CONSTRUCTION AND FIRST YEAR'S OPERATION OF THE JAERI AVF CYCLOTRON

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ABSTRACT

The construction of the JAERI AVF cyclotron was started in 1988. The first beam, 50 MeV $^4He^{2+}$ ion, was extracted from the cyclotron in March, 1991! The performance of the cyclotron has been tested with several kinds of ions in a wide energy range. The present report outlines the cyclotron system and shows major results in the first year's operation.

1. INTRODUCTION

Takasaki Ion Accelerators for Advanced Radiation Applications (TIARA) including an AVF cyclotron have been constructed at the Takasaki Radiation Chemistry Research Establishment of the Japan Atomic Energy Research Institute (JAERI).[1] The Advanced Radiation Technology (ART) project is intended to make effective use of the characteristics of ion beams and their interactions with matter for R & D on materials for space environment and nuclear fusion reactors, and for research on biotechnology and new functional materials.

The JAERI AVF cyclotron is of the model 930 of Sumitomo Heavy Industries, Ltd. (SHI), the same model as the CYCLONE (Université Catholique de Louvain, Belgium), the IRE cyclotron (Institut National des Radioelements, Belgium) and the NIRS-Chiba cyclotron (National Institute of Radiological Sciences, Japan). The latter three cyclotrons have movable panel type resonators with a peak RF voltage of 50 kV. The movable-panel type one originally proposed was replaced by the coaxial type resonator in order to make allowance for generating a higher maximum dee voltage of 60 kV, which is required for accelerating 90 MeV protons. In order to meet technical requirements in the research plan of the ART project, we modified or improved the design of the accelerator system as follows; (1) The system is equipped with two external ion sources, an ECR source for generating heavy ions and a multicusp source for generating light ions.[2] (2) The system is equipped with a beam chopping system[3] for pulsed beam operation and beam scanning systems for uniform irradiation to the wide area of target samples. (3) A distributed computer control system is introduced for rapid and reliable control of operation parameters.[4] (4) In order to reduce the radiation exposure of operators, the cyclotron is equipped with automatic changing systems for inflector and puller electrodes. A remote controlled conveying system makes a deflector remove from the cyclotron and guide to a cooling room.

The construction of the cyclotron was started in 1988. The field mapping for the main magnet was carried out from December, 1988 to March, 1989 and the performance of the RF system was tested from October, 1989 to March, 1990 at the Niihama works of SHI. The cyclotron was installed at JAERI, Takasaki, in July, 1990. The beam generation test has been started from March 1991. The cyclotron has been used for experiments since January 1992.

2. OUTLINE OF JAERI AVF CYCLOTRON

Figure 1 shows a photograph of the cyclotron. A schematic drawing of the cyclotron is shown in Fig.2 and the major characteristics of the JAERI AVF cyclotron are shown in Table 1.

The cyclotron is a 4-sectored variable-energy AVF machine with an extraction radius of 923 mm. The acceleration electrodes consist of a couple of 86-degree dees, each connected with a resonant cavity. Beams of protons, deuterons and helium ions are available with maximum energies of 90, 53 and 108 MeV, respectively. Heavy ion beams can be accelerated to an energy range of (2.5×M) MeV to ($110\times Z^2/M$) MeV, where M is mass number and Z is charge state. Acceleration harmonic numbers of 1, 2 and 3 are available.

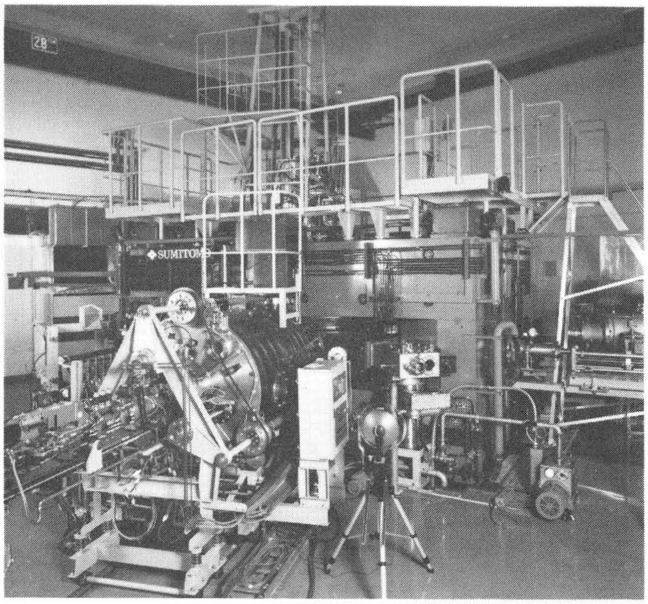


Fig. 1. Photo of the JAERI AVF cyclotron.

2.1. Magnet

The cyclotron magnet consists of a H-type with a pole diameter of 2156 mm and four spiral sectors. Twelve pairs of circular trim coils are wound concentrically on the sectors. Four pairs of harmonic coils are placed in the central region for centering the off-centered beam. Another four pairs of harmonic coils are placed in the extraction region for fine adjustment of turn separation. The field mapping on the median plane in the cyclotron was done in polar coordinates of (r,θ). A Hall probe was moved by 2 cm steps in r and 1.8 degree steps in θ.

The maximum field strength at the extraction radius is 16.7 kG, which is high enough to produce the isochronous field for heavy ions with high energy. The strength of the first harmonic field was less than 4G within the extraction radius, which can be corrected by optimizing the harmonic coil field.

Two pairs of the harmonic coils were excited at a maximum current with opposite polarity. The maximum first harmonic amplitudes at r=200 mm and r=860 mm at a base field of 850A are 17G and 27G, respectively. The isochronous field for light to heavy ions can be produced accurately based on the measured field of main and trim coils. The isochronous field is reproducible within a precision of 4×10^{-4}.

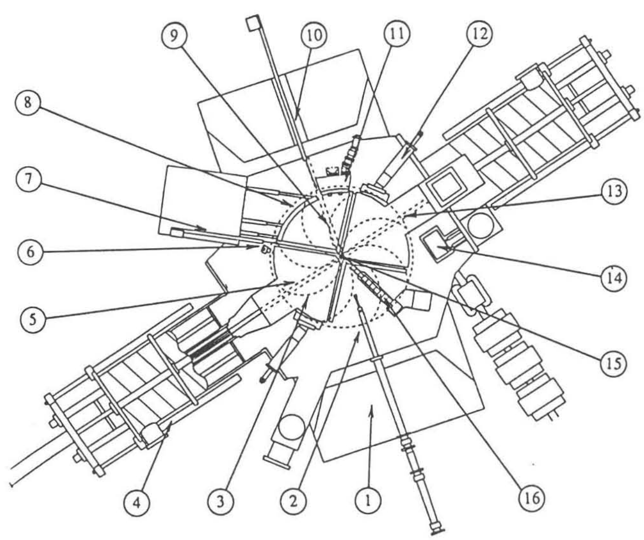
2.2. RF System

A maximum dee voltage of 60 kV was required to realize a constant orbit of harmonic 1 acceleration for 90 MeV protons. The power loss on the stem in the movable panel type resonator makes it difficult to generate the dee voltage of 60 kV. The asymmetrical structure of the cavity results in partial increment of a current density on the stem facing the tuning panel, causing thermal damage due to the local power loss. The final amplifier with large output power above 80 kW is required to generate 60 kV for movable-panel type resonator.

In consideration of the difficulty, the $\lambda/4$ coaxial type resonator with a movable shorting plate was adopted for JAERI AVF cyclotron. The coaxial type one has a higher Q-value because of the symmetrical current density distribution, allowing relatively low output power within 30 kW for the final amplifier. The resonant frequency ranges from 10.6 to 22.0 MHz, and is finely tunable within a relative frequency $\Delta f/f$ of 1.6 %. The maximum peak dee voltage of 60 kV at 21.14 MHz is generated within a stability of $\pm1\times10^{-3}$. The details of the RF system are reported in a separate paper at this conference.[5)]

2.3. Injection, Central Region, Extraction

Low-energy beams from the ion sources, located in the basement, are axially injected into the median plane of the cyclotron upwards through the hole of the bottom yoke. Four Glazer lenses and a steerer are placed inside the hole. The injected beam is guided to the median plane through a spiral inflector and a puller, which are prepared separately for each acceleration harmonic number from 1 to 3. The inflector is inserted downwards through the hole of the upper yoke. The layout of the central region is shown in Fig.3. Two movable phase defining slits are set inside the dee and the dummy



(1) Yoke, (2) Main probe, (3) Dee, (4) Resonator, (5) Puller, (6) Dee voltage pickup, (7) Deflector probe, (8) Deflector, (9) Phase slit(II), (10) Magnetic channel probe, (11) Magnetic channel, (12) Capacitive frequency tuner, (13) Phase slit(I), (14) Gradient corrector, (15) Inflector, (16) Phase probe

Fig. 2. Schematic drawing of the AVF cyclotron.

Table 1. Characteristics of JAERI AVF cyclotron

CYCLOTRON		
Number of sectors		4
Sector gap		166 mm
Pole gap		405 mm
Pole diameter		2156 mm
Spiral angle		53 degrees
Extraction radius		923 mm
Max. average field		16.7 kG
Circular trimming coils		12 pairs
Harmonic coils		8 pairs
Magnet weight		206 tons
Bending limit		110 MeV
Focusing limit		95 MeV
Number of dees		2
Dee angle		86 degrees
Frequency		10.6 - 22 MHz
Max. dee voltage		60 kV
Max. RF power		50 kW x 2
Resonator		movable short plate (mode $\lambda/4$)
Harmonic number		1,2,3
Main vacuum pump		Cryogenic (4000 L/s, 4 sets)
Range of M/Z (M:mass, Z:charge state)		$1 \sim 6.5$
RANGE OF ACCELERATION ENERGY		
Light ions	H^+	$5 \sim 90$ MeV
	D^+	$5 \sim 53$ MeV
	$^4He^{2+}$	$10 \sim 108$ MeV
Heavy ions	$2.5 \times M$	$\sim 110 \times Z^2/M$ MeV

dee within the first turn.

The beam extraction system consists of an electrostatic deflector and a magnetic channel and also of a gradient corrector to focus the beam horizontally. For the purpose of minimizing the deflector voltage to extract 90 MeV protons, the maximum field of magnetic channel was improved from 3.5 kG to 4.3 kG by adding a chilling unit in the water cooling system.

2.4. Beam Diagnostics

A main radial probe, a deflector probe, a magnetic channel probe and a set of phase probes are placed inside of the acceleration chamber of the cyclotron for beam diagnostics. The main probe is inserted through a hole of the side yoke and its stroke covers 1150 mm (r=40~1190 mm). The main radial probe head provides three finger-like electrodes to measure the beam current differentially and integrally. The phase probes consist of ten pairs of rectangular pickup electrodes of copper to measure the relative phase of beams on different turns (r=236~893 mm). The amount of field correction necessary for the outer 10 circular coils is calculated using the phase differences measured by this probe.

A baffle slit system consisting of four leaves is placed just before the entrance of the inflector. Other baffle slit systems are placed at the entrance of the magnetic channel and the gradient corrector. Another baffle slit system is also placed at the extraction hole of the acceleration chamber.

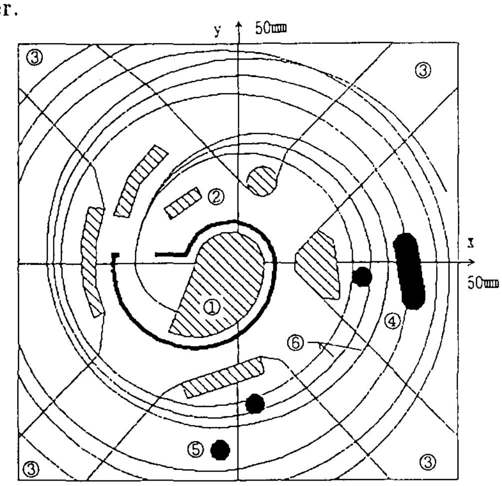


Fig. 3. Schematic drawing of the central region of the cyclotron. (1) Inflector, (2) Puller, (3) Dee gap, (4) Phase slit(II), (5) Phase slit(I), (6) Beam trajectories (dee voltage 40,50 and 60kV)

3. RESULTS OF FIRST YEAR'S OPERATION

3.1. Extraction Current and Transmission

The first beam, 50 MeV $^4He^{2+}$, was extracted from the cyclotron in March, 1991. The beam acceleration tests have been conducted for H^+(10, 45, 70 and 90 MeV), D^+(10, 35 and 50 MeV), $^4He^{2+}$(20, 50 and 100 MeV), $^{40}Ar^{8+}$(175 MeV), $^{40}Ar^{13+}$(460 MeV) and $^{84}Kr^{20+}$(520 MeV). The results of the beam acceleration test are summarized in Table 2. Protons and deuterons are generated by the multicusp ion source, and other ions by the ECR ion source.

The 90 MeV protons were successfully extracted with a beam current of 10 μA. The stability of extracted beam for light ions is typically ±5%. The overall transmission from ion source analyzing magnet to cyclotron external beam is typically 4~5%. The extraction efficiency is the intensity ratio of main probe at r=900 mm to magnetic channel probe (just after deflector). The best transmission and extraction efficiency are 15% ($^4He^{2+}$ 50 MeV) and 89% (H^+ 70 MeV), respectively! The phase slit I on the opposite side of the puller is effective to optimize the extraction efficiency through the deflector. The transmission from cyclotron entrance to r=200 mm is about 20%. This is limited by mainly the RF phase acceptance and the efficiency of a beam buncher installed just at the entrance of the cyclotron. Measured bunching efficiency is about 2.5. The estimated transmission is $2.5 \times 30/360 = 21\%$ assuming that the phase acceptance is 30 degrees.

Table 2. Results of extracted intensity and transmission.

Ion	Energy (MeV)	Harmonic No.	Frequency (MHz)	Injection Voltage (kV)	Extracted Intensity (e μ A)	Extraction Efficiency (%)	Overall Transmission (%)
H^+	10	2	14.97	3.10	10	54	3.8
	45	1	15.46	8.64	30	85*	4.0
	70	1	18.92	12.47		89*	4.0
	90	1	21.14	16.11	10	53*	2.0
D^+	10	2	10.63	3.10	11	45	3.7
	35	2	19.70	11.00	41	71*	4.6
	50	1	11.76	9.53	21	64*	7.2
$^4He^{2+}$	20	2	10.67	3.40	5.7	55	11
	50	2	16.77	8.53	20	82*	15
$^{40}Ar^{8+}$	100	1	11.81	10.15	10	51	6.4
	175	3	15.14	10.06	3.0	60	5.7
$^{40}Ar^{13+}$	460	2	16.24	11.71	0.011	26	2.8
$^{84}Kr^{20+}$	520	2	11.98	8.81	0.004	17	1.0

* Phase slit 1 is inserted.

3.2. Correction of Isochronous Field by Phase Probe

Deviation of magnetic field from the isochronous one can be corrected using the phase probe. The typical pickup signal induced by ion beams is shown in Fig.4. The signal voltage is adjusted by a variable attenuator and a 40 dB fast amplifier. The amount of correction to reduce the deviation for 10 outer circular coils is calculated by the least squares method. After corrections repeated a few times, the phase difference becomes negligibly small.

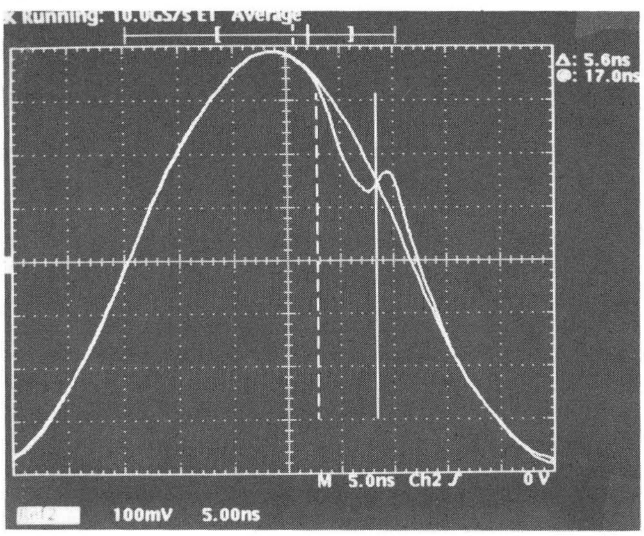


Fig. 4. Typical beam signals measured by the phase probe(CH10) in case of 70 MeV protons.

3.3. Emittance

The phase space configuration of extracted beams can be measured by an emittance monitor at the exit of cyclotron. The horizontal and vertical emittance for $^{40}Ar^{8+}$ 175 MeV are 14.0 πmm·mrad and 9.9 πmm·mrad, respectively.

4. REFERENCES

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