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KURNS Institute for Integrated Radiation and Nuclear Science, Kyoto University

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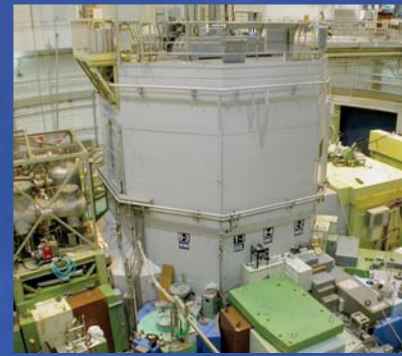





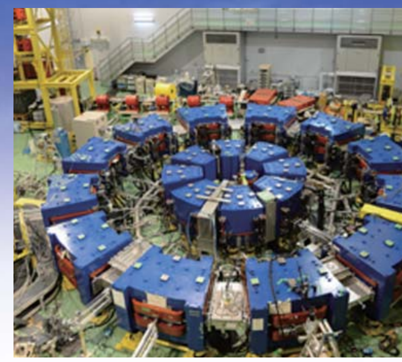

KURNS

Institute for Integrated Radiation and Nuclear Science, Kyoto University

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Preface

On 1 April 2018, the Research Reactor Institute was renamed the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS).

We will focus increasingly on the interdisciplinary research for further global development and aim to take a leading role in the study on nuclear science and uses of radiation.

We are renowned as an institute that provides access to large-scale facilities such as nuclear reactors and accelerators. Since we fostered to open our facilities to various experts and students for scientific breadth, we encompass diverse fields including physics, chemistry, biology, engineering, agriculture, environment and medical research.

We are proud that our cross-academic culture among internal and external scientists has developed uniquely for more than 50 years, producing many opportunities for personnel and information exchanges for new challenges.

We believe something new could be generated from a combination of different types of research fields. We will strategically arrange a new combination out of our cross-academic culture.

Meanwhile, one of the prime obligations as a university is to contribute to nuclear-educated human resources for mid- and long-term periods. We have carried out educational courses in reactors since 1975. We have programmed it such that students can actively take part in all the steps of the reactor operation in the Kyoto University Critical Assembly (KUCA), including fuel composition, loading, running of the reactor, and so on. The courses for each practical program are highly praised. In recent times, the number of participants, including international participation, has also greatly increased.

We are involved in the national science strategy. The Science Council of Japan(SCJ), which is the representative organisation for the Japanese scientist community, adopted our proposal in their MASTER PLAN 2017.

Our unique academic network and substantial human resources could provide scientists unexpected and unpredictable new fields and applications, thus engendering an infinite diversity of interdisciplinary research at KURNS.

Yuji Kawabata
Director

Institute for Integrated Radiation and Nuclear Science, Kyoto University

History

1956 Nov. The Preparatory Committee for the founding of a research reactor was organized with Prof. Hideki Yukawa as the first chair.
1958 Sep. The Kansai Committee was formed.
1960 Dec. Kumatori in Osaka was chosen to be the location.
Head office was formed in Kyoto University Engineering Laboratory (now Institute of Advanced Energy).
1961 Sep. Application for the foundation was filed.
1962 Mar. The application was accepted.
1963 Apr. The Research Reactor Institute was established as an Inter-University Research Institute and started as a Joint Research Institute. (Administration Office, Research Reactor, Workshop, Tracer Laboratory, Research Building, Waste Management Facilities and Guest House were completed. Further, six research divisions; Reactor Physics and Engineering, Reactor Facilities, Hot Laboratory Facilities, Scientific Instrument, Waste Management Facilities and Radiation Monitoring System were formed.) Prof. Kiichi Kimura became the first director.
1964 Mar. The Neutron Generator Room was completed.
June The Research Reactor reached the critical stage.
Aug. A nominal maximum power of 1000 kW was achieved.
1965 Jan. Joint research started.
1968 July The nominal maximum power was increased to 5000 kW.
1969 Mar. The Gamma-Ray Irradiation Laboratory was constructed.
Apr. The Reactor Thermal Properties Management Division was established.
1974 Mar. KUCA (Kyoto University Critical Assembly) was constructed.
Aug. KUCA reached the critical stage.
1975 Apr. The Reactor Utilization Center was opened.
1976 Apr. The Radiation Physics Division and Reactor Nuclear Properties Division were established.
May The Radiation Oncology Research Laboratory was constructed.
1977 Apr. The Technical Staff Office was established.
Nuclear Biology Division, Nuclear and Radiation Physics Division, Reactor Physics Division, Slow Neutron Physics Division, Radiochemistry Division, Reactor Chemistry Division and Reactor Chemistry and Engineering Division were further established.
1978 Oct. The application for constructing HFR was approved.
1982 Feb. The Environmental Radionuclide Laboratory was completed.
1986 Jan. The Spent Nuclear Fuel Laboratory was completed.
1995 Apr. The research divisions were entirely reorganized (16 research divisions were restructured as six research divisions: Nuclear Safety Research, Neutron Research, Nuclear Energy Science, Fuel Cycle and Environment, Applied Nuclear Science, and Radiation Life Science. 2 laboratories; Reactor Utilization Center and Radiation Oncology Laboratory were completed)
2003 Apr. The research divisions were entirely reorganized.
(Six research divisions were restructured as three research divisions: Nuclear Engineering Science, Quantum Beam Material Science and Radiation Life Science.)
2004 Mar. The Innovation Research Laboratory was completed.
2005 Apr. The Rediation Oncology Laboratory was reorganized as the Particle Radiation Oncology Research Center.
2006 Apr. The Reactor Utilization Center was reorganized as the Research Center for Safe Nuclear System.
2008 Apr. The Research Division of Advanced Neutron Therapy was established.(～2017 Mar.)
2010 Apr. The KUR low-enriched uranium core reached the first criticality.
2010 May The KUR low-enriched uranium core achieved the rated power of 5000 kW.
2017 Apr. The Research Division of Biochemical Gerontology (Endowed Research Section) was established.
2017 June KUCA has restarted under the new regulation rules after 3 years shutdown.
2017 Aug. KUR has restarted under the new regulation rules after 3 years shutdown.
2018 Apr. Kyoto University Research Reactor Institute (KURRI) was renamed Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS)

Organization

- **President**
  - **Director**
    - Executive Board
    - Director's Office
    - Staff Meeting
    - Advisory Board
      - Research Project Committee
      - Personnel Committee
      - Radiation Oncology Committee
    - Joint Study Advisory Board
      - Joint Study Committee
    - **Administration Office**
    - **Technical Staff Office**
    - **Division of Nuclear Engineering Science**
      - Research Reactor Safety
      - Nuclear Material Control
      - Radiation Control
      - Radioactive Waste Management
      - Nuclear System
      - Environmental Radionuclide Science & Engineering
      - Condensed-matter Chemistry in Actinides
      - Quantum Beam System (Guest Research)
    - **Division of Quantum Beam Material Science**
      - Neutron Material Science
      - Neutron Optics
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      - Particle Radiation Oncology
      - Particle Radiation Medical Physics
    - **Research Center for Safe Nuclear System**
      - Nuclear Disaster Prevention System
      - Accelerator Physics, Engineering and Applications
      - Thermal Energy System
    - **Head Office for Safety Management**
    - **Head Office of Academic Information**

ORGANIZATION 2018.10.1

Organization

Research Divisions

This institute has three divisions and two centers for scientific research: Division of Nuclear Engineering Science, Division of Quantum Beam Material Science, Division of Radiation Life Science, Research Center for Safe Nuclear System, and Particle Radiation Oncology Research Center.

These divisions and centers conduct progressive studies in various research fields, such as nuclear science, radiation utilization, beam science , nano-technology, material science, life science, and radiation oncology etc., and these serve as the basis for the collaborative researches done by the researchers coming from other universities and institutes.

All research laboratories cooperate in educating students of five Graduate Schools of Kyoto University: Graduate School of Engineering, Graduate School of Science, Graduate School of Energy Science, Graduate School of Agriculture, and Graduate School of Medicine.

Administration Office

The Administration Office of Institute for Integrated Radiation and Nuclear Science, Kyoto University is composed of 8 sections.

The structure of the Administration Office is as follows:

Administration Office
- General Affairs Section
- Joint Use Program Section
- Library Section
- Accounting Section
- Contract Section
- Facility Management Section
- Equipment Management Section
- Travel Expenses and Rewards Section

Head Office for Safety Management

In order to command and control the safety sections related to reactors, nuclear material facilities and radioisotope facilities, Head office for Safety Management is organized. The Head office also takes charge of security of the site. The director of this office may substitute for the Director for only safety and security issues.

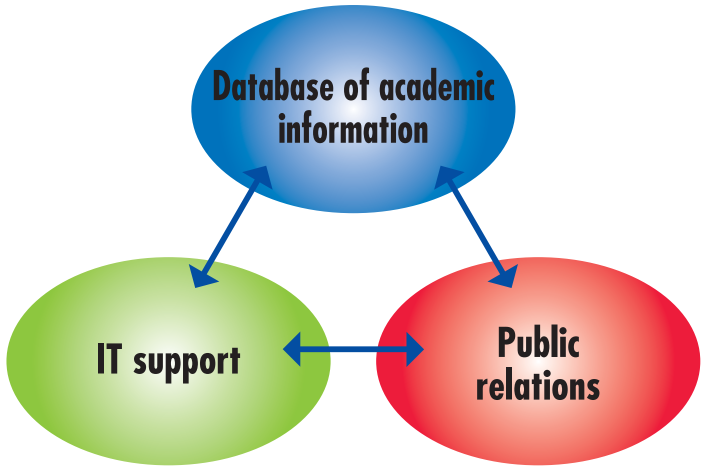
Head Office of Academic Information

This office supports the institute in information-related aspects. It has mainly three duties interrelated with each other.

1)Database of academic information: For example, the office maintains the information of research papers published by the staff members and through joint researches with researchers outside the institute. The library is a constituent unit of the office. Meeting the multidisciplinary character of the institute, it possesses a wide variety of research journals, books, and other documents, especially, related to nuclear science and engineering.

2)IT support: the office provides the platform for the website of the institute, and is making complicated paper works in the institute more IT based. Through the computer network, elec tronic journals and databases subscribed by Kyoto University are also available.

3)Public relations: the office introduces to the public the activi ties of the institute through web pages, by issuing several kinds of brochures and research reports, and by holding open lecture meetings, open campus, and also science schools.



Division of Nuclear Engineering Science

• Research Reactor Safety •
• Nuclear Material Control •
• Radiation Control •
• Radioactive Waste Management •
• Nuclear System •
• Environmental Radionuclide Science & Engineering •
• Condensed-matter Chemistry in Actinides •
• Quantum Beam System (Guest Research) •

Division of Nuclear Engineering Science

Research Reactor Safety

The Kyoto University Research Reactor (KUR) is a light water moderated, tank-type nuclear reactor, to utilize for general nuclear researchers cooperated by all Japanese university researchers. It is used as a strong neutron source, which is applicable for a broad range of research fields. Besides the KUR, a 46 MeV electron linear accelerator (LINAC) is used as a pulsed neutron source to measure the nuclear data by using the time-of -flight method.

Using these facilities, we are conducting the following research works:

1) Reactor physics and criticality safety
The experimental research works on reactor physics and criticality safety are conducted using the KUR and critical assemblies, and the research works on nuclear characteristics and safety for the next generation reactors are also carried out.
In addition, the improvements of numerical methods for reactor physics are conducted.
2) Measurement of nuclear reaction data (nuclear crosssection)
The nuclear cross sections of minor actinides and long-lived fission products are measured using the LINAC or the KUR, which are basic and important data for the researchers on nuclear reactors and nuclear transmutation.
3) Development of Non-destructive Methods Adopted for Integrity Test for Next generation nuclear fuels
The development of non-destructive methods for next generation nuclear fuels using a pulsed neutron source (LINAC) is conducted. Researchers can identify and quantify target nuclides in the nuclear fuels and observe temperature distribution in the nuclear fuels.

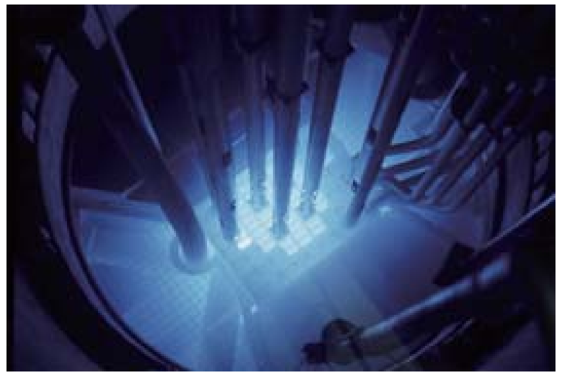


Fig.1 Core of KUR(Cherenkov Radiation)

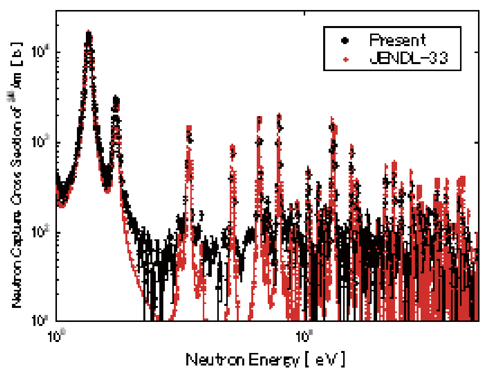


Fig.2 Neutron Capture Cross section of Am243

Nuclear Material Control

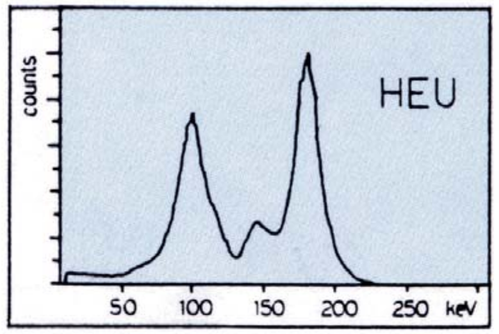
The activities of this laboratory are focused on optimum control and use of nuclear materials and development of innovative nuclear energy system to solve future energy issues. The current research subjects include:

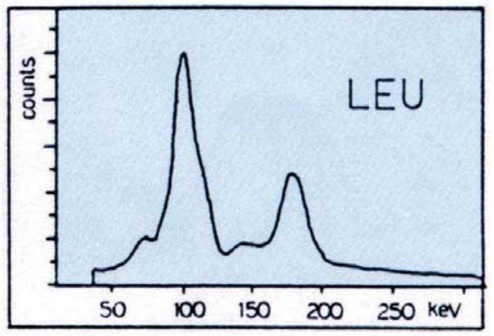
1. Study on innovative nuclear energy system with high potential on non- proliferation and nuclear material saving.
2. Study on energy policy issues, with special emphasis on the role of nuclear energy.
3. Study on nuclear material transportation, safeguards and physical protection methodology.

This laboratory is related to the Department of Socio-Environmental Energy Science (Energy Policy), Graduate School of Energy Science, Kyoto University. Most of the studies conducted in this laboratory are made from the viewpoint of socio-technological interest, which we believe is inevitable for discussing the role of nuclear materials as energy resource today and in the future.

As practical studies based on the above mentioned themes, the following topics are performed with collaboration with Office of Nuclear Material Management:

1. Regulatory guidance for the receipt/shipment, use and storage of nuclear material.
2. Education and training on the handling of nuclear material.
3. Actual management including physical protection and transportation measures concerning nuclear material.
4. Enrichment reduction and removal methodology of the high enriched nuclear fuel for research and test reactors.
5. Cooperation with the IAEA inspections.





Gamma-Ray Spectra of High Enriched Uranium (HEU) and Low Enriched Uranium (LEU).

Radiation Control

Researches on the 'Radiation Safety Control' are essential and important for the safety of nuclear industry workers and surrounding public. In this laboratory, following subjects are carried out with collaboration of multi-disciplinary researchers including technology, biology, environmental science, and medicine.

1) Research on Radiation Safety in Surrounding and the Nuclear Plant:
Advanced radiation safety management systems and control procedures are studied using experiences with the KUR and KUCA. Additionally, the level and movement of radon gas is also investigated as a model.
2) Behavior and Kinetic of Radionuclides Originating from Nuclear Waste in Soil and Plants:
With relation to the disposal of nuclear waste, there is anxiety regarding the accidental release of radionuclide into the environment. It is necessary to accumulate fundamental parameters for evaluating the movement of radionuclide and for assessing the adverse effects on the human health. We are focusing so far on the modeling of transfer of radio-carbon from soil to plant.
3) Measurement and Control of Induced Radioactivity in Nuclear Plants and Accelerators:
The induced radioactivity is an important issue for radiation protection, but the detail data has not been sufficient yet. Here, the radionuclides induced by neutron and charged particles are measured in a few nuclear and accelerator facilities and the cross-sections were obtained to evaluate residual activities.
4) Health Effects and Risks of Radiation and Radioactive materials:
The health effects of radiation, especially neutron for boron neutron capture therapy, are investigated in in-vitro as well as in vivo systems from a view point of radiation safety and protection. In addition, the combined effects of radiation with those of environmental toxicants are also studied.

Fig.1 Scintillation light from plastic materials with excitation by UV light and ionizing radiation.

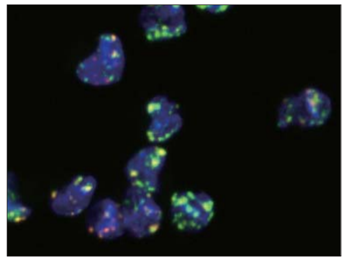
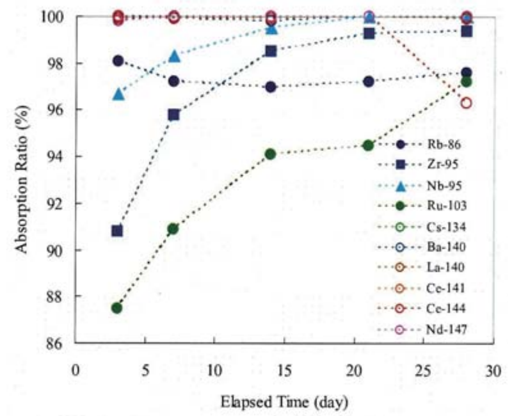


Fig.2 Focus formation of 53BP1, repair protein of DNA double strand breaks, in the Chinese hamster ovary (CHO) cells.

Radioactive Waste Management

Careful attention must be paid to manage radioactive waste because of its special property for radiological safety. Investigated topics on liquid waste treatment are as follows: dehydration/immobilization of high salt-content concentrate arising from evaporation treatment. Migration of radionuclides through soil has also been studied to evaluate its influence on the safety of waste disposal sites. Monitoring of radioactivity contamination from nuclear facilities has been performed for evaluating environmental impact. In addition, we have been analyzing various aspects of demerits of nuclear energy. Detailed research topics are as follows:

1) Measurement, Decontamination and Treatment of Radioactive Pollution from Nuclear Facilities
Radionuclides including Cs-137 were released to the environment by nuclear facilities accidents. For decontamination and treatment of radioactive pollution, new types of sorption medium are been investigating.
2) Fundamental Research on Waste Disposal
Radionuclides in waste materials were disposed of on land. They reach the food chain via surface and underground water, resulting in public risk and potential health hazard. Absorption tests with a multi-tracer produced at the KUR is conducted for fundamental study of radionuclides migration in soil.
3) Risk Assessment of the Use of Nuclear Energy
One of important issue, in which our society is now involved, is whether we should depend on nuclear energy or not. In order to find a reasonable answer to this issue, it is necessary to clarify merits and demerits accompanying the use of nuclear energy. We have been analyzing various aspects of the demerits including radiological consequences of the nuclear accidents.



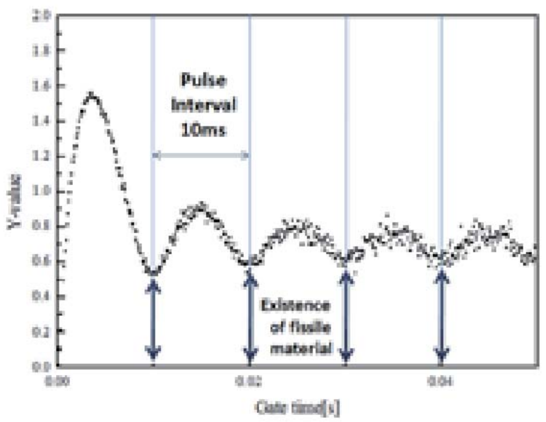
Changes in adsorption ratio of multitracer with elapsed time.

Division of Nuclear Engineering Science

Nuclear System

To realize an innovative nuclear system with enhanced safely and high efficiency, this laboratory is performing basic studies on the nuclear characteristics of nuclear systems, which are subject to neutron transport and nuclear reactions. Also, new neutron and gamma-ray measurement methods have been investigated to apply for nuclear security purpose based on technique used for reactor experiments. Those research works have been mainly based on reactor physics experiments using the Kyoto University Critical Assembly (KUCA) and the Kyoto University Research Reactor (KUR), the current research subjects of this laboratory are as follows:

1. Nuclear characteristics of next generation reactors, such as thorium fueled reactors, reactors for incinerating long-lived radioactive elements.
2. Development of accelerator driven system.
3. Criticality safety in the nuclear fuel cycle, especially development of subcriticality measurement method, which can be used for decommissioning of damaged Fukushima NPP.
4. Development of detection system for hidden illicit materials by new radiation detecting techniques.



Subcriticality measurement experiment at KUCA combined with pulsed neutron source by neutron noise analysis method

Environmental Radionuclide Science & Engineering

1) Investigation of the Behavior and Remediation Technology of Radioactive and Non-Radioactive Pollutants in the Environment:

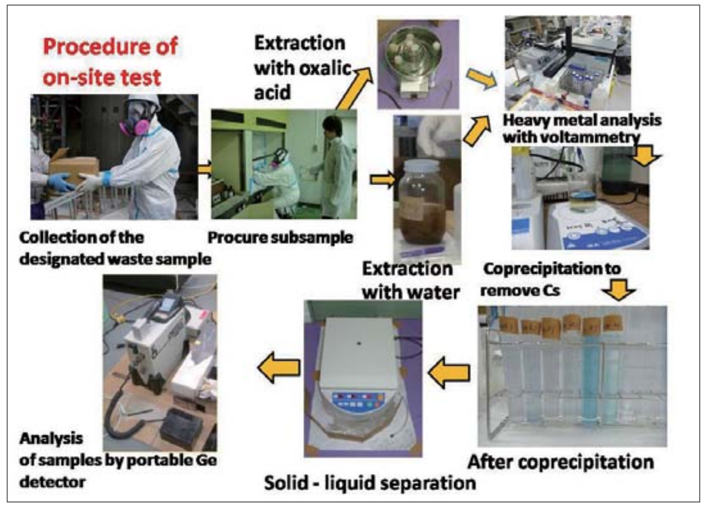
We have investigated the behavior of radioactive and non-radioactive pollutants, as well as environmental remediation technologies, with special focus on the geo-hydrological environment.

Our research activities encompass the laboratory test to clarify the distribution of pollutants among geological media, water, and living plants etc., development of analytical methods to determine the concentration and chemical speciation of pollutants as well as the application of the developed method, field research of distribution radioactive Cs, U and Pu isotopes, development of decontamination technologies for soil and water, contaminant transport modeling, and safety assessment of radioactive waste disposal.

2) Toward the Safe Disposal of Nuclear Wastes and Municipal Solid Wastes Contaminated with Radioactive Cesium from the Fukushima Accident:

Wastes are inevitable products of everyday life as well as industrial and agricultural activities. Once generated, wastes have to be disposed after appropriate pretreatment, but the siting of waste landfill has always been a big challenge. This is especially true for wastes containing radioactive materials. To contribute to the safe disposal of radioactive wastes, we have conducted basic study on the transport and distribution of important radionuclides originating from nuclear wastes (e.g., I-129, Se-79, Cs-135, Co-60, uranium isotopes and transuranium elements) in the geosphere.

The Fukushima Daiichi Nuclear Power Plant accident in 2011 has created an entirely new dimension in environmental problems: radioactive cesium (rad-Cs hereafter) contamination of the general environment. The contamination has lead to the generation of huge amount of removed soil from clean-up work and municipal solid wastes, both containing rad-Cs. Our most recent research activities are related to the volume reduction of such wastes. In particular, we have investigated a technique that washes the waste (rad-Cs > 8,000 Bq/kg, so-called designated waste) with aqueous solvents to extract rad-Cs, and removes the extracted rad-Cs using hexacyanoferrate coprecipitation procedure. We have conducted on-site tests to prove the effectiveness of the technique (images of the test are shown below).



Condensed-matter Chemistry in Actinides

Condensed-matter chemistry in actinides reveals hidden nature of 5f-electrons which encompass application of actinides such as nuclear medicine, MA separation and/or storage etc.

Fig. 1 Condensed-matter chemistry of actinides for stable storage, nuclear medicine, etc

Quantum Beam System (Guest Research)

This guest research division is prepared to invite and to exchange state-of-the-art research information with leading and remarkable scientists in various research fields related to nuclear safety.

Division of Quantum Beam Material Science

- • Neutron Material Science •
- • Neutron Optics •
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- • Nuclear Radiation Physics •
- • Radiation Material Science •
- • Materials Radiation Effects •
- • Isotope Production and Application •

Division of Quantum Beam Material Science

Neutron Material Science

The neutron is a powerful probe for the study of condensed matter (disordered [amorphous, glass], crystalline, non-equilibrium, and nanocomposite materials) in the world around us. Neutron scattering gives detailed information about atomic level structure and dynamics, that is, where atoms are and how they are moving. Neutrons used in our experiments have wavelengths that are similar to atomic spacing, allowing the structures of materials to be studied by diffraction on scales from atomic dimensions to macromolecular scales. At the same time, the neutrons have energies similar to those of atomic processes like molecular transitions, rotations, vibrations, and lattice modes.

Recently, the subject of our group is focused on getting structural information of functional materials: rechargeable batteries, hydrogen storage materials, air-separating membranes, cement clinkers, etc. In particular, three dimensional locations of light atoms, lithium and hydrogen, in the condensed matter can be precisely determined by the Rietveld and pair distribution function (PDF) analyses, and the reverse Monte Carlo (RMC) modeling based on neutron and X-ray diffraction data (Fig. 1). Moreover, from a viewpoint of dynamics of water, the hydration reaction in cement paste can be observed using the quasi- elastic neutron scattering (QENS) technique, by taking advantage of the difference in diffusion constant between free and bound water (Fig. 2).

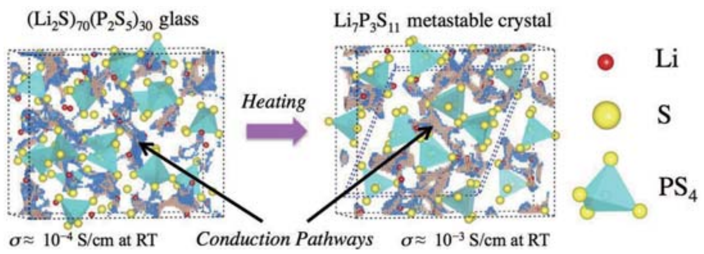


Fig.1. Three-dimensional structures of $(Li_2S)_{70}(P_2S_5)_{30}$ glass and $Li_7P_3S_{11}$ metastable crystal, which are a lithium ion conductor. The electrical conductivity of $Li_7P_3S_{11}$ is approximately one order of magnitude larger than that of $(Li_2S)_{70}(P_2S_5)_{30}$ glass.

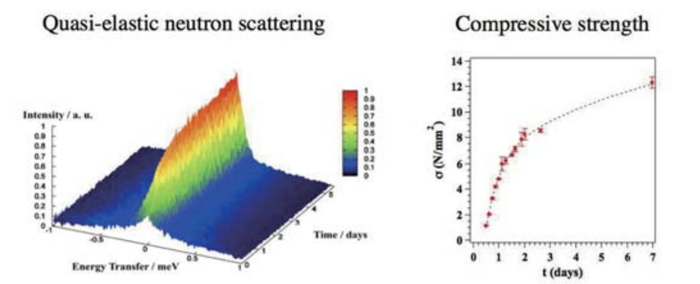


Fig.2. Time evolution of quasi-elastic neutron scattering (QENS) spectrum of cement paste.

Neutron Optics

Slow neutrons are very powerful and useful in various research fields, such as material and life sciences, particle physics, fundamental engineering. It is necessary for production of neutron beam to use any nuclear reaction and it requires, in general, large facility to obtain high intensity of the neutron beam. More and more intensity is still desired even in advanced large facility. Neutrons are electrically neutral and it is very difficult to control (bent). It is quite important for transportation and shaping of neutron beam from the source to the experimental instrument. We are developing various neutron optical devices, in particular high performance neutron multilayer mirrors, to control slow neutrons and analyze neutron spin precisely.

Kyoto University and the High Energy AcceleratoResearch Organization (KEK) are jointly installing neutron resonance spin echospectrometers at BL06 at J-PARC MLF. We named the spectrometers “VIN ROSE” (VIllage of Neutron ResOnance Spin Echo spectrometers), which will spawn a new field of spectroscopic methods to investigate the slow dynamics of nanostructures in various materials. All neutron mirrors were fabricated and tested in our laboratory.

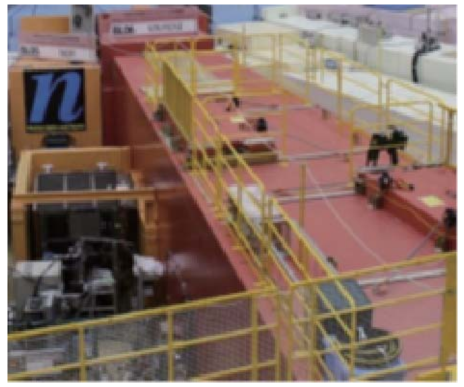


Fig.1 Photographs of the VIN ROSE at BL06 at J-PARC MLF.

Neutrons have strong penetrating characteristics and it is powerful tool to investigate the behaviors of water in various interesting materials, such as advanced industrial parts, concrete, moisture changes in plants, archeological samples.

We are exploring the new fields of neutron imaging (radiography) with advanced neutron optics.

Furthermore we are also developing various luminescent plastics reactive to ultraviolet rays and radiation for promoting the development of inexpensive and highly sensitive radiation detectors.

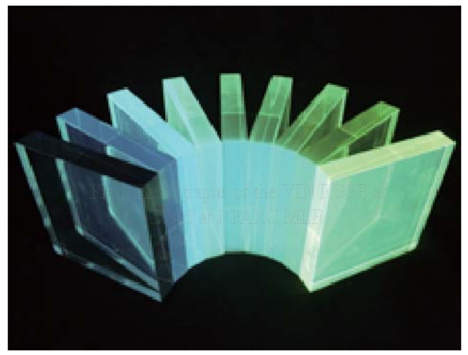


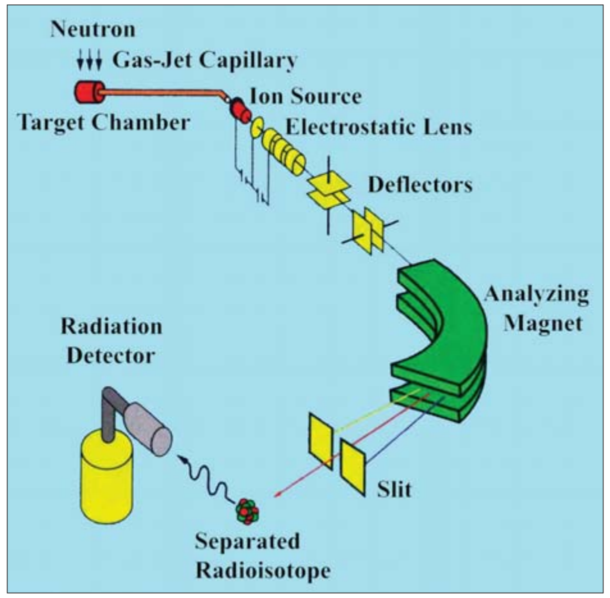
Fig.2 Photographs of the luminescent plastics reactive to ultraviolet rays.

Division of Quantum Beam Material Science

Nuclear Beam Material Science

This laboratory conducts production and advanced uses of ion beams of short-lived nuclei. By using the nuclear beam facility which is based on the gas-jet on-line isotope separator (ISOL), systematic studies on new isotopes in the rare-earth mass region have been intensively performed and five new isotopes were identified so far in this laboratory. Precise measurements have been made to obtain nuclear data such as half-lives, $Q\beta$-values, γ-ray energies and intensities on neutron-rich nuclides in collaboration with Nagoya and Tokushima University groups.

Advanced utilization of the nuclear beam for material science is another important research subject of this laboratory. By implanting the radioactive probe atoms from the nuclear beam facility, electromagnetic properties of a variety of materials such as zinc oxide and silver iodide have been investigated with the perturbed angular correlation (PAC) method in collaboration with research groups of Kanazawa University and National Institute of Technology, Ichinoseki College. Measurements of magnetic moments of unstable nuclei have also been carried out.

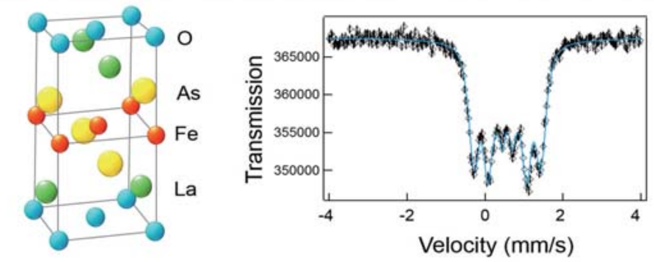


The outline of the nuclear beam facility based on the on-line isotope separator for fission products. A post accelerator is attached to implant separated ions deeper into materials.

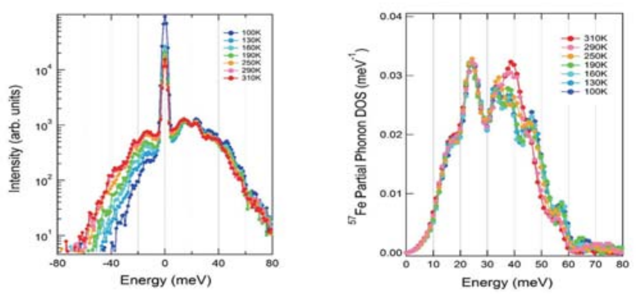
The nuclear beam facility with two beam lines; nuclear study course with a tape collector (left side) and material study course with a post accelerator (right side).

Nuclear Radiation Physics

In recent condensed matter physics, nuclear methods have been actively applied and offered many fruitful results. Mössbauer spectroscopy is one of the most useful and effective nuclear methods, where nuclear resonant excitation process is used. The nuclear resonant excitation is attained with γ-rays from radioactive isotopes generated by reactors and accelerators, and also with synchrotron radiation. In this spectroscopy, the electronic states are analyzed through changes in the nuclear energy levels affected by hyperfine interactions. Using this spectroscopy, we have studied various materials: high-Tc superconductors, conducting organic polymers, low-dimensional conducting materials and biological materials. Furthermore, we have successfully developed the nuclear resonant inelastic scattering spectroscopy with synchrotron radiation, for the first time. We are investigating further possibilities of nuclear methods and are applying them to the condensed matter physics. In addition, by using electron linear accelerators, the nature of X-rays emitted through interactions between relativistic electrons and crystals – especially parametric X-ray radiation and coherent bremsstrahlung – is investigated.



^{57}Fe Mössbauer spectrum of LaFeAsO, which is the parent material of iron-pnictide superconductors.



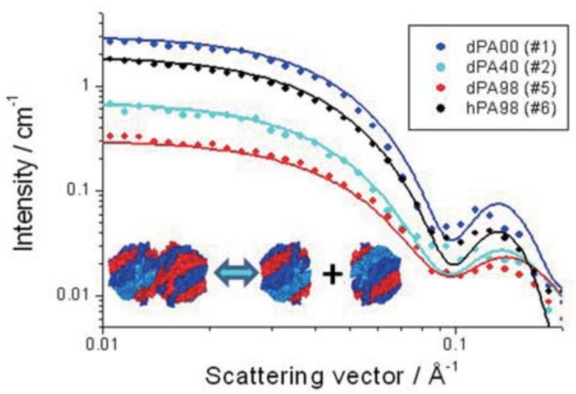
Temperature dependence of the nuclear resonant inelastic scattering spectra of iron perovskite $CaFeO_3$, which exhibits charge disproportionation (left), and the temperature dependence of phonon densities of states obtained from the nuclear resonant inelastic scattering spectra (right).

Radiation Material Science

It is well known that a material structure and its dynamical character are deeply related. The interaction between the constituents determines the material structure and the dynamical character is a response of the structural interaction against the external disturbances. In the case of a functional material with a nano-scale structure, it is essential to reveal a mechanism of function to understand its dynamical character based on the structure. Along this line, this research group studies the static and dynamical structures of functional materials with nano-scale structures such as supercritical fluid, polymer aggregates, gel and protein.

Main methods to measure nano-scale structure are scattering techniques with X-ray or neutron: especially, neutron scattering utilizing its ability identifying isotopes, proton and deuteron, is a very powerful tool to reveal a quaternary structure of protein. Recently, we reveal a state of PA28 (Proteasome Activator 28) in an aqueous solution: PA28 is a regulator protein of the 20S proteasome, which is protease for an ubiquitinated protein. Figure 1 shows the SANS analysis of the state of PA28 in an aqueous solution. The structural simulation well reproduces the experimental SANS profiles.

In addition, we are developing a spectrometer and analyzing methods. Therefore, we are joining the TAIKAN project (SANS in J-PARC) and also developing a SANS and SAXS simulation with RMC algorism.



Structural model, SANS profiles. Circles denote experimental data and lines show the result of the simulation.

Materials Radiation Effects

Irradiation of high energy particles induces the interaction with atoms in solids and the loss of their energies. In this division, we perform (1) understanding irradiation effects for various materials such as metals and semiconductors, (2) developments of neutron, ion and electron irradiation facilities, (3) research on characterization techniques for irradiated materials using positron annihilation spectroscopy and electron microscopy, and (4) numerical simulation for interactions of irradiation-induced defects.

As high-energy particle irradiation techniques, neutron irradiation at high temperatures by Material Controlled Irradiation Facility (SSS) of Kyoto University research Reactor (KUR), and irradiation at low, ambient and high temperatures by an electron linear accelerator (KURRI-LINAC). Further developments of irradiation facilities using a heavy-ion accelerator are in progress.

As surface characterization techniques for irradiated materials, a reactor-based slow positron beam system using KUR is under development. This system is one of the most advanced facilities in the world and has been developed for positron annihilation lifetime spectroscopy, Doppler broadening, and coincidence measurements with these analytical techniques. Other analytical techniques such as radioisotope-based positron annihilation lifetime spectrometry have been used for applied research for various materials.

It is expected that research in this field promotes materials developments for new-type nuclear systems and fusion reactors. In addition, it is possible to get information on damage mechanism and lifetimes of nuclear materials under neutron irradiation, irradiation-damage reduction in semiconductor device processes and irradiation-induced new-material synthesis.

Reactor-based slow positron beam system at the KUR B1 hole.

Division of Quantum Beam Material Science

Isotope Production and Application

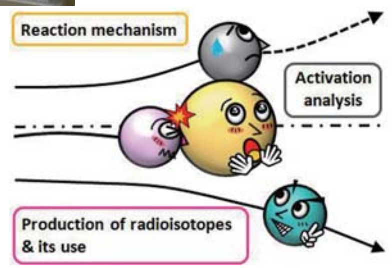
Our group produces several radioisotopes using KUR and some accelerator facilities and uses them to study 1) radioactive aerosols, 2) trace elements of materials, and 3) nuclear reactions in the field of natural sciences including chemistry and physics.

1) Study on formation mechanism of radioactive aerosol A large amount of radioactive materials have been released as radioactive aerosols to the atmosphere during Fukushima nuclear disaster. However, their properties and generation mechanism have not been elucidated. We have studied the chemical and physical properties of radioactive aerosols by generating radioactive aerosols using radioisotopes to elucidate the generation mechanism. And from the viewpoint of radiation protection, we study property and formation mechanism of radioactive aerosols (airborne nano particles) formed in radiation fields of radiation facilities, especially in accelerator facilities using various radiochemical techniques. In addition, we develop a convenient technique for particle size measurement of radioactive airborne fine particles.

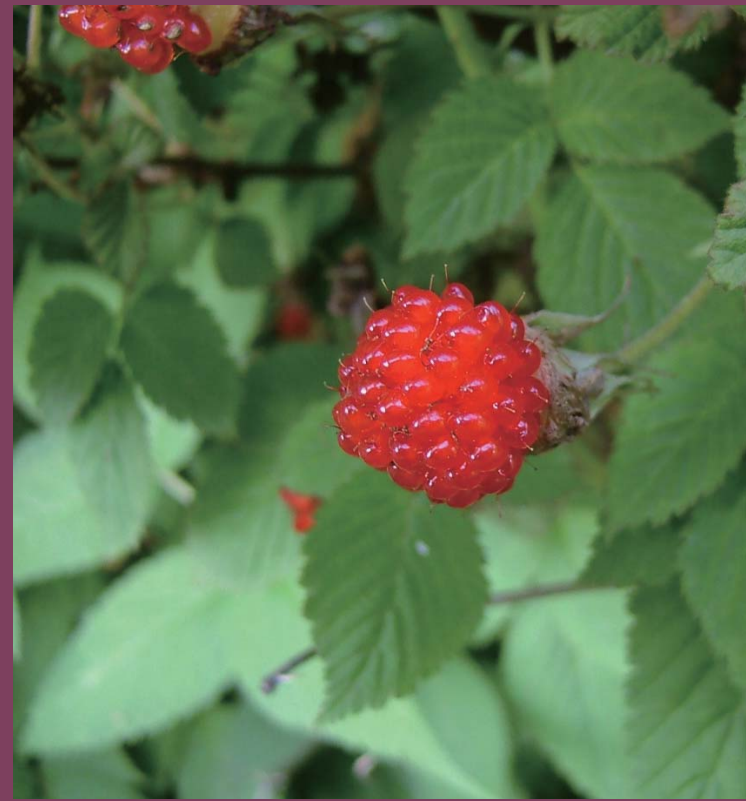
2) Neutron activation analysis (NAA) of cosmic and terrestrial samples To determine trace amount of elements with high accuracy and sensitivity, we apply the NAA method using KUR to various samples; mantle xenolith specimens to search for inner earth objects, shale rocks that is a potential energy source in the near future, and cosmic samples. Using this method, impurities are determined and evaluated in some kinds of semiconductor materials to make them work with high-performance.

3) Study of nuclear reaction mechanism and the isotope production and use using nuclear reactor and accelerators Nuclear reaction mechanism for intermediate and heavy nuclei such as nuclear fission and spallation/fragmentation is studied in cooperation with other groups using ion-beam accelerators and nuclear reactor. We investigate those reaction mechanisms with various energy regions systematically. As further applicative study of nuclear reactions using electron and ion-beam accelerators, we carried out the precise life-time measurements of characteristic radioisotopes such as radioactive beryllium, basic research for medical use of radioactive scandium, copper, etc. and isotope-production and its use as tracers in the environment study.

Ge detector with auto sample changer



Chemistry, physics, geology and environment come together to understand nuclear reactions.



Division of Radiation Life Science

• Radiation Biochemistry •
• Particle Radiation Biology •
• Biomolecular Structure •
• Biochemical Gerontology •
(Endowed Research Section)

Division of Radiation Life Science

Radiation Biochemistry

In our research field, the biological effects caused by radiation are studied separately on molecular, cell and individual scales. At the molecular level, we are studying the damage of the protein caused by radiation and its following physiological influence. Reactive oxygen species, which is produced by collision of radioactive rays with water molecules in our body, affect various biological macromolecules. In particular, DNA base damage is well known, but it has also been pointed out that the formation of D-isomer of aspartic acid residues (Asp) also occurs in proteins. As D-Asp was actually found in the causing protein related to age-related diseases, such as Alzheimer's disease and cataracts, it was suggested that D-Asp formation causes the pathological degeneration of normal proteins. On the other hand, there is some evidence to suggest the existence of an unknown signal transduction system, which physiologically utilizes small-scale conformational change by the formation of D-Asp exist. We are currently working to prove this. D-Aspartyl endopeptidase, which is a specific degrading enzyme for the D-Asp-containing protein was discovered in the above research process, would be not only a quality control mechanism for denatured D-Asp-containing proteins, but would also negatively control the signal transduction system. Therefore, its enzymological properties are investigated in detail. Further, in order to elucidate the fundamental defense mechanism of living organisms at the cellular level, the acquisition mechanism of radioresistance in bacteria and the sorption mechanism of radioactive cesium by microalgae are studied. At the individual level, we are constructing a biological effect assessment system of low dose and long term exposure by radioactive cesium using silkworm as a model animal. It is the philosophy of our research field to develop cross-disciplinary research to the results obtained at each biological scale and deepen the understanding of the biological effects of radiation.

In addition, we are working on elucidating the physiological function of boron in plants utilizing the neutron capture reaction of boron-10 for the effective use of nuclear power other than generating electricity. Boron is an essential nutritional element for all plants. However a deficiency or an excess of boron causes various growth disorders in them. For all those disorders of crops due to boron-toxicity that occur frequently world-wide, drastic solutions have not been prepared, because a boron analysis method with high resolution has not been well-developed yet and we have a poor understanding of the physiological function of boron in plants. In order to collect multidimensional information on how much boron is localized in which tissue/cell at any stage of growth, *in situ* visualization technique capable of detecting the localization of boron with high resolution is being developed by applying α-autoradiography with solid-state nuclear track detector, CR-39. We expect that this technique will contribute to the establishment of the nutritional diagnosis method for boron in plants.

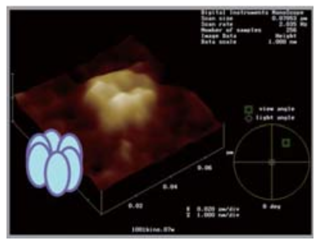


Fig. 1. 3D image of D-Aspartyl Endopeptidase particle analyzed by atomic force microscopy. A proposed model is drawn.

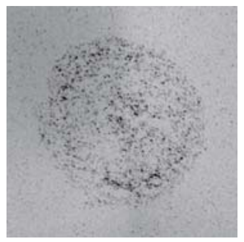
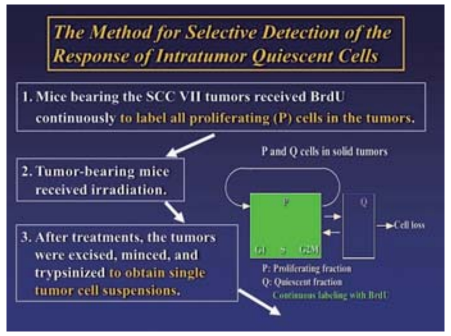


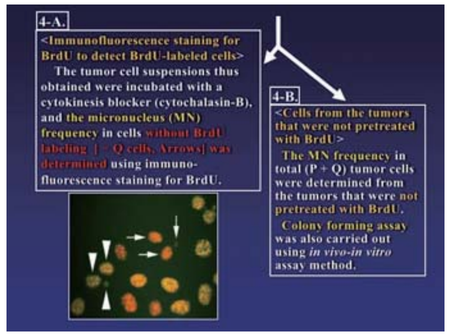
Fig. 2. Autoradiography indicating the localization of boron in radish.

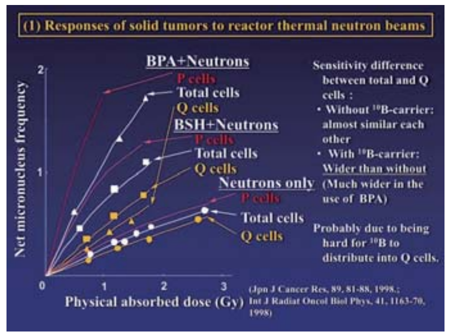
Particle Radiation Biology

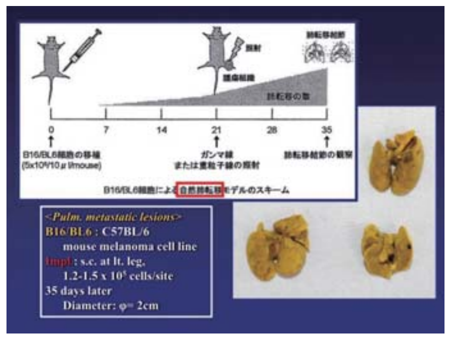
For supporting the development of cancer therapy , we are carrying out basic research in biology , bioscience and medical science, especially focusing on BNCT (Boron Neutron Capture Therapy) that have been performed at Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS) actively for these tw entyfifive years.

Our research highlights are on: DNA repair and intracellular mechanism, evaluation of anticancer treatment through detecting the susceptibility of solid tumors, impact on distant metastase through controlling local tumor , screening for newlydeveloped boron capture agents for BNCT , and so forth. At KURNS, some researchers in the fifield of engineering or chemistry are studying on biological matter. Based on the current status of our research backgrounds, we also have a plan to collaborate them to launch a new project for searching novel scientifific fifindings on BNCT .









Biomolecular Structure

The crystal structure analysis by quantum beams, X-ray, synchrotron and neutron, is the most powerful technique to investigate and clarify the structure and function of bioor supramacromolecule at the atomic resolution, and its effect is more accelerated by collaboration with other methods, such as electron diffraction or cryoelectron microscopic methods. We have concentrated on X-ray and neutron studies of structural biology of the macromolecule from viewpoints of hydrogen atoms and bonds, strategic structural research for protein complexes under the crystal and/or solutions, the structure of various kinds of polymeric or drugs. Also we have actively collaborated with other highflux neutron facilities: J-PARK(Tokai), SNS-HFIR(OakRidge), ANSTO(Australia), and SLS(Swiss), Spring-8(Harima), PF(Tsukuba) synchrotron radiation sources.

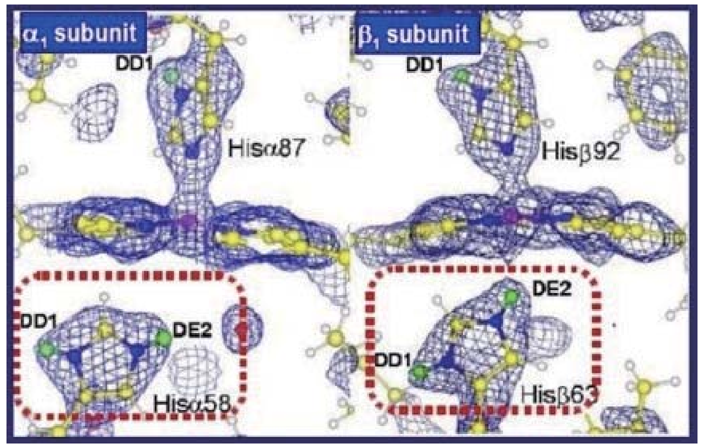
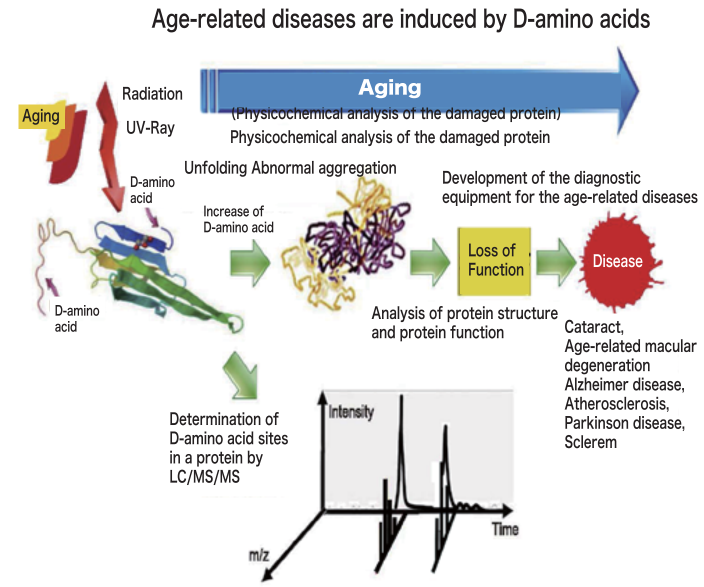


Fig. 1. Deuterium in the human blood hemoglobin molecule by crosssection density maps calculated from neutron diffraction data.

Biochemical Gerontology (Endowed Research Section)

Aging-associated diseases, including cataracts, agerelated macular degeneration, Alzheimer disease, atherosclerosis, Parkinson disease, sclerema are called the protein folding diseases. One of the cause of the diseases due to the misfolding and aggregation of the proteins in the tissues. Recent studies show that these damaged proteins contain biologically uncommon D-aspartate (D-Asp). The presence of D-Asp in aged tissues of living organisms is a result of the spontaneous racemization of Asp residues during aging. The appearance of D-Asp isomers in a protein can cause major changes in the 3-D structure because the different side chain orientation may induce an abnormal peptide backbone. That's why the D-Asp is a useful aging molecular maker. The aim of our research is to 1) elucidate the correlation between the posttranslational modifications including racemization, oxidation, deamidation, and loss of protein function, 2) find the molecular marker of the agerelated diseases, 3) develop the noninvasive diagnostic equipment for the agerelated diseases before the onset.



Particle Radiation Oncology Research Center

• Particle Radiation Oncology •
• Particle Radiation Medical Physics •

Research Center for Safe Nuclear system

• Nuclear Disaster Prevention System •
• Accelerator Physics, Engineering and Applications •
• Thermal Energy System •

Particle Radiation Oncology Research Center

Particle Radiation Oncology

Boron neutron capture therapy (BNCT) has a unique feature which can deliver tumor-cell selective heavy-particle irradiation (Fig.1, 2). This feature makes BNCT possible to deal with patients suffering from malignant tumors that are refractory to conventional radiotherapy and particle radiotherapy (Fig. 3). Since 1990, reactor-based BNCT (RB-BNCT) greater than 500 have been carried out by our center in collaboration with outside researchers in medicine.

In 2008, accelerator-based BNCT system (AB-BNCT system) was constructed in KURRI. Using this system, clinical trials of BNCT for recurrent malignant brain tumors and head and neck tumors have been started since October in 2012 and April in 2014, respectively. Development of an AB-BNCT system is an important first step for a future in which BNCT will be available in the hospital equipped with AB-BNCT system.

The mission of this division is to make BNCT a safe and effective treatment option for the patients suffering for refractory or recurrent tumors. The main practical and research subjects are as follows;

1) Clinical trial using AB-BNCT system.
2) RB-BNCT for common cancer.
3) Research on effect of BNCT for normal organs or tissues.

Particle Radiation Medical Physics

Medical physics is the general term for the physics and technology which are supporting medicine, especially radiation therapy and particle therapy. As it covers many different fields, the important subjects are "promotion for the advance of radiation therapy" and "quality assurance for radiation therapy". Our group is focusing on "boron neutron capture therapy (BNCT)", which is one kind of particle therapies. We are studying mainly about the following subjects for the advance of BNCT, in corporation with Particle Radiation Oncology Research Center.

1) We are studying about the advance of the BNCT irradiation systems, based on the clinical experience at the Heavy Water Neutron Irradiation Facility of KUR. We are also performing the design studies for accelerator-based irradiation system, which is superior to the reactor-based irradiation system in availability.

2) We are developing the separative estimation methods for four components such as thermal neutron (<0.5 eV), epi-thermal neutron (0.5 eV to 10 keV), fast neutron (>10 keV) and gamma ray. Our final goal is the completion of the real-time system for two-dimensional and/or three-dimensional dose estimation under BNCT.

3) The recent wider application of BNCT uplifts the recognition degree of this therapy, and then BNCT is possible to become a universal therapy. On these backgrounds, we are establishing the quality assurance for BNCT, such as the standard dosimetry for the irradiation field, the dose estimations for pre- and post-treatment, the external and internal exposure estimation for patient, etc.

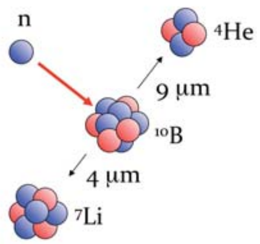


Fig.1.Boron neutron capture reaction. Non-radioactive isotope, ^{10}B atom, absorbs low energy (<0.5 eV) neutrons (thermal neutron) and disintegrates into an alpha (^{4}He) particle and a recoiling lithium nucleus (^{7}Li). These particles deposit large energy along their very short path (less than 10μm).

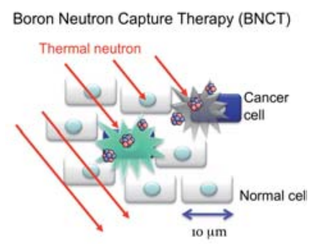
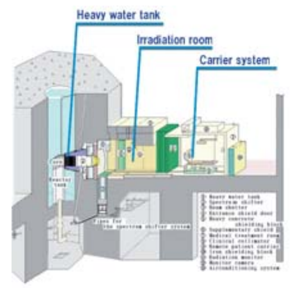
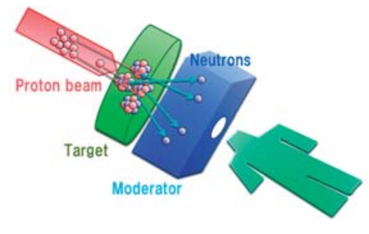


Fig.2 Boron neutron capture therapy (BNCT).
Boron neutron capture reaction can destroy tumor cells selectively due to extremely short ranges of the particles.



KUR Heavy Water Neutron Irradiation Facility.



Outline of the accelerator-based irradiation system.

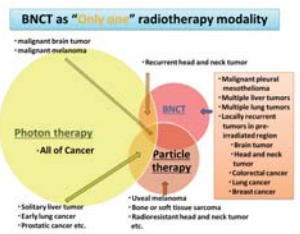
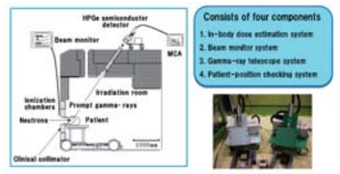
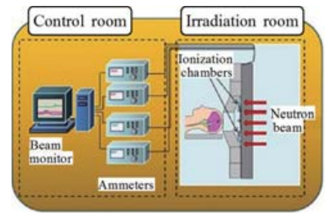


Fig.3 BNCT as "Only one" radiotherapy modality.
BNCT can treat multiple or diffusely spread tumors in radiosensitive organs such as lung and liver. BNCT can be applied to the recurrent tumor in the pre-irradiated lesion.



Dose estimation joint-system.



Multi ionization chamber system.

Research Center for Safe Nuclear System

Nuclear Disaster Prevention System

Energy-related buildings such as nuclear power plants and high-rise apartments are significant structures that constitute the very foundation of our society, life, and infrastructure, and they have a massive impact on the surrounding environment. Therefore, they require much stricter earthquake safety standards, as an overview of the damage caused by recent major earthquakes has confirmed. Additionally, studies suggests that southwest Japan has entered into a period of considerable seismic activity that began after the 1995 Hyogoken-Nanbu Earthquake（Great Hanshin-Awaji earthquake） and that this period would likely continue up to or through the next set of Nankai megathrust earthquakes.

In order to contribute to the advancement of the earthquake safety evaluation for the above mentioned buildings, we are mainly conducting research on the following three subjects: (1) evaluation of the degree of structural damage and its evaluation method, (2) evaluation of the foundation input motion with spatially-variation seismic motions and soilstructure interaction and (3) strong ground motion prediction and modeling and exploration method of subsurface structure used for the prediction. In our laboratory, we pursue a wide variety of earthquake engineering studies that range from fieldwork with observation data collection and analysis to numerical simulations based on physical models.

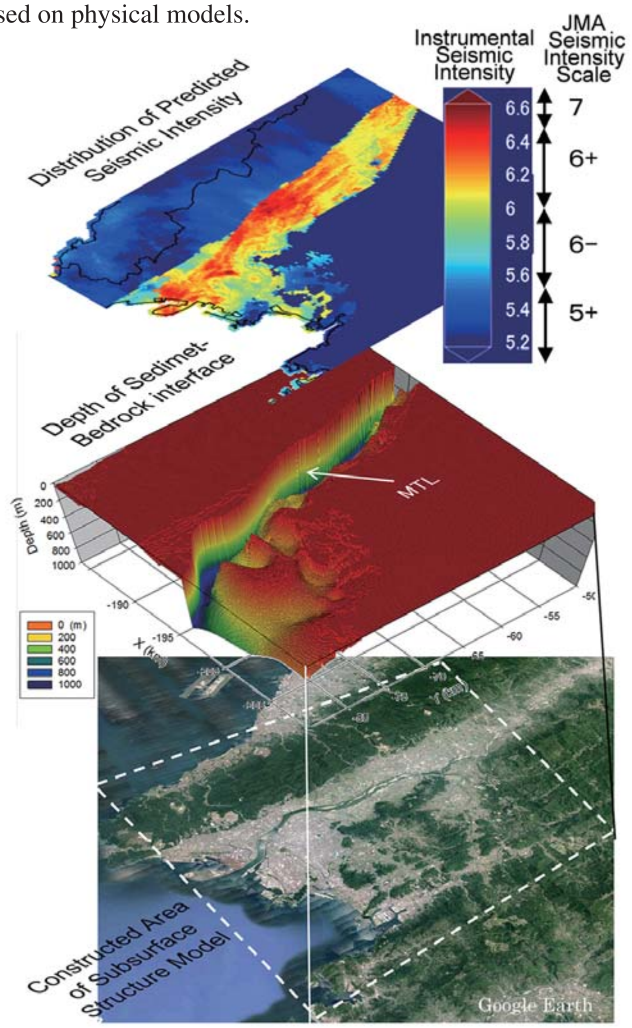
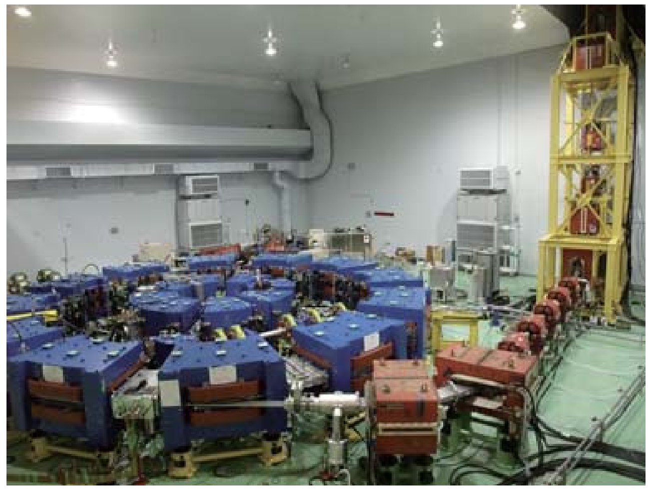


Fig. 1. Constructed three-dimensional subsurface structure model (middle) beneath the Wakayama Plain and measured seismic intensity distribution (upper) derived from the strong ground motion simulation due to assumed fault rupture model of the Median tectonic line.

Accelerator Physics, Engineering and Applications

In this research division, we are conducting research using an FFAG proton accelerator and an electron linear accelerator. The FFAG proton accelerator is used for a fundamental research of ADS (stands for accelerator driven system). ADS is a system in which an accelerator and a nuclear reactor are coupled to drive a subcritical fuel system with a beam from an accelerator. It is a device capable of shortening the lifetime of long-lived radioactive substances generated after reactor operation by transmutation. KURNS is the only research institute in the world capable of ADS experiments using spallation neutrons. These experiments have been continuously implemented since 2009, and it collects basic data necessary for practical use of ADS. The FFAG proton accelerator is used not only for ADS experiment but also for irradiation experiments of materials.

The accelerator-based intense light source in the terahertz region has been developed and its application to the spectroscopic research has been progressed with the electron linear accelerator in KURNS.



A full view of FFAG proton accelerator

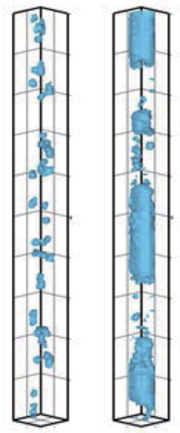
Thermal Energy System

This laboratory pursues safe and efficient use of high-density thermal energy produced in various next generation nuclear energy systems, such as an advanced nuclear reactor, fusion reactor and an accelerator-driven system (ADS). The research activity covers basic studies on the characteristics and the control of thermal-hydraulic phenomena and neutron behavior under various extreme conditions which are encountered in the next generation nuclear energy systems. In addition, study on the application of neutron imaging to multiphase fluid measurement is being performed taking advantage of KURNS in neutron utilization. On going research subjects are as follows:

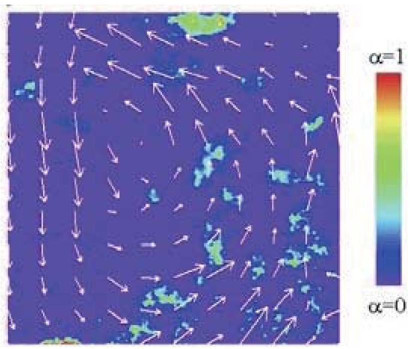
1. Thermal-hydraulics of lead bismuth eutectic (LBE) for ADS development,
2. Development of high heat flux cooling method using microbubble emission boiling (MEB),
3. Application of Neutron Imaging for thermal-hydraulic study,
4. Development of innovative fluid measurement method,
5. Enhancement of boiling heat transfer by radiation induced surface activation (RISA),
6. Mechanism of subcooled boiling CHF and its modeling,
7. Thermal-hydraulics of multiphase flow under severe accident conditions of nuclear reactors,
8. High-precision numerical simulation of multi-phase flow,
9. Modeling of gas-liquid two-phase flows with highly-intensified vortices,

These researches are performed using mainly the Thermal Hydraulic Test Facility and its accessories, and cobalt-60 gamma ray source for RISA and neutron imaging facilities of KUR, J-PARC, JRR-3 in the Japan Atomic Energy Agency and HANARO in Korean Atomic Energy Research Institute.

Micro-Bubble Emission Boiling



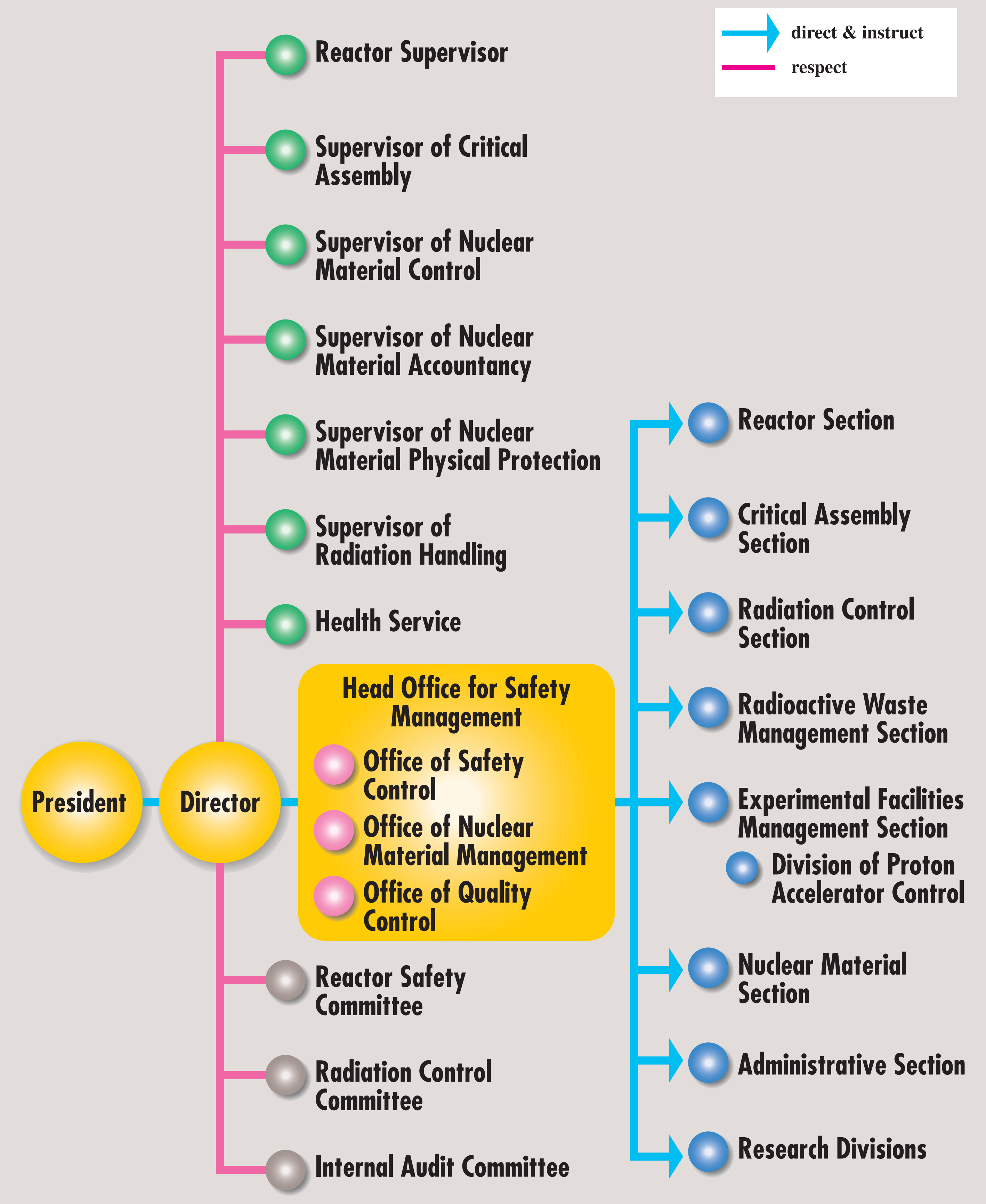
3D-distributions of bubbles measured by Wire Mesh Sensor (WMS)
Left: bubbly flow
Right: Slug flow



2D-distributions of velocity and void fraction in a molten LBE two-phase flow measured using neutron imaging

High-precision simulation result ofv dynamic interfacial deformation

Safety Organization



SAFETY ORGANIZATION 2018.10.1

Laboratories and Facilities

• Kyoto University Research Reactor (KUR) •
• Hot Laboratory •
• Kyoto University Critical Assembly (KUCA) •
• Thermal-Hydraulic Test Loop •
• Electron Linear Accelerator •
• Tracer Laboratory •
• ^{60}Co γ-Ray Irradiation Facility •
• Radioactive Waste Management Facility •
• Radiation Monitoring System •
• Neutron Mirror Fabrication System •
• Innovation Research Laboratory •

Kyoto University Research Reactor (KUR)

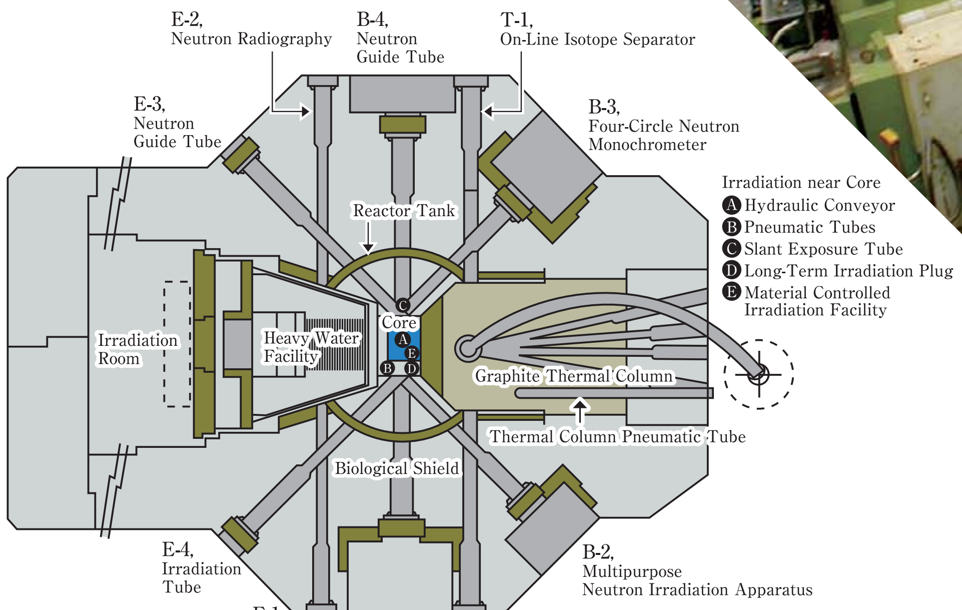
Kyoto University Research Reactor (KUR) is a light-water moderated tank-type reactor operated at the rated thermal power of 5 MW. The core consists of plate-type fuel elements using about 20% enriched uranium and graphite reflector elements. KUR is operated by using four shim rods and a regulating rod; those are made of the stainless steel containing boron. The core is constructed at the bottom of the aluminum core tank with the size of 2-m diameter and 8-m depth, which is filled with light-water.

KUR is widely used for the experimental studies in physics, chemistry, biology, engineering, agriculture, medicine etc. Since its first criticality in 1964, it has been successfully operated for over than 40 years, and has served as one of the most useful inter-university research reactors in Japan.

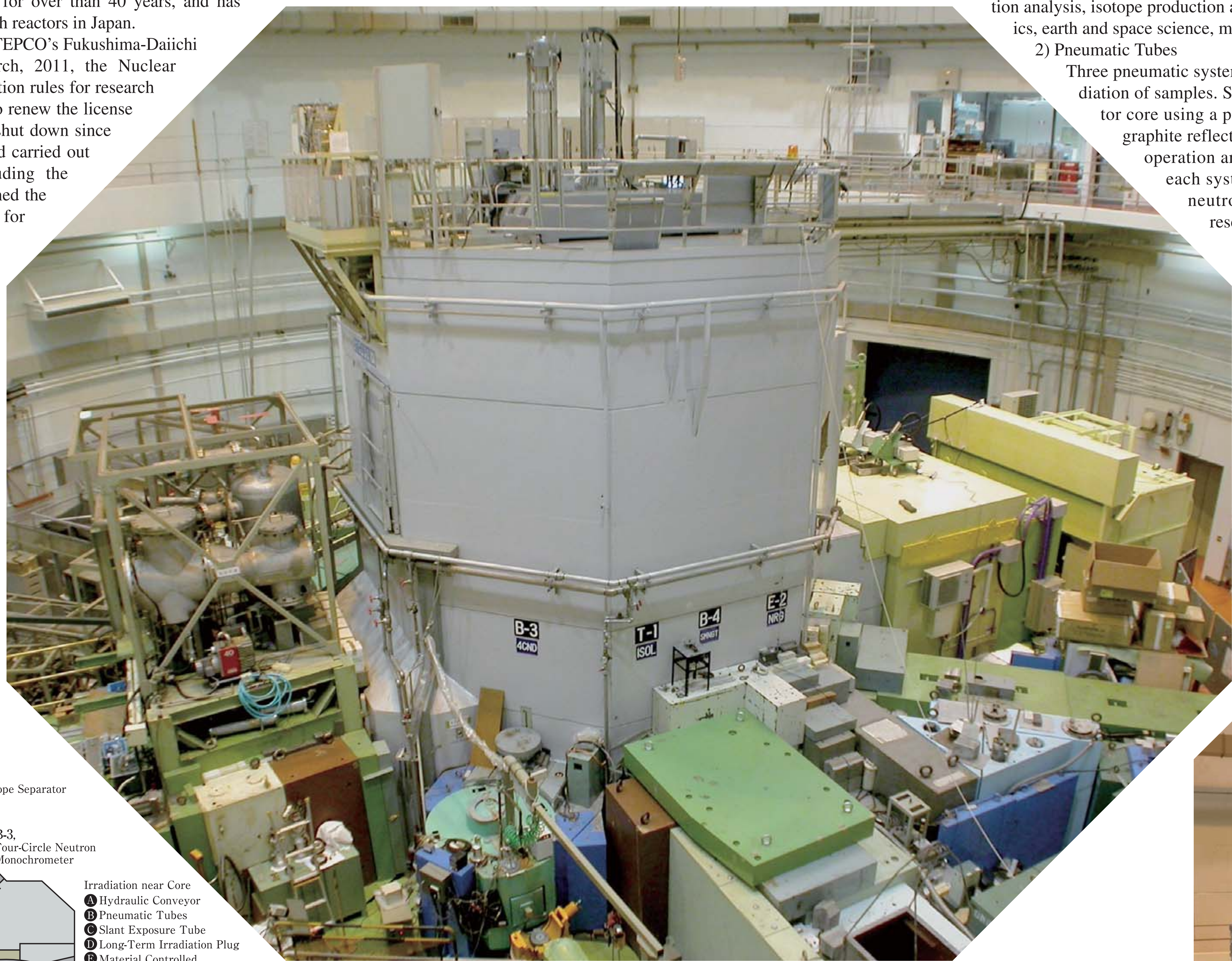
By reflecting the lessons learned from the accident of TEPCO's Fukushima-Daiichi Nuclear Power Plant which occurred on 11th March, 2011, the Nuclear Regulation Authority (NRA) has formulated the regulation rules for research reactors, and all the research reactors inb Japan have to renew the license under the new regulation rules. Then, KUR has been shut down since May 2014 to have the safety review by then NRA, and carried out the subsequent refurbishment of the facility including the inspections by the NRA. In August, 2017, KUR obtained the new license for operation and started its operation for joint-research works

KUR Neutron Guide Tube

When low energy neutrons are incident on a nickel mirror evaporated on an optically flat glass, total reflection occurs below the critical angle which is a function of the reflecting material and neutron wavelength. The long neutron guide tubes utilizing the total reflection of the nickel mirror were constructed in E-3 as the first neutron guide tube in Japan, for extracting thermal neutrons to a distant wide experimental hall of 10 meters away from the reactor. The nickel/titan supermirror composed of layers whose thickness are varied gradually layer by layer, has a reflective angle larger than the total reflection angle and reflects neutrons with a wavelength range shorter than the nickel mirror. The supermirror guide tube in B-4 is the first one in the world. The neutron flux at the exits are 2×10^6 n/cm²s (E-3 for prompt gamma-ray analysis for BNCT), 5×10^7 n/cm²s(B-4 for neutron imaging), 5×10^7 n/cm²s(CN-2 for SANS) and 2×10^7 n/cm²s(CN-3 for neutron reflectometry and neutron device development).



Plane Figure of KUR



B-1 Filtered Beam Hole

An iron-filtered beam facility was installed in the beam hole B- 1 with an iron-filter of 45 cm in thickness and an aluminum filter of 35 cm in thickness to obtain quasi-monochromatic neutrons near 24 keV. The characteristic neutron spectra were studied by a transport calculation and also by measurements using a spherical proton recoil counter and activation foils. The neutron flux at 24 keV was estimated to be about 6.8×10^6 n/cm²/s behind the filters. The absorbed doses just behind the filters and the position at 50 cm behind the filters were about 1 Gy/h and about 0.05 Gy/h, respectively.

Experimental Facilities in KUR

1) Hydraulic Conveyer

Users can irradiate samples at the center of the reactor core. The thermal neutron flux at 5 MW operation is 1.06×10^{14} n/cm²/s. The sample encapsulated in an aluminum capsule is transported from the top of the reactor to the center of the reactor core through a tube. The irradiated capsule is transferred to a canal of hot cave room at hot laboratory. This irradiation facility is used for neutron activation analysis, isotope production and other research purposes in fields of chemistry, physics, earth and space science, material science and others.

2) Pneumatic Tubes

Three pneumatic systems (Pn-1, Pn-2 and Pn-3) are available for neutron irradiation of samples. Samples are transported from hot laboratory to the reactor core using a polyethylene capsule. The irradiation position is in the graphite reflector beside the core and thermal neutron fluxes at 5 MW operation are 1.89×10^{13}, 2.78×10^{13} and 2.39×10^{13} n/cm²/s for each system, respectively. This irradiation facility is used for neutron activation analysis, isotope production and other research purposes in fields of chemistry, physics, earth and space science, environmental science, medical and biological science, material science and others.

3) Slant Exposure Tube

Large-size samples can be irradiated using the slant exposure tube. The irradiation position is outside of the graphite reflector, and the thermal neutron flux at 5 MW operation is 4.82×10^{12} n/cm²/s.

Material Controlled Irradiation Facility (SSS)

This facility has an improved control capability of irradiation conditions, such as irradiation temperature and atmosphere. The irradiation temperature of specimen is between 340 K and 773 K. The neutron flux is 9.4×10^{12} n/cm²s (E > 0.1 MeV) and 3.8×10^{13} n/cm²s (all). The maximum size of specimen is 38 mm × 60 mm. The photo is the specimen loading chamber.

Material Controlled Irradiation Facility

Heavy Water Neutron Irradiation Facility

The Heavy Water Neutron Irradiation Facility (HWNIF) was updated in March 1996, mainly for an improvement in boron neutron capture therapy (BNCT). The main purposes of the updating were as follows: (i) an improvement in the safety and maintainability of the facility, (ii) an improvement in the performance for BNCT utilizing both thermal and epi-thermal neutrons, and (iii) the realization of BNCT clinical irradiations during full-power continuous KUR operation.

This facility has a heavy water tank of approximately 2 m^3 adjacent to the KUR core. In the heavy water tank, an aluminium-heavy water mixture (Al/D_2O=80/20 in volume percent), and a neutron-energy spectrum shifter of heavy water whose thickness changed from 0 to 90 cm, are installed in order from the core side. Outside of the spectrum shifter, two thermal neutron filters of 1mm-thick cadmium plate are installed. The energy spectrum of the neutron beam can be controlled from almost pure thermal to epi-thermal within five minutes by remote control under a continuous reactor operation.

After the updating, the KUR Advanced Irradiation System for BNCT was organized. Clinical irradiation utilization under the fullpower continuous KUR operation can be performed by employing both a Radiation Shielding System consisting of a shielding door and an irradiation room, and a Remote Carrying System for a patient. The safety and utility of the facility are kept by the Safety Observation System.

As of the end of July 2018, 510 BNCT clinical irradiations have been performed, namely, 254 for brain tumours, 193 for head and neck tumours, 27 for malignant melanomas, 44 for lung tumours, 10 for liver tumours, and 19 for tumours of the other body-parts, using the three standard irradiation modes of thermal-neutron, mixed-neutron and epi-thermal neutron.

Heavy Water Neutron Irradiation Facility

On-Line Isotope Separator (T-1 Through Tube)

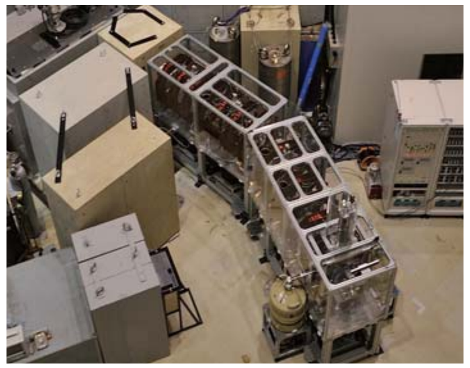
The On-Line Isotope Separator (ISOL) is an apparatus used to study short-lived nuclides produced by thermal neutron fission reaction. A target of 93 % enriched ^{235}U is irradiated by a thermal-neutron flux of 3×10^{12} n/cm²s and produced fission fragments are transported to an ion source by a gas-jet within a few seconds. The ionized activities are extracted from the ion source and accelerated up to 30 keV. They are electromagnetically focused and mass-separated to form a chemically pure atomic beam of the nuclides to be studied.

In this system, a surface ionization ion source is employed to ionize efficiently alkali elements (Rb, Cs), alkali-earth elements (Sr, Ba) and light rare-earth elements (La, Ce, Pr, Pm and Nd). The RI beams thus obtained are used to study the nuclear structure by nuclear spectroscopy, and to apply nuclear methods to solid state physics by, e.g., a perturbed angular correlation (PAC) technique. A post accelerator is equipped to implant the RI ions with the kinetic energy of up to 200 keV.

On-Line Isotope Separator (KUR-ISOL)

Slow Positron Beam System (B–1)

The Slow Positron Beam System provides positron beams through the electron-positron pair-creation reaction with reactor γ-rays for materials analysis by positron annihilation spectroscopy. Positrons generated at the source position with energies of the order of 10 eV are extracted and fed into the beam line, accelerated up to 30 keV before sample irradiation. Positrons recombine with electrons and emit two γ-rays of 0.511 MeV. Positron lifetimes and Doppler broadening can be measured from the emission time and the energy dispersion of annihilation γ-rays. It is well known that when positrons annihilate at atomic-scale vacant spaces such as vacancies and voids, positron lifetimes get longer and also Doppler broadening is influenced. It is possible to obtain information of vacant spaces based on these phenomena.



Slow Positron Beam System (B–1)

Multipurpose Neutron Irradiation Apparatus (B–2)

A neutron irradiation apparatus using B-2 beam hole was installed in 2012. Samples on a truck are transported from a neighboring measurement room into the B-2 beam hole to be irradiated by neutrons. Samples of large size (60 mm × 60 mm × 300 mm) and liquid form (static or flowing liquid) can be irradiated. Monitoring and controlling irradiation conditions are feasible by connecting the transport truck and monitoring/controlling devices in the measurement room with cables. Variable irradiating position enables neutron irradiation with a range from 10^7 to 10^{11} n/cm²s. Irradiating neutron spectrum is also variable by placing neutron shielding/moderating materials around samples on the transport truck.

Multipurpose Neutron Irradiation Apparatus

Neutron Imaging Facilities (E-2 & B-4)

Neutron imaging can be performed using thermal neutrons generated in the Kyoto University Research Reactor (KUR), which has two irradiation port; E-2 port and B-4 guide tube room. E-2 port is located in the reactor room of the KUR, which has relatively large field of view ϕ150 mm) with the thermal neutron flux of 3.2×10^5 n/cm²s. This port is mostly utilized to obtain the static images including 3-D computed tomography. B-4 neutron guide tube facility has the world' s first super mirror neutron guide tube. The thermal neutron flux of B-4 port is 5×10^7 n/cm²s at 5 MW thermal power of the KUR and it is possible to apply not only for static image acquisition but also for dynamic imaging using a high speed camera combined with an image intensifier.

B-4 guide tube room is equipped with a stabilized DC power supply (max. 20 V×1,200 A) and a cooling water unit for boiling two-phase flow researches. Furthermore, X-ray imaging system has been installed for complementary use to neutron imaging.

Boiling Two-Phase Flow Loop at B-4 Guide Tube Room

Compact Small-Angle Neutron Scattering Instrument (CN–2)

Small-angle neutron scattering (SANS) is an experimental method to analyze nanostructure and frequently used for various materials such as polymers, micelles, proteins, metals, and magnetic materials. A SANS instrument is installed at CN-2. It uses a multilayer monochromator, a ^{3}He two-dimensional detector, and a transmission monitor. Compared to a neutron velocity selector used at general SANS instruments, the multilayer monochromator is compact, highly stable, and easily maintained. The wavelengths of 0.3 nm and 0.46 nm are available. A magnetic field of 0.5 T can be applied to the sample. The data acquisition system operates in an event-recording mode, which enables flexible data reduction.

KUMASANS (CN-2)

Hot Laboratory

Hot Laboratory is an auxiliary experimental facility for the research reactor, which is built connectedly with the reactor room. In this facility, various post-irradiation examinations, radiochemical analysis, and other related chemical treatments are safely carried out.

Hot Cave Room

Highly activated materials, 185 TBq of maximumradioactivity, can be safely treated in three heavy- shielded hot cells (A,B, and C-cell) equipped with remote-controlled devices and manipulators.

Samples irradiated by hydraulic conveyer system or long-period irradiation device can be transferred from the reactor core through a canal into A-cell, and disassembling of the samples and pre-treatment for post-irradiation experiment are carried out in the cell.

Mössbauer spectrometry using various short-lived nuclides produced by neutron irradiation in KUR is available in B-cell.

Irradiation test for LSI circuits of artificial satellites can be performed using Cf-252 spontaneous fission source in a vacuum chamber in C-cell. Stations for the pneumatic capsule transfer system for the irradiation at the core (Pn-1) and the thermal column (TC-Pn) are located in this room.

Heavy-ion irradiation facility, which uses Hill-Nelson type sputtering ion gun for ion source, is placed in this room for studying the elementary process of radiation damage of metals and semi-conductors. Irradiation with heavy ions from nitrogen to tungsten at 80 keV is possible by this facility.

Junior Cave Room

Chemical experiments and sample preparation using nuclear fuel materials, trans-uranium and α-active nuclides are available in chemical hood and glove boxes. Station for the pneumatic capsule transfer system (Pn-2) is located in this room. By use of the lead-shielded cell for receiving irradiated capsule, this bench can handle with highly irradiated samples.


Junior Cave Room


Hot Cell


Mössbauer Spectrometer

Instrumental Analysis Room

For various physical and chemical analysis, instrumental analysis devices are installed in this room. ICP-AES, atomic absorption spectrophotometer, powder X-ray diffractometer, and scanning electron microscope are installed.

Cryogen Service Room and Workshop

Cryogens (liquid helium and nitrogen), which are necessary for low temperature experiments, are supplied from this room. Cryostats are used for the stable supply of cryogens. This room also has a function as a workshop for the maintenance of experimental devices, and is equipped with machine tools, such as lathe turning machine, milling machine, and drilling machine. From this workshop, parts, accessories, and components, are supplied to the researchers, and other various supports are provided.


Ge Detector

Radiation Measurement Room and Dark Room

This room is equipped with γ-ray detectors and multi-channel pulse height analyzers.

They are used for activation analysis and other radiochemical assessments. Dark room is used for autoradiography and other radiochemical purposes.

Semi-hot Laboratory (Laboratory-1~3)

Three rooms are used for the treatment of the radioactive samples irradiated by the reactor. Radiochemical treatments are system (Pn-3) is the analysis of trace conducted using various types of draft chamber and glove box. Station for the pneumatic capsule transfer located at Lab.-1. ICP mass spectrometer is placed in a clean room installed in Lab.-3, and this is used for elements in samples.

Kyoto University Critical Assembly（KUCA）

The KUCA is a multi-core type critical assembly established in 1974 as a facility for the joint use study in reactor physics for researchers of all universities in Japan. It has three independent cores, namely, two solid moderated cores (A, B cores) and one light water-moderated core (C core). A pulsed-neutron generator is also installed, which can be used in combination with the A-core.

In the KUCA, basic studies on reactor physics and reactor engineering have been performed. Recent research topics includes 1) nuclear characteristics of thorium fueled reactor, 2) nuclear transmutation studies on transuranic elements, 3) critical experiments on highly-enriched uranium cores with various spectrum indices, 4) subcriticality measurements using various techniques, 5) nuclear characteristics of coupled core systems, with special interest to the eigenvalue separation which is an index of reactor stability, 6) development of innovative techniques for the neutron measurement and their application to reactor physics experiments, and 7) simulation experiments of the accelerator driven system (ADS) using combination of subcritical cores and the neutron generator,new FFAG 100 MeVproton accelerator.

For education, the reactor laboratory course on reactor physics is offered every summer for 12 Japanese universities since 1975. Approximately 150 students majoring in nuclear engineering are joining this course every year. The subjects offered in the experimental course include 1) critical mass measurements, 2) control rod worth calibration, 3) measurement of neutron flux distribution, and 4) reactor operation and fuel handling for educational purpose. The same reactor laboratory course for Korean undergraduate students was started in 2003, that for Swedish students in 2006 and that for Chinese students in 2011.

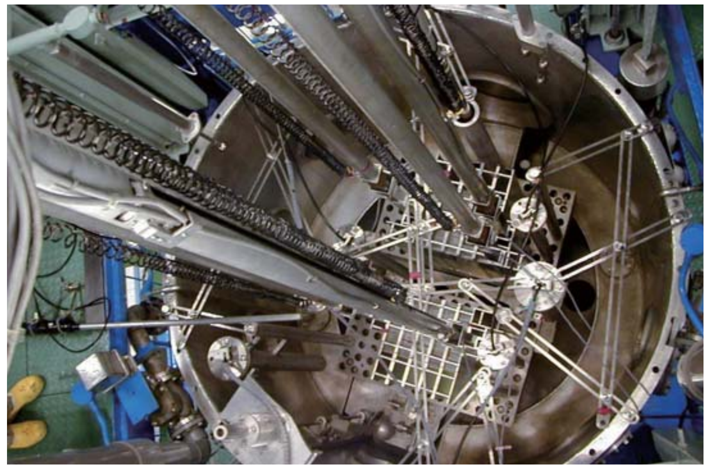
Solid Moderated Cores

The A and B cores are solid moderated cores, which use enriched uranium fuel and moderator plates (polyethylene or graphite) of coupon type to form the core. These material plates are stacked in an aluminum sheath to form the fuel element. Fuel elements are vertically arranged on the grid plate to constitute the core. Various neutron spectra can be realized by varying the combination of fuel and moderator plates in the fuel element. Experimental material plates such as natural uranium and thorium metal are also usable.


Solid Moderated Cores

Light Water Moderated Core

The C core is a light water moderated core of a tank type. A fuel element is assembled by inserting enriched uranium fuel plates with Al cladding between the side plates of the fuel element. Fuel elements are arranged on the grid plate inside the core tank and are immersed with light water that acts as moderator and reflector. Fuel plates can be arranged inside the fuel element with three different fuel pitches in order to vary the neutron spectra in the core. The grid plate can be separated into two parts in order to enable coupled core experiments.


LightWater Moderated Core

Pulsed Neutron Generator

The A core is equipped with a Cockcroft-Walton type accelerator, which can inject 14 MeV neutrons by D-T reactions into the A core.

At this facility, pulse neutron experiments are carried out to measure reactor physics parameters, including subcriticality, reaction rates, neutron spectrum and so on. Pulsed neutrons can be also generated by spallation reactions in a heavy metal target with high energy proton beams supplied from the FFAG accelerator, and these pulsed neutrons have been utilized for the ADS basic experiments.

Pulsed-Neutron Generator

Thermal-Hydraulic Test Loop

The research activity of Heat Transport Laboratory of the Research Reactor Institute of Kyoto University (KURRI) is being performed with the use of four test loops (two for boiling water, one for air-water two-phase flow, and one for lead-bismuth flow) and their peripherals, which are located in the Thermal-Hydraulic Test Facility. The boiling water test loop consists of a circulating pump, a pre-heater and a condenser, circulates purified water at a pressure up to 2 MPa. The range of measurable flow rate by three turbine flow meters in the loop is 0.028 to 4 L/min. Test section for boiling experiments can be heated by Joule heating with a stabilized direct-current (DC) power supply (max. 20 V×5,000 A). The power supply can be operated not only at a steady output current but also a transient output which is controlled by a function generator. The two-phase flow loop is an ad-hoc apparatus for air-water two-phase flow at atmospheric pressure and room temperature and used for development and improvement of two-phase flow measurement techniques. The lead-bismuth test loop consists of an electro-magnetic pump, a calibration tank, a gas-liquid separator, flow meters, and a dump tank, which is used for thermal-hydraulic study in relation to liquid-metal cooled nuclear systems. The accessories available in the Heat Transport Laboratory include data acquisition systems, wire-mesh sensor, laser displacement meter, high-speed video camera and so on.

Thermal-Hydraulic Test Loop and Heat Transfer Laboratory

Electron Linear Accelerator

The electron linear accelerator is used as various types of particle beam source, i.e. electrons, neutrons, and photons. The electron beam is generated by a thermionic gun and accelerated to a maximum energy of 46 MeV in two accelerator tubes by L-band (1.3 GHz) microwave. The pulse width is variable from 2 ns to 4 µs. A low energy beam below 10 MeV, an ultra-low current beam by field emission, and a single-bunched beam are also available. The research region covers a wide field of nuclear data acquisition with the neutron time-of-flight method and a lead slowing-down spectrometer, isotope production by the (γ,n) (γ, p) reaction, low-temperature electron irradiation, a photon activation analysis, and a spectroscopy with coherent THz radiation.

Electron Linear Accelerator

Tracer Laboratory

The tracer laboratory, where researches using tracer-level activities are widely carried out, is composed of a main building and its outbuilding for biological use.

The laboratory is connected to the Hot Laboratory via a pneumatic transport tube so that short-lived activities produced at the KUR can be conveyed from the Hot Laboratory to the laboratory within several seconds. The building has experimental rooms for physical, chemical, biological and materials researches, and a radioactive isotope storage room, etc. For experiments of material science, materials science and engineering, and nuclear physics, apparatuses such as an electron microscope, X-ray diffractometers, Mössbauer spectrometers, γ-rays perturbed-angular-correlation systems are available. Stainless-steel draft chambers are installed in the chemistry rooms, one of which chambers has the pneumatic transport station to accept irradiated capsules from the Hot Laboratory. In the biological rooms, equipments are installed to treat biological samples containing radioisotopes.

^{60}Co γ-Ray Irradiation Facility

The central equipment of this facility is a lift-up type ^{60}Co γ-ray source. For γ-ray irradiation, the ^{60}Co source normally stored in the lead container under the floor is raised into the irradiation room by remote control. The maximum dose rate available as of April 2018 is 9.5 kGy/h. The irradiation room 15 m^2 in area allows irradiation in a wide range of dose rate for numerous sorts of samples in various sizes and shapes. It is also possible to carry out low-temperature irradiation using various cryogens and customized irradiation by use of special equipments.

An ESR spectrometer is available in the measurement room adjacent to the irradiation room, which enables the prompt measurement after irradiation. There are several curved holes connecting the irradiation room and the measurement room to guide signal wires for experiments. A lead-glass window is installed in between the irradiation room and the operation room for direct observation of the irradiation room.

Extensive researches in various fields such as physics, chemistry, biology, geology, engineering, and medical science are in progress using pure γ-rays which are available in this facility. Thus this facility complements other facilities in our institute.

^{60}Co γ-Ray Irradiation Facility

Radioactive Waste Management Facility

Liquid Waste Storage Tanks

Radioactive waste management facility consists of several waste treatment plants, storage tanks, a waste repository, analytical instruments for examining chemical properties and measuring radioactivity, etc.

Radioactive solid wastes are assorted by their properties (combustible, incombustible etc.), and then packaged in drums predetermined for each property. These drums are stored in a repository with other wastes such as high level liquid wastes, concentrate by evaporation, dehydrated sludge by chemical coagulation etc. Parts of these wastes in a repository are transferred about once a year to the waste dealer granted legal license for radioactive waste management.

High level liquid wastes (greater than 3.7×10^4 Bq/cm^3) are temporarily stored for cooling till they can be handled, then stored in a repository without any condensing operation. Other radioactive liquid wastes (medium and low level) are treated adequately to their radioactivity and physicochemical properties as follows.

1) Evaporation

Medium level liquid wastes (0.37-3.7×10^4 Bq/cm^3) and/or liquid wastes with high salt content are treated by an evaporator that separates evaporated steam from remaining concentrate, which contains most of radioactivity in the waste. Entraining droplets are removed from steam stream by three particle separators; cyclone, packed column and perforated plate column. Concentrate by evaporation is accommodated in containers, and purified liquid is introduced to monitoring tanks. The treating capacity of the evaporation plant is 0.5 m^3/h.

2) Chemical Coagulation and Freezing-and-Thawing

Low level radioactive liquid wastes (below 0.37 Bq/cm^3) are treated by two series of chemical coagulation plants, which consist of chemical tanks, rapid mixing tanks, flocculator-sedimentators, anthracite filters etc. In this treatment process, radioactive materials are removed from liquid waste into sediment slurry by chemical coagulation followed by precipitation. This coagulator has the treating capacity of 5 m^3/h for one series. Sediment slurry is dehydrated by two freezing-thawing plants, whose treating capacity is 0.2 m^3/d for one series. Dehydrated slurry is accommodated in containers. Decontaminated effluent from the coagulator is filtered by anthracite, and purified liquid is introduced to monitoring tanks.

3) Ion Exchange

Liquid Waste Treatment Facilities

Two series of ion exchange plants are used for low salt content liquid waste, or they are utilized also for further treatment of liquid wastes already treated by the evaporator or the coagulator, if necessary. One ion exchange plant consists of a cation exchange column, an anion exchange column, a mixed column and an inorganic resin column. The inorganic resin column is particularly capable of cesium removal. Liquid waste is treated by proper combination of columns considering nuclides in liquid waste. The ion exchange plant has the treating capacity of 5 m^3/h. Liquid waste is purified by adsorbing ionic radionuclides onto functional groups of ion exchange resin, and purified liquid is introduced to monitoring tanks.

Treated liquids are stored in monitoring tanks, and then released into the environment after confirmation that concentrations of radionuclides in the liquid are below the legal permissible limits.

Radiation Monitoring System

Radiation Monitoring Panel for KUR

Indoor Radiation Monitors

1) Gamma Radiation Monitors

Fixed-position γ monitors are installed in many areas to warn of increased radiation levels.

2) Neutron Monitors

The monitors are set in the reactor rooms of the KUR and KUCA to measure external dose rates by neutrons.

3) Dust Monitors

To monitor the concentration of anthropogenic radioactivity in the exhaust gas from both the reactor buildings and radiation facilities, dusts are collected on a filter paper and measured continuously for α, β and γ emitters.

4) Water Monitors

Water monitors are installed to observe the radioactivity level in primary/secondary coolant waters of the reactor.

5) Hand-Foot-Cloth Monitors

The monitors set at the exit of corridor will detect small quantities of β/γ contamination on shoes, clothing, etc. Nobody goes out of the controlled area without checking contamination by this instrument.

Indoor Radiation Monitors

Monitoring Post

1) Monitoring Posts

Monitoring posts with a NaI probe are installed at five locations near the border of KURRI to observe and record external γ-ray dose rates continuously.

2) Monitoring Stations

At four sites in the vicinity of KURRI, i.e., Wada, Shimogawaraya, Ichiba, and Hineno, γ-ray monitors equipped with data recorders and data transmission systems are set. Monitoring data are transmitted to the meteorological observatory in the KURRI site by a telemeter system.

Most of signals obtained by the monitoring system mentioned above are transmitted to the radiation control room and radiation levels are watched to cope with any incidents.

3) Meteorological Observatory

Data observed on various meteorological factors such as wind direction, wind speed, and solar radiation are accumulated and utilized to estimate the radiation dose due to airborne radioactivities either chronically or accidentally released from nuclear and radiation facilities.

Others

1) Low Background Ge(Li) Instrument

Radionuclide concentrations in various field samples such as soils, vegetables, surface water, sea water, river and lake sediments are determined by using a γ-ray emitter analysis system equipped with a Ge(Li)-detector.

2) Whole Body Counter

The content of radioactivity inhaled/ingested in a human body is analyzed to assess the internal exposure dose by the instrument with a NaI detector in a shielding condition.

3) Survey Maters

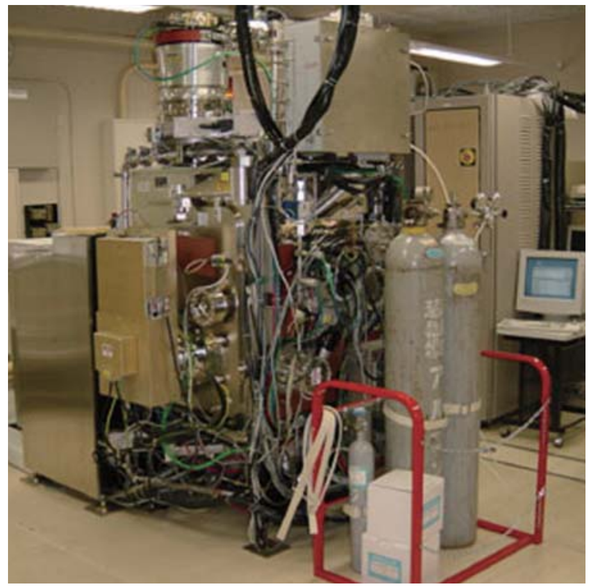
Appropriate survey meters capable of detecting and measuring α, β, γ-ray and neutron radiation are available at KURRI.

4) Glass Badge

A glass badge is mounted on a body and changed monthly to monitor the external radiation dose.

Neutron Mirror Fabrication System

Ion Beam Deposition and Vacuum Evaporation for Large Neutron Mirrors



Ion Beam Deposition System (Veeco, IBD-350)

A Multilayer mirror is one of the most useful devices for slow neutron experiments. Multilayer mirrors and supermirrors are applied to neutron optical devices, such as neutron guide tube.

The multilayer mirror consists of alternating layers of two materials with different potential energies for the neutron. It has artificial lattice spacing (*d*-spacing) and gives one-dimensional optical potentials for a neutron beam. Supermirror is a stack of multilayers with gradually increasing value of the *d*-spacing. A multilayers with small *d*-spacing and supermirror with large-*m* are desirable to enlarge utilization efficiency for neutron scattering experiments. Recently we succeeded in fabricating large-*m* （*m*=5） NiC/Ti using ion beam sputtering technique. The Ion beam deposition system is used for high quality mirror fabrication. It has ion sources for sputtering and assist. The sample size is 20 cm diameter and the number of target in this system is 5. The vacuum evaporation system is used for large size mirrors. Eight mirrors of 11×35 cm^2 can be fabricated at once.

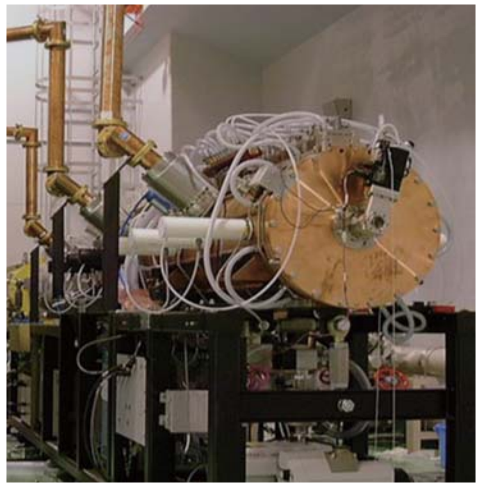
Innovation Research Laboratory

Innovation Research Laboratory

This building was built next to the KUCA building in FY 2003. It consists of two independent parts: the experimental facility which accommodates 150 MeV FFAG accelerator and 11 MeV negative hydrogen ion beam linear accelerator; the medical facility which accommodates 30 MeV cyclotron and medical treatment equipments.

11 MeV Negative Hydrogen Ion Beam Linear Accelerator

This apparatus consists of a negative hydrogen ion source, 7 MeV DTL and 11 MeV DTL. It is used as the injector of the 150 MeV FFAG accelerator. A negative hydrogen ion is composed of one proton and two electrons. Once injected to the FFAG ring, a negative hydrogen ion hits a thin carbon foil and becomes a proton, the two electrons being stripped off. This injection scheme can realize a long-term injection such as over 100 turns. The beam specifications are the energy of 11 MeV, the current of 1 mA at the peak, the repetition rate of 200 Hz and pulse width of 100 µs. Other than an injector to the FFAG ring, it can be used for irradiation experiments with 11 MeV and 7 MeV.

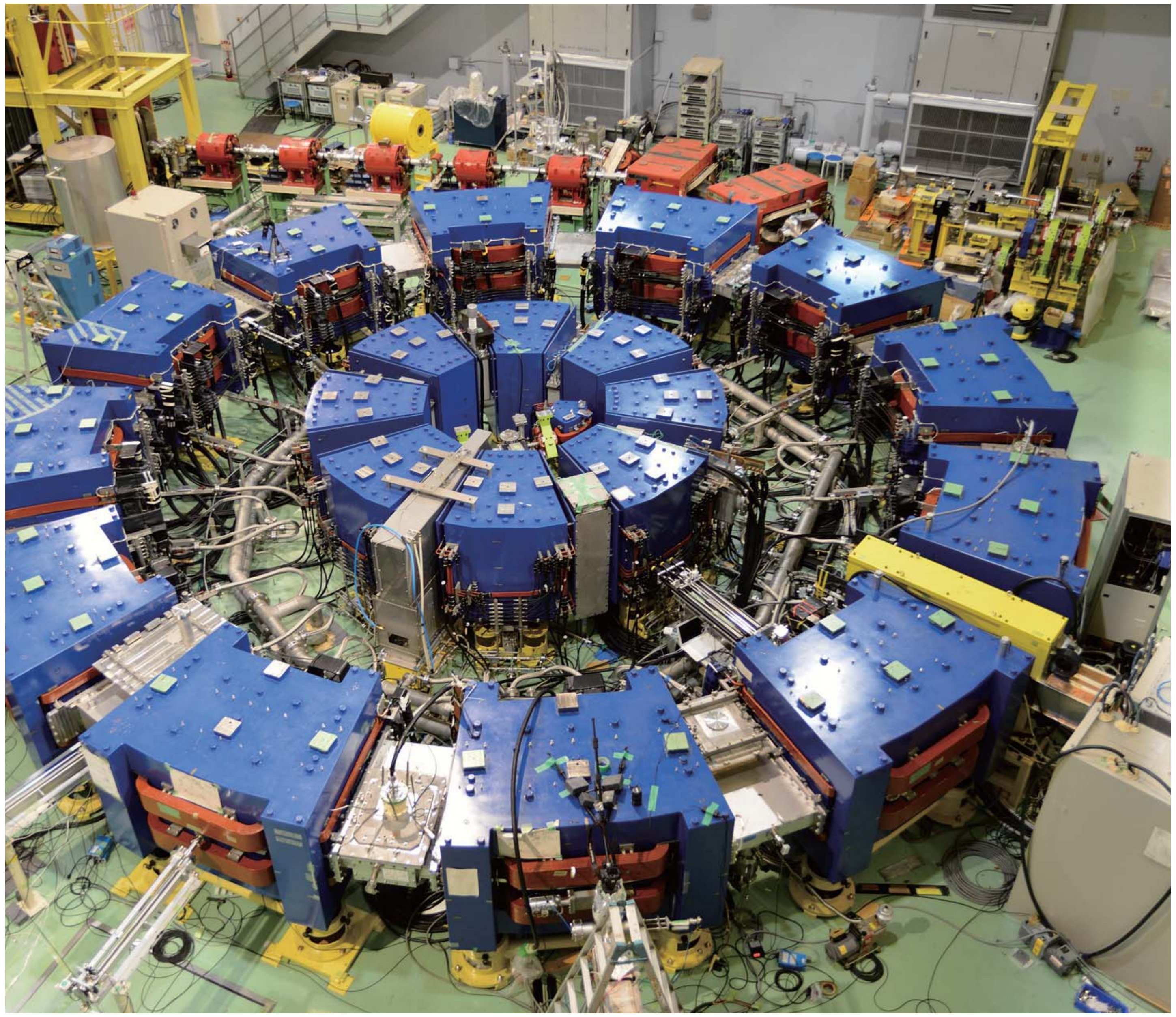


11 MeV Negative Hydrogen Ion Beam Linear Accelerator

30 MeV Cyclotron

30 MeV cyclotron is the proton accelerator that can produce epithermal neutrons for boron neutron capture therapy. This cyclotron produces proton beams with the energy and current of 30 MeV and 1 mA, respectively. Epithermal neutron flux of 1.2×10^9 n/cm^{2}s is supplied by the combination of neutron production target and neutron moderator. Cyclotron was install in innovation research laboratory medical area on December 2008. The test of neutron production was started on March 2009. After the physical irradiation and biological irradiation using small animals and cells, the first clinical trial in the world was started on October 2012.

30 MeV Cyclotron and Beam Transport Tube



150 MeV FFAG Accelerator

150 MeV FFAG Accelerator

A Fixed Field Alternating Gradient (FFAG) accelerator complex was installed in the experimental facility for the basic study of Accelerator Driven System (ADS) under the support from the Ministry of Education, Culture, Sports, Science and Technology (MEXT). The world first ADS experiments were performed in March 2009 by using the combination of 100 MeV proton beams from the FFAG accelerator and the subcritical nuclear fuel system assembled in A-core in the KUCA. The experiments are still ongoing with different conditions of the core and the beam.

The present beam specifications at 2015 are the energy of 150 MeV, the current of 1 nA, the repetition rate of 30 Hz and pulse width less than 100 ns. Other than ADS experiments, irradiation for the materials, aerosol and living animals e.g., rats are performed for the basic studies in various research fields. In future, considering the usages of the beams for a pulsed neutron source, the beam intensity upgrade is ongoing aiming to the beam current of 1 µA.