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ION IRRADIATION FACILITY IN JAERI, TAKASAKI FOR STUDY OF ADVANCED RADIATION TECHNOLOGY

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ABSTRACT

Construction of the ion irradiation facility including an AVF cyclotron has started in JAERI for the advanced applications of radiation. The accelerators and the facility under planning are outlined with main features of the cyclotron and the beam characteristics.

INTRODUCTION

Construction of the ion irradiation facility has started in Takasaki Radiation Chemistry Research Establishment of the Japan Atomic Energy Research Institute for the advanced applications of radiation with ion beams in the research and development on radiation-resistant materials in severe environment and research on bio-technology and new functional materials(1). This project is based on the background that ion beam irradiation is becoming an effective means for research not only in fundamental physics but also in advanced technologies and that the national guideline to emphasize basic and pioneering fields recently was set forth for research and development. The research items are divided into four categories and a related research on ion beam technology, as shown in Table 1.

The main components of the new facility are an AVF cyclotron (maximum proton energy: 90 MeV) with an ECR ion source and a duoplasmatron ion source, a 3 MV tandem accelerator, a 3 MV single-end type Van de Graaff accelerator, and a 400 kV ion implanter.

This report outlines the accelerators and the facility under planning with main features of the AVF cyclotron and the beam characteristics.

OUTLINE OF ACCELERATORS

The research plan requires various kinds of ion species and wide ranges of energy and beam current for acceleration. Table 2 shows the ion accelerators and the characteristics which were chosen and optimized to satisfy the research plan.

The items basically required for the high-energy ion accelerator are: 1) Protons can be accelerated up to several tens MeV or more, 2) heavy ions (C ~ Xe) can be accelerated in energy range of a few MeV/nucleon to a few tens MeV/nucleon, 3) the beam current of light ions more than a few tens micro-ampere is necessary, 4) a wide variety of ion species can be accelerated to wide ranges of energy, and 5) the accelerator functions effectively as an irradiator which can be simply and easily operated and maintained.

The AVF cyclotron of K=100 or more equipped with an electron cyclotron resonance (ECR) ion source is the only choice to satisfy the above requirements.

The main requirements for the medium and low energy ion accelerators are: 1) Three accelerators for accelerating protons, helium and heavy ions in energy range of several hundreds keV to a few MeV are necessary for the triple-beam irradiation which is planned to simulate the radiation damage of materials for nuclear fusion reactor, 2) heavy ion microbeam with energy of 10 MeV or more is necessary for studies on single event upsets of memory devices and logic LSIs and on cell processing, and light ion microbeam of a few MeV for study on ion beam analysis, 3) dual-beam to implant and analyze a target material alternately is necessary for the advanced beam analysis with light and heavy ion probes, and 4) simultaneous dual-beam irradiation with electron and proton beams is required for simulating space environment for evaluation of radiation resistance of solar cells. The tandem accelerator, the single-end type Van de Graaff accelerator, each with a maximum voltage of 3 MV, and the ion implanter with a maximum voltage of 400 kV were chosen to fit the above requirements on the multiple-beams.

Table 1. Research Items on Advanced Application of Radiation by Ion Beam Technology

RESEARCH AND DEVELOPMENT ON RADIATION-RESISTANT MATERIALS IN SEVERE ENVIRONMENT
1. Materials for Space Environment
   * Research on Space-Radiation Resistance of Semi-conductor Devices and Sensors
   * Research on Space-Environment Endurance of Construction Materials for Satellites
2. Materials for Nuclear Fusion Reactor
   * Research on Radiation Damage Mechanism of First Wall and Breeder Blanket Materials
   * Research on Radiation Resistant Organic Composite Materials

RESEARCH ON BIO-TECHNOLOGY AND NEW FUNCTIONAL MATERIALS
1. Bio-Technology
   * Research on Environment-Tolerant Gene Resources
   * Research on Bionics Materials
   * Research on Ion-Beam Radiation Chemistry of Bio-Materials
   * Research on New Labeled Compounds
2. New Functional Materials
   * Research on Creation and Modification of Materials
   * Research on Novel Analysis Technology

RELATED RESEARCH
   * Ion Beam Technology

Table 2. Accelerators for the Ion Beam Irradiation Facility

Type	ion	Energy (MeV)	Max. Current (μA)	Characteristics
AVF Cyclotron	p	5~90	40	ECR Ion Source
	d	5~53	40	Expanded Irradi-
	He	10~108	30	ation Field
	C	30~330	5	Pulsed beam
	Ne	50~550	5	Microbeam
	Ar	100~700	5	Neutron Beam
	Kr	200~630	1	Combined Beam
	Xe	310~620	0.1	Vertical Beam
Tandem Accelerator (3MV)	p	0.8~6.0	5	
	C	0.8~15.0	5	Microbeam
	Ni	0.8~15.0	5	Combined Beam
	Au	0.8~9.0	10	
Van de Graaff Accelerator (3MV)	p	0.4~3.0	300	
	d	0.4~3.0	150	Microbeam
	He	0.4~3.0	300	Combined Beam
	e^-	0.4~3.0	100	
Ion Implanter (0.4MV)	He	0.025~0.4	50	
	Ni	0.025~0.4	30	Combined Beam
	Au	0.025~0.4	30	

Figure 1 shows the time schedule for construction of the facility. The construction is divided into two phases. In the first phase the AVF cyclotron and the tandem accelerator are to be installed, and also the cyclotron building, a part of the multiple-beam building for medium and low energy accelerators, and the research building are to be constructed. These accelerators are to come into operation by 1991. The second phase will be followed in 1991-2.

AVF CYCLOTRON AND FACILITY

Cyclotrons so far have been used mainly for fundamental research of nuclear physics, medical radioisotope

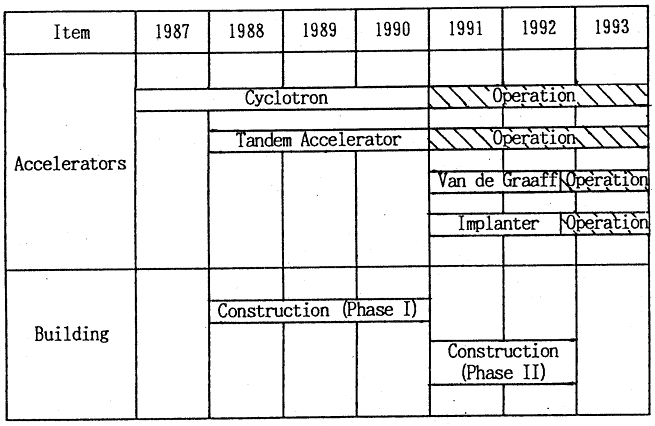

Fig. 1 Time Schedule of Construction of the Facility

Table 3 Main Parameters of JAERI Cyclotron

K-value	110
Extraction Radius	0.923 m
Maximum Magnetic Field	1.64 T
Maximum Magnetomotive Force	3.96 x 10^5 AT
Weight of Magnet	~200 ton
Number of Sectors	4
Number of Dees	2
RF Range	11 ~ 22 MHz
Dee Voltage	50 kV
Harmonic Number	1, 2, 3
Range of Acceleration Energy (Heavy Ions)	2.5 M ~ 110 Z^2/M (MeV)
Range of M/Z	1 ~ 6.5
Ion Source for Light Ions	Duoplasmatron
Ion Source for Heavy Ions	ECR Ion Source

production, and radiation therapy. The JAERI cyclotron will be the first one in Japan which is mainly applied for research and development of material science. The main parameters of the cyclotron is shown in Table 3. The model of the cyclotron is the model 930 AVF cyclotron of Sumitomo Heavy Industry Co. Ltd. with a K number of 110 and an extraction radius of 923 mm, which is basically the same as the AVF machine in the National Institute of Radiological Science. The acceleration electrode consists of two dees, and the frequency range of the RF system is from 11 ~ 22 MHz. Heavy ion beams extracted from the ECR ion source is axially injected into the cyclotron. The cyclotron also will be equipped with the other external ion source, the duoplasmatron source to inject light ion beams. Beams of proton, deuteron and alpha will be available in wide ranges of energies of up to 90, 53, 108 MeV, respectively, and heavy ion beams of Carbon to Xenon will be accelerated to the energy of 2.5 M to 110 Z^2/M MeV (M:mass number, Z:charge state) by changing the harmonic mode.

The marked features of the JAERI AVF cyclotron are:
(1) Both light and heavy ions are injected into cyclotron by external ion sources,
(2) in order to meet various technical needs in research and development of materials, the cyclotron will have several beam characteristics for irradiation such as expanded irradiation field, pulsed beam, microbeam, combined beam utilization with the tandem accelerator, secondary produced neutron beam, etc., and
(3) a computer aided control system is introduced for rapid setting and switching various control parameters, which results in improvement of the machine utilization efficiency required for multi-purpose uses.

In consideration of independence of each sub-system, the computer system has three stage hierarchy consisting of system control unit (SCU), group control unit (GSU) and universal device controller (UDC). The SCU is connected with GCU by using local network of a few or severel computers. The GCU is connected with UDC by high speed serial transmission line using optical fibers.

The performance of ECR ion source coupled with cyclotron has made remarkable progress in energy, intensity, reliability, and a variety of ion species in the last decade(2). Several ECR sources have produced excellent results with similarity in charge state distribution and extracted intensities, and in regular operation with cyclotron in the university of Louvain-la-Neuve, CEA-Grenoble, Lawrence Barkeley Lab., etc.. Easy maintenance, high beam controllability and reduction of radiation exposure to workers strongly required for an irradiation machine will be also expected by using the ECR ion sources. We decided to introduce OCTOPUS developed in Louvain, one of advanced ECR ion sources, to accelerate heavy ions of helium to xenon. Addition of another ECR ion source is under consideration, to improve the performance of the cyclotron. Metallic ion beam production in the ECR ion source using a simple resistance heated oven is also planned.

The center region geometry of the cyclotron for axial external injection of heavy and light ion beams has been designed on the basis of the injection system of CYCLONE in Louvain. The inflecter and puller will be exchanged with harmonic modes to optimize multi-harmonic mode operation (h=1-3). Optimization of the beam bunching condition and the beam transport system has been carried out to maximize beam transmission in the injection line(3). High transmission of helium ions in the injection line is especially desired because of relatively low beam current extraction from the ECR and the duoplasmatron ion sources compared with proton and deuteron.

The layout of the beam transport of the cyclotron is shown in Fig. 2. The cyclotron will have eight horizontal beam cources; four cources are for light ion beams and the others for heavy ion beams. It also will have four vertical beam cources branching away from the horizontal cources. The beam extracted from the cyclotron can be transported in doubly dispersive mode

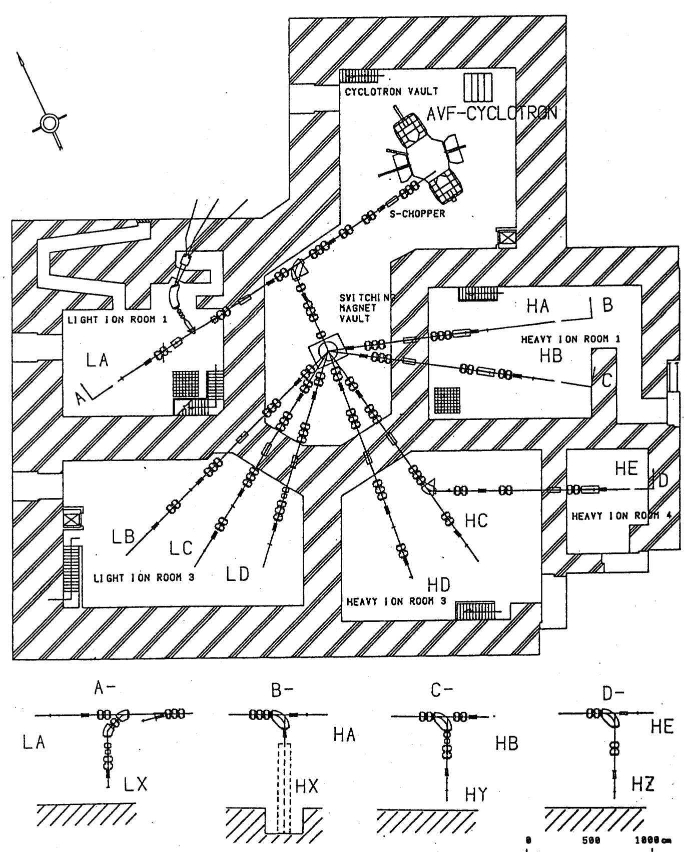

Fig. 2 The layout of the beam transport of JAERI cyclotron

in the most of the beam cources and in doubly achromatic mode in a few beam cources through an 80° analysing magnet and a beam switching magnet with maxmum bending angle of 74°. The cyclotron has four main target rooms on the first floor and four sub-target rooms, each attached to a main-target room, in the basement or on the first floor.

MAIN CHARACTERISTICS OF ION BEAMS

Several characteristics of ion beams in the facilities are summarized in Table 4.

The ion microbeams are required for studies on single event upsets in semiconductor devices, cell processing technology and microdosimetry with wide energy range of heavy ions from several MeV to several hundreds MeV by using the tandem accelerator and the cyclotron, and also required for study on dual-beam analysis with light ions of 1 to 3 MeV by using the Van de Graaff accelerator.

Ion microprobe technology with accelerators has made rapid progress in recent years mainly for the purpose of beam analysis with light ions (4). A spatial resolution of 1 - 2 μm for light ion beams with beam current higher than several tens pA has been achieved in several laboratories by using various lens configurations. The features of our plan are: 1) We intend to apply the microbeam to new fields other than ion beam analysis, and 2) we put emphasis on heavy ion microbeam which so far has been tried little. The first target of this plan is to design a microprobe system for ion beams of Ni and Fe with energy higher than 10 MeV and beam demension of 2 μm or less by using the tandem accelerator, which is required for study on single event upsets. For study on dual-beam analysis with light ion probes, achievement of sub-micron beam is planned with the Van de Graaff accelerator. AVF cyclotrons are basically disadvantageous in microbeam performance, because of the higher energy, the relatively poor energy resolution and the large beam emittance. The optimization of the microprobe design for heavy ions from the cyclotron is an important subject to meet user's requirements.

Expanded irradiation field of high energy proton beam within a fluence uniformity of ±10% is required for evaluation of total dose effects on solar cells and semiconductor devices used in space environment and simulation of radiation damage of organic composite materials exposed to high-energy neutrons. That of high-energy heavy ion beams is also required for study on radiation induced mutation.

Two-dimensional beam scanning with electromagnets will make the best choice for expansion of intense radiation field, though it results in discontinuous exposure. For uniform, high-intensity irradiation of materials and electric parts, it will be necessary to develop the method to measure the profile of fluence or dose and to monitor fluence rate in the expanded field.

Pulsed beam irradiation of high-energy ion beams is required for real time observation of the process of radiation induced chemical reactions, time-resolved analysis of dynamic behavior in ion beam processing and in-beam analysis using recoiled excited nuclei.

Beam chopping in cyclotron enables us to pulsate high-energy ion beams at various intervals (100 ns ~ 1 s) required in the research plan. The duration time of the extracted pulsed beam will be from a few ns to ten ns. It is basically desirable to use fast beam chopping with high-frequency electric field in the injection line, in combination with slow mechanical chopping at the end of beam cources. However, multi-turn extraction in the AVF cyclotron makes it difficult to extract only a single beam bunch from the cyclotron. To solve this problem, another beam chopper with high-frequency sinusoidal electric field(5) is additionally installed after beam extraction from the cyclotron is planned.

Utilization of multiple-beams from plural accelerators is required for ion beam analyses and for various simulation studies on radiation resistance.

Secondary produced neutron beam from a thick berrylium target bombarded with deuterons of energy up to 50 MeV will be used for limited purposes such as studies on the radiation deterioration of organic composite materials. A target room specially designed for neutron irradiation will be arranged in the basement from the standpoint of radiation safety control.

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Table 4. Main Characteristics of Ion Beams Required for the Facility

beam	Accelerator	Ion	Energy Range	Characteristics	Main Applications
Microbeam	T V C	He, C Ni, Fe LI HI	5~15MeV 1~3MeV 30~several hundreds MeV	Beam Dimension ≦2μm Current ~≧数10pA Beam Dimension ≦1μm Current ≧1nA Beam Dimension ≦10μm	Single Event Upset Cell Processing Beam Analysis with Dual-Beam Cell Processing Single Event Upset
Expanded Irradiation Field	C	P HI	5~50MeV ≧300MeV	Field Size ≦100×100mm (High Beam Current) Field Size ≦ 50×50mm	Evaluation of Radiation Resistance Mutation Breeding
Pulsed Beam	C	LI HI	as wide as possible	Pulse Width : several ns Interval : 100 ns~1s	Beam Analysis Radiation Chemistry
Multiple Beam	T + V + I T + I V + I C + T T + V	HI+P+He LI+HI LI+HI O,Cl+HI P+e-	≦several MeV 1~3MeV 1~3MeV ≦100MeV(C) ≦several MeV	Triple-Beam Irradiation Dual-Beam Microbeam(V) Dual-Beam Dual-Beam Irradiation	Nuclear Fusion Reactor Beam Analysis Beam Analysis Beam Analysis Space Radiation Effect
Neutron Beam	C	d(→Be)	10~50MeV	Fluence ≦10^{17}cm^{-2} Field Size : 20×20mm	Materials for Nuclear Fusion Reactor

C : AVF Cyclotron, T : Tandem Accelerator, V : Van de Graaff Accelerator
I : Ion Implanter, LI : Light Ions, HI : Heavy Ions