のためのレイトレーシングコード開発」、長崎百伸、水内亨、小林進二、大引得弘、V.Tribaldos 他

核融合科学研究所、「LHD における ECH/ECCD プラズマでのイオンテールの発生に関する実験研究」、小林進二、長崎百伸、水内亨

日本原子力研究開発機構、「高ベータプラズマの安定維持のための能動的制御と MHD モード解析」、長崎百伸，水内亨，小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリカル閉じ込めの最適化のための双方向型共同研究」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリオトロン J を使ったヘリカル系におけるプラズマ電流の駆動機構の解明」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリオトロン J 装置における ICRF 加熱実験」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリオトロン J における改善閉じ込めに対する磁場構造の効果についての理論解析とその実験的検証」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「Heliotron J プラズマ中の中性水素および不純物挙動の研究」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

核融合科学研究所、「ヘリカル磁場によるプラズマ閉じ込めの物理」、水内亨

核融合科学研究所、「高次高調波 ECH によるプラズマ生成の物理」、長崎百伸、水内亨、小林進二

日本原子力研究開発機構、「イオン温度・回転速度の実時間計測手法の確立と分布制御への適用」、小林進二、長崎百伸、水内亨

Advanced Energy Conversion Division

Advanced Energy Materials Research Section

オークリッジ国立研究所（米国）等、「先進ブランケットの照射下特性とシステムインテグレーション（Jupiter-II）」、香山晃、檜木達也、Y. Kato、L. Snead 等

オークリッジ国立研究所（米国）、「JUPITER-II 計画の高温ガス冷却ブランケット開発を目指した、SiC/SiC 複合材料の作製技術開発と基本特性評価

（Task 2-1)」、香山晃、檜木達也、L.L. Snead、Y. Katoh、B.A. Pint

オークリッジ国立研究所（米国）、「JUPITER-II 計画の高温ガス冷却ブランケット開発を目指した、SiC/SiC 複合材料の照射特性評価（Task 2-3）」、香山晃、檜木達也、Y. Katoh、L.L. Snead

東義大学（大韓民国）、「核融合炉材料理工学」、香山晃、檜木達也、尹漢基

東義大学（大韓民国）、「新プロセスによる先進 SiC/SiC 複合材料の開発と耐環境特性評価」、檜木達也、Han-Ki Yoon

東北大学金属材料研究所付属量子エネルギー材料科学国際研究センター、「原子力エネルギー用 SiC 及び SiC/SiC 複合材料の中性子照射効果」、香山晃

核融合科学研究所、「核融合炉ブランケット用低放射化フェライト鋼の寿命評価」、香山晃

核融合科学研究所、「SiC/SiC 複合材料の接合技術開発」、檜木達也

大阪大学、「レーザー核融合用 SiC/SiC 複合材料の超高温までの耐照射特性を含む基本データ調整と材料設計」、香山晃

日本原子力研究開発機構、「先進核融合炉構造材料の照射特性評価」、檜木達也

日本原子力研究開発機構、「先進核融合炉構造材料の照射特性評価」、香山晃

北海道大学、「ガス冷却高速炉用先進材料ナノメカニクス接合解析技術の開発」、香山晃

Advanced Laser Science Research Section

University of Bielfed（ドイツ）、「高強度フェムト秒レーザーによる分子の配向と制御」、宮崎健創、F.H.M. Faisal

Johns Hopkins University（米国）、「フェムト秒レーザーによる表面ナノ構造生成過程のモデル構築」、宮崎健創、A.E. Kaplan

宇宙科学研究所（ルーマニア）、「高強度超短パルスレーザーによって誘起される非摂動相互作用の理論研究」、中嶋隆、G. Buica

ボルドー第 1 大学（フランス）、「超短レーザーパルスのチャープおよびキャリアエンベロープ位相依存の超高速非線形光学現象について」、中嶋隆、E. Cormier

上海光学精密機械研究所（中華人民共和国）、「高強度レーザー場によって生じる光イオン化における原子内クーロン力の影響について」、中嶋隆、J. Zhang

Advanced Energy Storage Research Section

Pacific Northwest National Laboratory (USA)、「フェライト鋼のヘリウム鋼脆化に関する検討」、木村晃彦、D.S. Gelles

韓国先進科学技術大学（大韓民国）、「酸化物分散強化鋼の開発研究」、木村晃彦、In-sup Kim

韓国原子力研究所（大韓民国）、「先進鉄鋼材料の照射効果研究」、木村晃彦、Jun-Wo Hong

UCSB（USA）、「次世代原子炉材料の開発研究」、木村晃彦、G.R. Odette

Russian Research Center, Kurchatov Institute（Russia）、「Irradiation effects on high Cr ODS steels」、木村晃彦、A. Ryazanov

UCSB（USA）、「Advanced ferritic stels R&D」、木村晃彦、G.R. Odette

PSI（Swizerland）、「In-situ creep behavior of ODS steels under ion irradiations」、木村晃彦、M. Pouchon

Pacific Northwest National Laboratory (USA)、「Multiscale Modeling of Radiation Damage Processes in Materials」、森下和功、H.L. Heinisch, F. Gao, R.J. Kurtz

東北大学金属材料研究所附属量子エネルギー材料科学国際研究センター、「ITER-TBM の作製に向けた低放射化フェライト鋼における照射影響評価」、木村晃彦、笠田竜太、大窪秀明、Cho Hang-Sik、奥田直之，藪内聖皓

東北大学金属材料研究所附属量子エネルギー材料科学国際研究センター、「軽水炉寿命延長時における照射脆化支配因子の検討」、木村晃彦、笠田竜太、大窪秀明、Cho Hang-Sik、奥田直之，藪内聖皓

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Hang-Sik、奥田直之，藪内聖皓

京都大学原子炉実験所、「原子力用鉄鋼材料の照射損傷蓄積過程に及ぼす合金元素・母相組織の影響」、木村晃彦、義家敏正、徐虬、笠田竜太、大窪秀明、奥田直之、高橋宏昌、藪内聖皓

九州大学応用力学研究所、「核融合炉材料のガス不純物挙動に関する研究」、森下和功、金田保則、加藤太治、坂口紀史、徐虬、渡辺淑之、岩切宏友、吉田直亮

核融合科学研究所、「核融合炉材料中の照射損傷過程のマルチスケールモデリング」、森下和功、金田保則、加藤太治、坂口紀史、徐虬、渡辺淑之、岩切宏友、吉田直亮

Complex Plasma Systems Research Section

Univ. Wisconsin（米国)、Univ. Wisconsin（米国)、ORNL（米国)、Max Planck Institute（ドイツ)、Provence Univ.（フランス)、CIEMAT(スペイン)、ANU（オーストラリア)、Kharkov Institute（ウクライナ)、SWIP（中華人民共和国)、「先進ヘリカルにおける改善閉じ込めの研究」、佐野史道、水内亨、長崎百伸、岡田浩之、小林進二、花谷清、D. Anderson、F.S.B. Anderson (Univ. Wisconsin), J.H. Harris (ORNL)、F. Wagner (Max Planck Institute), S. Benkadda (Provence Univ.), E. Ascasibar, C. Hidalgo, A. Baciero, B. Zurro, A. Cappa, A. Fernandez, V. Tribaldos (CIEMAT), B. Blackwell, H. Punzmann (ANU), V. Chechkin (Kharkov Institute), Q. Yang (SWIP)

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリカル閉じ込めの最適化のための双方向型共同研究」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリオトロン J を使ったヘリカル系におけるプラズマ電流の駆動機構の解明」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリオトロン J 装置における ICRF 加熱実験」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「ヘリオトロン J における改善閉じ込めに対する磁場構造の効果についての理論解析とその実験的検証」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

大学共同利用機関法人自然科学研究機構核融合科学研究所、「Heliotron J プラズマ中の中性水素および不純物挙動の研究」、佐野史道、水内亨、花谷清、長崎百伸、岡田浩之、小林進二

Advanced Energy Utilization Division

Chemical Reaction Complex Processes Research Section

カリフォルニア大学サンディエゴ校（米国）、「Rugate Structure Formation on Si and Its application to Chemical Sensing」、尾形幸生、M. Sailor

ノルウェー工科大学（ノルウェー）、「Surface and interfacial phenomena related to preparation of nanostructured materials」、作花哲夫、G. Oye

産業技術総合研究所、「液相レーザーアブレーションによるナノ構造体の創製」、作花哲夫、佐々木毅

Molecular Assemblies Design Research Section

ロンドン大学インペリアルカレッジ（連合王国）、「機能性高分子の合成」、佐川尚、Joachim H. G. Steinke

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吉川潔、戦略的創造研究(科学技術振興機構)、「人道的観点からの対人地雷探知･除去活動を支援するセンシング技術，アクセス・制御技術の研究開発」

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香山晃、奨学寄附金（宇部興産株式会社)、「SiC/SiC 複合材料に関する研究助成」

香山晃、双方向型共同研究（核融合科学研究所）、「レーザー核融合固体壁用 SiC/SiC 複合材料の超高温までの耐照射特性を含む基本データ整備と材料設計」

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檜木達也、共同研究（独立行政法人日本原子力研究開発機構)、「先進核融合炉構造材料の照射特性評価」

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木村晃彦、受託研究（科学技術振興機構）、「原子力システム高効率化に向けた高耐食性スーパーODS 鋼の開発の研究」

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笠田竜太、受託研究（科学技術振興機構）、「その場補修可能なナノ･マイクロ複合微粒子防食被覆法の開発」

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