JAERI AVF CYCLOTRON FOR RESEARCH OF ADVANCED RADIATION TECHNOLOGY

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ABSTRACT

An K = 110 AVF cyclotron is being constructed at the Japan Atomic Energy Research Institute mainly for extensive applications to research and development in materials science. The outline of the cyclotron and accomodations, the ion beam characteristics, and the main application plan are presented.

INTRODUCTION

Ion beam irradiation facilities are under construction for the Advanced Radiation Technology (ART) project in the Takasaki Radiation Chemistry Research Establishment of the Japan Atomic Energy Research Institute. The ART project is based on the background that ion beam irradiation is developing into 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 set forth for research and development.[1] This project is intended to make the most of the characteristics of ion beams and their interactions with matter for various fields of R & D: materials for space environment, materials for nuclear fusion reactors, biotechnology and new functional materials. The main research items are summarized in Table 1.

The main components of the facilities will be an AVF cyclotron (K = 110), a 3 MV tandem accelerator, a 3 MV single-end type Van de Graaff accelerator, and a 400 kV ion implanter. The project is scheduled the commissioning of the first two accelerators is expected to start in 1991. This project requires that the facilities cover many different accelerated ions and a wide range of ion energy to promote the various fields of R & D.[2,3]

Table 1. Main Research Items Planned in the Advanced Radiation Technology Project

I. Research and Development on Radiation-Resistant Material in Severe Environment
- 1) Materials for Space Environment
  - * R & D on Space-Radiation Resistance of Semi-Conductor Devices and Sensors
  - * R & D 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
  - * R & D on Radiation Resistant Organic Composite Materials

II. Research on Bio-Technology and New Functional Materials
- 1) Bio-Technology
  - * Research on Environment-Tolerant Gene Resources
  - * Research on Bionics Materials
  - * Research on Radiation Chemistry of Bio-Materials
  - * Research on New Laveled Compounds
- 2) New Functional Materials
  - * Research on Creation and Modification of Materials
  - * Research on Novel Analysis Technology

III. Related Research
- * Ion Beam Technology

OUTLINE OF AVF CYCLOTRON

The main charactristics of the JAERI cyclotron is shown in Table 2. The cyclotron is of the model 930 of Sumitomo Heavy Industries with a radio-frequency range of 11 - 22 MHz, and is basically the same model as that of The National Institute of Radiological Science in Japan. Moving-panel type resonators originally proposed with the model 930 was replaced by moving-short type ones generating a higher maximum acceleration voltage of 60 kV to make allowance for extracting 90 MeV protons. The coaxial type RF cavity was designed on the basis of a RF feeding test using a 1/4 scale model cavity.

For applying the cyclotron to a wide variety of R & D in materials science, it is required that the cyclotron can accelerate many kinds of ions ranging from proton to xenon in a wide range of energies. Recent development of ECR ion sources and axial beam injection system allowed us to meet the requirement considerably. Both light and heavy ions are axially injected into cyclotron by two external sources, a multi-cusp and an ECR type ion sources. Beams of protons, deuterons and helium ions are available with maximum energies of 90, 53 and 108 MeV, respectively. Heavy ion beams of carbon to xenon can be accelerated

Table 2. Characteristics of JAERI AVF Cyclotron

Cyclotron	
Machine model	Sumitomo Heavy Industries 930
K-number	110
Extraction radius	920 - 930 cm
Number of sectors	4
Number of dees	2
Dee angle	86
Maximum dee voltage	60 kV
RF range	11 ～ 22 MHz
Resonator	Moving short type
Harmonic mode	1, 2, 3
Range of M/Q	1 ～ 6.5
(M:mass number, Q:charge number)	
Charge extraction efficiency	more than 80% (H^+ 90 MeV)
Ion source and injection system	
Injection	Vertical injection
Ion source for light ions	Multi-cusp type
Ion source for heavy ions	ECR type (Octopus)

Range of acceleration energy

H^+	5 ～ 90 MeV	He^{2+}	10 ～ 108 MeV
D^+	5 ～ 53 MeV	Heavy ions	2.5 x M～110 x Q^2/M (MeV)

Extraction current

H^+	90 MeV	10 eμA	He^{2+}	50 MeV	20 eμA
	45 MeV	30 eμA	Ar^{8+}	175 MeV	2 eμA
D^+	50 MeV	40 eμA	Ar^{13+}	460 MeV	10 enA
He^{2+}	100 MeV	10 eμA	Kr^{20+}	520 MeV	10 enA

Beam transport system

Number of main beam courses	8
Number of branch beam courses	6 (4 for vertical courses)

to a energy range of 2.5 M MeV to 110 Q^2/M MeV (M: mass number, Q: charge number). The beam extraction efficiency of 90 MeV protons is designed to be not less than 80 %. We install the ECR ion source OCTOPUS developed in Louvain, and also are planning to develop another ECR ion source to extend the beam utilization of the cyclotron by diversifying species of accelerated ions such as metallic ones and by effective usage of the three external ion sources.

The schematic layout of the two ion sources and the beam injection line are illustrated in Fig. 1. The horizontal part of the line consists of a 90° analyzing magnet (AM) for heavy ion beams from the ECR ion source, an inflection magnet (IM) which also serves for analyzing light ion beams from the multi-cusp ion source, and six solenoids. A 90° bending magnet (BM) brings the beam to the vertical part of the injection line consisting of two solenoids and Glaser lenses. The solenoid lenses were adopted to transport ion beams with large profiles extracted from the ECR ion sources.[4] The spiral inflector guiding the axially injected beam to the median plane and the puller are prepared individually for each harmonic mode (h = 1, 2, and 3).

The schematic layout of the beam transport system for the cyclotron is illustrated in Fig. 2. The system has eight main horizontal beam courses; four cources, LA～LD, are for light ion beams, and the other four, HA ～ HD, for heavy ion beams. It also has two horizontal branch beam courses, LE and HE, and four vertical branch beam courses, LX and HX～HZ. The beam extracted from the cyclotron can be transported in doubly achromatic mode in several courses through an 80° analyzing magnet and a beam switching magnet with a maximum bending angle of 74°. The focused beam diameter at the end of all the beam courses are estimated 5 - 10 mm from calculation of particle trajectories by using the computer code TRANSPORT.

The experimental area on the first floor consists of four main target rooms separated from each other by thick concrete walls of 3 - 3.5 m thickness. Other three target rooms for vertical beams are located in the basement. Each basement room is not independent from its adjacent main room in radiation safety.

The cyclotron system can be almost fully controlled by three mini-computers. In consideration of independence of each sub-system of the cyclotron, the computer system has three-stage hierarchy consisting of a system control unit (SCU), group control units (GCU), universal device controllers (UDC). SCU is connected with GCU by using a local area network. GCU is connected with UDC by a high speed serial transmission line. It is expected that rapid parameter setting and switching by computer control result in improvement of the machine utilization efficiency required for many purpose uses of the cyclotron.

Present status of the cyclotron construction is as follows; Magnetic field measurements of the cyclotron magnet has finished and assembling the whole system is going to start in Sumitomo Heavy Industries. Both ion sources are now tested in Ion Beam Application s.a..

The first harmonic in the field is desired to be less than a few gauss, because the radial oscillation frequency ν_r nearly equals 1. The first harmonic is less than 4 gauss in the accelerated beam region at all excitations. It can be corrected by adjustment of four extraction harmonic coils.

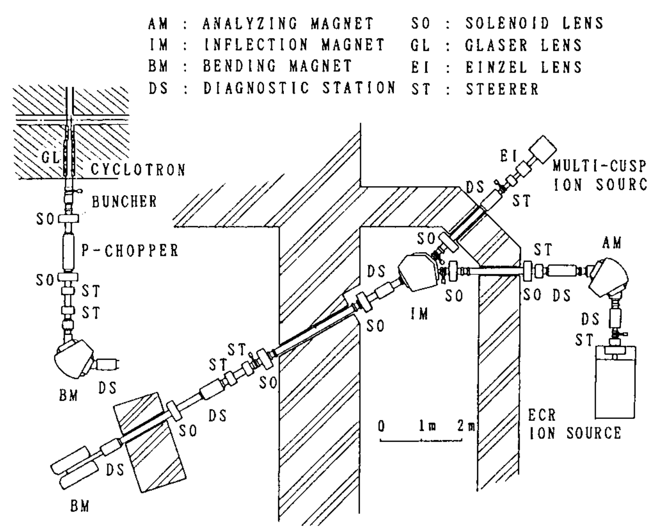

Fig. 1. The layout of the two ion sources and the injection beam line

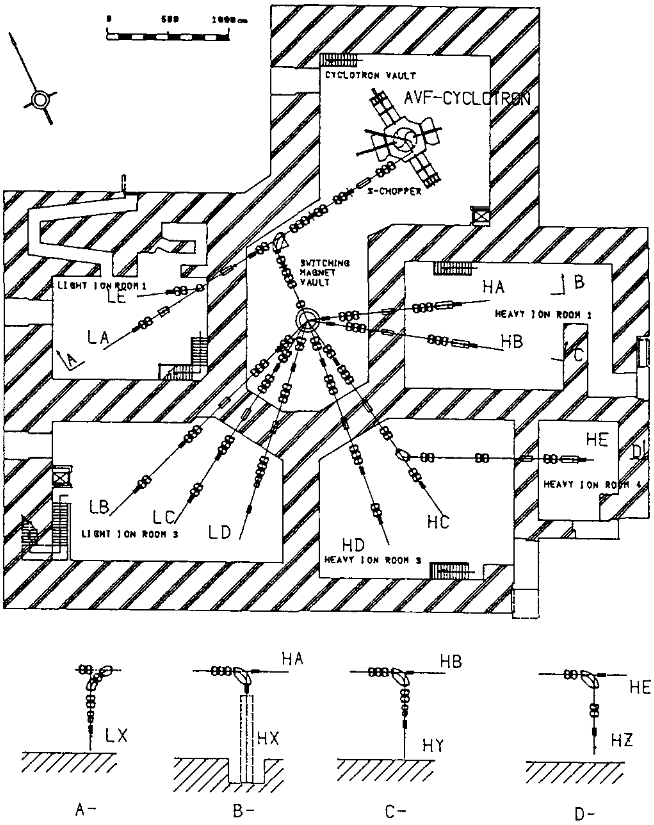

Fig. 2. The layout of the beam transport system for the cyclotron

The ion beam facilities to be completed in 1992 are illustrated in Fig. 3. It consists of the cyclotron building, the multiple beam building and the ion beam research building, all of which are combined functionally as a whole.

ION BEAM CHARACTERISTICS AND APPLICATION

Cyclotrons have been so far used mainly for fundamental research of nuclear physics and medical applications to radioisotope production and radiation therapy. The JAERI cyclotron is the first one in Japan which will be mainly applied to wide fields of R & D in materials science. In order to meet various requirements for beam utilization in the above research program shown in Table 1, the cyclotron provides several ion beam characteristics which are summarized in Table 3; those are high-energy, intense ion beam scanning for uniform irradiation over a wide area, beam chopping for pulsed beam irradiation, secondary produced neutron beams, etc.. The utilization of high-energy, heavy-ion microbeams and a dual-beam combined with a beam line from the tandem accelerator are also planned as advanced applications of the cyclotron.

Heavy ion beams with particle energies up to several hundreds MeV, providing high linear energy transfer (LET) and relatively deep penetration, will be in use especially for simulating error rate due to single event upsets of semiconductor devices such as the LSI memories in galactic cosmic-ray environments. The irradiations for simulating the single event are planned in heavy ion room No. 4 which will be kept in the lowest radiation-level environment. The above heavy ion beams is also planned in use for studying the uniqueness of mutations induced by the beams.

Uniform proton beam irradiation over wide area, within a field size of 100 x 100 mm, will be available in LD course by using two dimensional beam scanning with electromagnets. It is to be used mainly for evaluating aged deterioration (total dose effect) on solar cells and semiconductor devices for use in space, and for assessing high-energy neutron induced deterioration in the nuclear fusion reactor environments of organic composite materials. These proton irradiation effects will be compared with gamma-ray and electron beam irradiation effects. The Takasaki site of JAERI will fulfil the function as a centre laboratory for irradiation tests of various materials with different radiation quarities.

The cyclotron is planned in use for two high-energy neutron sources by bombarding a thin beryllium target with protons in the switching magnet room and a thick beryllium target with deuterons in LX course. The first one provides a monochromatic fast neutron sourse with an energy range of 20 to 90 MeV. It is to be mainly applied to produce basic experimental data on neutron shielding required for shielding design of high-energy accelerator facilities. The second one is intended to provide more intense neutron beams within an integrated fluence of about 10^{17} cm^{-2} and uniform irradiation within a field size of 20 x 20 mm. It will be mainly used for basic research on the bahavior of aged deterioration of organic composite materials and electronic devices for nuclear fusion reactors, though it does not provide high fluence enough to be applied for direct evaluation of the radiation resistance.

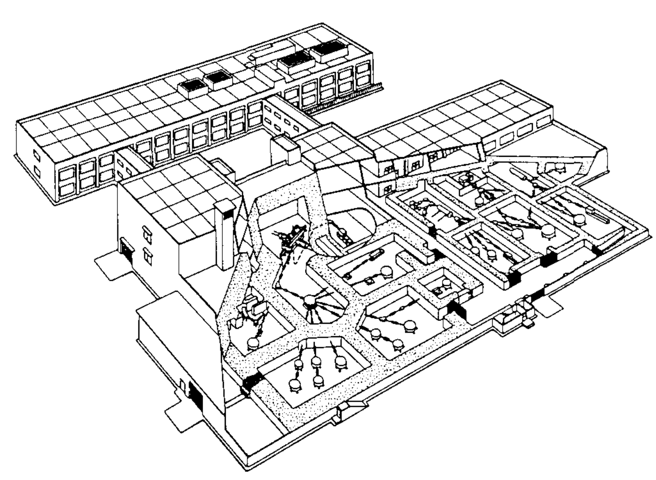

Fig. 3. Ion beam irradiation facilities under construction for the Advanced Radiation Technology Project

Pulsed beam irradiation of high-energy heavy-ion beams is planned in use for the in-situ analysis of the elementary process in the materials exposed to ion beams, basic research on radiation chemical reaction process, etc.. The first one includes research on microdosimetry and track structure of heavy-ions using low beam current density microbeams. The second one includes time-resolved analysis of dynamic behavior in ion beam processing, in-beam analysis of ion-implanted materials using excited nuclei produced by nuclear reaction and recoil, etc..

Beam chopping for the cyclotron enables us to provide high-energy ion beam pulses at various intervals (1 μs ~ 1 ms) required in the above research plan. It is basically easy to equip the injection line with a pulse-type beam chopper with the injection beam line. However, multi-turn extraction from the cyclotron and limitation of the beam chopper performance make it difficult to extract only a single beam pulse from the cyclotron. To solve the problem, we install another beam chopper applying high-frequency sinusoidal voltage wave after beam extraction from the cyclotron.[5] The minimum duration time of the single extracted pulse will be expected to be within a few nano seconds.

Heavy-ion microbeam with energies up to several hundreds MeV will be also one of beam characteristics of the cyclotron. Use of the microbeams is planned in HA and HX courses for research on cell remodeling technology, microdosimetry, and single event upsets in semiconductor devices, etc.. AVF cyclotrons have inherent disadvantages for focusing ion beams because of the limited brightness and large energy spread and divergence. In most microbeam applications under planning, however, a much simpler beam collimation method to restrict the beam area by use of a pinhole at the end of microbeam line will be used at the first stage of our plan, because extremely low beam current density is enough at the targets for the applications. The application to the cell remodelling technology requires a single ion hit into a localized region to be aimed in a cell.

Another plan for characterizing beam utilization is the dual-beam combined with a beam line from the 3 MV tandem accelerator at the end of HZ course. It will be applied to the in-situ analysis of the elementary processes in modification of semiconductor materials.

The cyclotron is also applied to R & D of radioisotopeproduction and labeling technique for use in medicine, agriculture, biochemistry and pharmacology in LA and LE courses. An electromagnetic on-line isotope separator with high mass resolution is installed and connected with the LE course. Production of relatively long-life positron emitters are planned for developing the production technique of monochromatic positron beams.

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Table 3. Main Caracteristic Beam Applications of the JAERI AVF Cyclotron (LI:Light ions, HI:Heavy ions)

Utilization method	Particle	Energy range	Beam characteristics	Applied research field
Uniform irradiation for expanded field	p HI	5 - 50 MeV ≧ 300 MeV	Field size≦ 100 x 100 mm (high beam current) Field size≦ 50 x 50 mm	Research on aged deterioration of materials and devices Mutation breeding
Pulsed beam	All the particles	Almost full range of energy	Pulse width:~ a few ns Pulse interval:1 μs - 1 ms	Radiation chemistry Ion beam analysis
Neutron beam	d (→Be)	10 - 50 MeV	Field size≦ 20 x 20 mm Fluence ≦ 10^{17} cm^{-2}	Research on radiation deterioration, etc.
	p (→Be)	20 - 90 MeV	Monochromatic neutron beam	Data base for neutron shielding
Microbeam	HI, He	Almost full range of energy	Extremely low fluence rate and single ion hit	Cell remodeling technology Research on single event upset
Multiple-beam from accelerators	O, Cl He	≦100MeV(cyclo.) 1-3MeV (tandem)	Dual-beam (one from 3MV tandem accelerator)	Ion beam analysis
Vertical beam	He, HI	HI, He	Uniform irradiation in air Field size≦ 50 x 50 mm	Radiation chemistry and biology Microdosimetry