INJECTOR AVF CYCLOTRON AT RIKEN

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ABSTRACT

A K70 AVF cyclotron, which is used as an injector of the K540 RIKEN Ring Cyclotron (RRC) for light and light heavy ions, was completed at the end of March 1989. The first beam, 7 Mev/u $^{14}N^{5+}$ ion, was successfully extracted from the cyclotron in April. This paper gives a general description of the cyclotron and shows some results and experiences in its first operation.

1. INTRODUCTION

The RIKEN Ring Cyclotron (RRC) is designed to have two injectors, a heavy-ion linac (RILAC) and an AVF cyclotron, for both light and heavy ions. After its completion in November 1986, RRC has been in routine operation[1] coupled with RILAC, which offers mainly heavy ions. The AVF cyclotron is designed so as to be used as an injector to get high energies for light and light heavy ions. In coupled use with RRC, the final energies designed are 210 MeV for protons, 135 MeV/u for ^{12}C, ^{14}N and ^{16}O, 95 MeV/u for ^{40}Ar and so on.

Construction of the injector AVF cyclotron started in May 1987. The model 750PV[2] of Sumitomo Heavy Industries, Ltd. (SHI) was decided to be purchased and to be modified to meet the requirements for the injector as well as an external injection. After completion of the cyclotron magent, magnetic fields were measured at the factory of SHI in April 1988. From the begining of May to the end of November, other parts of the cyclotron including the vaccum chamber, the RF system, the main radial probe, the deflector and the magnetic channel were preliminarily assembled there. Almost all the problems found in a series of tests on leak, operation and RF were solved during this period. The installation of the cyclotron in the RIKEN cyclotron vault started at the begining of December 1988 with completion at the end of March 1989.

2. DESCRIPTION OF THE AVF CYCLOTRON

Figure 1 shows a photograph of the cyclotron as viewed from the downstream of the extraction beam line. A schematic drawing of the cyclotron is shown in Fig.2 and its characteristics in Table 1.

2.1 Magnet and Magnetic Field

The magnet is of the H-type with four spiral sectors. Pole diameter was chosen to be 1730 mm by taking account of the extraction radius of 714 mm, which was determined from the matching condition to RRC.[3] Nine pairs of circular trim coils are wound on the sectors and four pairs of harmonic coils are placed in the extraction region of valley sections.

Maps of base field and trim field were measured after determining the most appropriate field setting procedure similar to that in Ref.4). Base field maps were measured for eleven levels of main coil currents. Trim field maps were measured for the maximum current of each trim coil at each level of six main coil currents, after confirming for a few trim coils that the distribution is proportional to the trim coil current. The reproducibility of field distribution was better than 2×10^{-4}. The excitation characteristics as well as the flutter and the betatron frequencies agreed well with the design. An unexpected first harmonic field of several G at the maximum appeared at high excitation levels. The direction of this harmonic field lay nearly along one of the sector-center line. We found, however, from the computer simulation that this occurrence is tolerable and the designed extraction energy can be obtained. The data base of average fields along equilibrium orbits, which will be used to produce an isochronous field, was deduced from the results of the measurement.

2.2 RF

Two-dee system with a dee angle of 85° is adopted. The resonator is of the $\lambda/4$ coaxial type with a movable shorting plate. The coaxial part is perpendicularily connected to the dee plate as shown in Fig.2.* The frequency range is 12-24 MHz and the required voltage is 50 kV at the maximum. A capacitive tuner (a compensator) is used for automatic fine tuning. The acceleration gap is 12 - 24 mm (radially increasing) and the vertical aperture is 24 mm. Measured resonant frequencies, Q-values and shunt impedances were reproduced well by the calculations that were based on a transmission line approximation. The power amplifier system consists of a 500 W solid-state wide-band amplifier and a grounded-cathode tetrode amplifier (EIMAC 4CW50,00E). A schematic diagram of the system is shown in Fig.3. An all-pass network is adopted in the input circuit of the tube. A transformer is used to match the input impedance of the all-pass network (25 Ω) to the output impedance of the wide-band amplifier (50 Ω). The power tube is capacitively coupled to the resonator with a coupling capacitor.** The combination of the wide-band amplifier and the all-pass network system was adopted because of easiness for operation and maintenance.

* SHI patent
** SHI patent (pending)

2.3 Injection /Central Region/Extraction

An electrostatic inflector is used to bend a beam onto the median plane of the cyclotron. The inflector is of the spiral type whose electric radius and magnetic radius are 26 mm and 16.3 mm, respectively. The gap between two copper electrodes is 5 mm and voltages of up to ±5 kV are fed to the electrodes. By taking the effective field boundary into account, each of the entrance and exit ends of the electrode were cut by 2.5 mm from the position calculated with a hard edge approximation. The inflector is inserted through the hole of the lower yoke. It can be rotated by 5° and can be adjusted vertically by ±5 mm. Figure 4 shows a photograph of the inflector.

One of the most significant changes from the 750 PV is that with respect to the central region of the cyclotron. To design this region, a computer program was developed that simulates a beam orbit and the acceptance of the cyclotron and so on. The layout in the central rgion thus determined is shown in Fig. 5. This was designed only for the case of harmonic number equal to 2.* Pillars are placed at the first two gaps. The nose part of the electrode in this region is remountable for maintenance or repair. A movable phase defining slit is set on the first turn inside the dummy dee. The position and the gap of the slit are remotely movable by 10 mm each.

* The cyclotron was before designed to be used not only as an injector but also as a stand-alone machine which can accelerate, for example, protons up to 60 MeV[3]. The acceleration harmonic number was adopted to be 2 and 1 for each purpose. The harmonic number 1 designed for a stand-alone machine, however, was abandoned at least for the time being because if both harmonic numbers are used the central region of the injection system will be very complicated.

A beam is extracted by means of an electrostatic deflector and a magnetic channel. After the magnetic channel a gradient corrector is placed to focus a beam radially. The gradient corrector is of the passive type that produces inside it an opposite field gradient to that of the fringe field. The gradient changes from 0.6 kG/cm to 2.6 kG/cm according to the excitation level of the cyclotron. The linearity of radial distribution of the measured gradient was quite good. The positions of the deflector, the magnetic channel and the gradient corrector can be remotely controlled by 20, 10 and 5 mm, respectively.

The details of beam dynamic aspects of the injection, the central region and the extraction are given elsewhere at this conference.[5]

2.4 Beam Diagnostics

The concept of design of beam diagnostic system is the same as that of RRC.[6] As shown in Fig. 2, a main radial probe, a deflector probe and phase probes are placed inside the cyclotron for beam diagnostics. The main probe is inserted through the hole of the side yoke. The probe head has three finger-like electrodes for the differential measurement and an electrode for the integral measurement. An orbit pattern near the extraction can also be measured with the deflector probe in front of the entrance of the deflector. The probe head consists of three tungsten wires of 0.1 mm in diameter, the surfaces of which are gold-plated. Its stroke is 100 mm. The phase probes are used to measure the relative phases of beams on different turns. They are made of parallel plates of glass epoxy on which six pairs of rectangular pickup electrodes are formed by coating solder. These probes are very helpful to get an isochronous field. In front of the entrance of the inflector a buffle slit divided into four leaves is placed to get information on whether a beam clears the element or not. A buffle slit vertically divided into two is placed in front of the electrode of the deflector, and that horizontally divided into two is attached to the entrance of the magnetic channel and the gradient corrector.

Details of the diagnostic devices used in the beam trnsport line are given in Ref.6).

2.5 Vacuum

The vacuum chamber is made of alminum. Two cryopumps of 6,500 and 4,000 l/sec and a turbo-molecular pump of 1,500 l/sec are used to evacuate the chamber. Because trim coils and harmonic coils are sources of outgassing, they are sealed with the grounded plate of RF from the high vacuum. The pressure inside this section is 10^{-2} - 10^{-3} Pa. A pressure of better than 1×10^{-5} Pa was achieved with this evacuation system.

2.6 Injection and Extraction Beam Transport

Ion sources such as an ECR source and a duoplasumatron are used for this cyclotron. The ECR soruce has been completed and provides us with a good performance.[7] A beam from these ion sources, which are situated in the room over the cyclotron vault, is injected axially through the hole of the upper yoke.

A beam buncher is placed at 2 m upstream from the inflector. The buncher has a single gap formed with two meshes, one of which is excited by an optimal combination of f_0, $2f_0$ and $3f_0$ giving a sawtooth-like wave.[8] The maximum required voltages are 380, 230 and 80 V for f_0, $2f_0$ and $3f_0$, respectively. Figure 6 shows an example of wave-form measured with an oscilloscope. This is expected to make the bunching efficiency significantly high.

A beam rebuncher is used in the beam line between the AVF cyclotron and RRC to make a beam time-focused at the injection point of RRC. The resonator of the rebuncher is of the shielded Lecher-wires type with two stems. At the end of each stem a drift tube is mounted, which forms three gaps. The resonant frequency is twice that of RRC, i.e. four times that of the AVF cyclotron. The maximum required voltage is 40 kV. The maximum power loss is estimated to be 2 kW. Figure 7 shows a photograph of the beam rebuncher being installed in the beam line.

Layouts of the injection and extraction beam transport lines as well as beam optics in these systems are given elsewhere at this conference.[5]

2.7 Control

All the system of the cyclotron is remotely controlled and monitored by means of the same computer control system as that of RRC[9].

3. FIRST OPERATION

We succeeded in extracting the first beam from the AVF cyclotron in April 1989 . The ion accelerated was 7 MeV/u $^{14}N^{5+}$. Two days had passed from the start of operation when we detected a beam with the profile monitor at the downstream of the cyclotron. (The time consumed for actual operation was as short as twelve hours.) Figure 8 shows the orbit pattern measured with the main radial probe. The number of revolutions is about 100. It is noted that the turn separation can be seen up to the last revolution. During this operation many parameters such as the dee voltage and the position of the inflector, the phase defining slit, the deflector and the magnetic channel were kept at their precalculated values. The isochronous field was obtained only by adjusting the main coil current. The measurement with the phase probes showed that the phase excursion stayed within $\pm 5^{\circ}$. Slight change of the inflector voltage from its calculated value was enough to get the maximum injection efficiency. It was necessary to fed higher voltage and lower current than the calculations to the deflector and the magnetic channel, respectively. The gradient corrector was shifted outward by 3 mm from the presetted position. The beam buncher was excited by only the fundamental frequency in this operation. The extracted beam current doubled with the buncher switched on. A beam current of 20 eμA reduced to 2 eμA after injection and further reduced to 0.2 eμA after extraction. No loss of the beam was seen during the acceleration. It is noted that some of the beam was lost by the buffle slit in front of the inflector and that the gap of the phase slit was set to define a beam within $\pm 10^{\circ}$. Although the transmission efficiency of 1 % is not yet so good, it is expected to be improved by sufficient tuning in the future. Use of various beam diagnostic devices including the buffle slits of the injection and extraction elements was essential for the smooth operation.

REFERENCES

1) Y. Yano , "Status Report on RIKEN Ring Cyclotron," presented at this conference.
2) K. Fujii et al., "25-70 MeV Variable Energy Cyclotron for Radio-Isotope Production," in Proceedings of the 11th Int. conf. on Cyclotrons and their Applications, 1986, pp. 626-629.
3) N. Nakanishi et al., "AVF-Cyclotron as an Injector for RIKEN Ring Cyclotron," in Proceedings of the 11th Int. Conf. on Cyclotrons and their Applications, 1986, pp. 511-514.
4) A. Goto et al.,"Isochronous Fields for RIKEN Ring Cyclotron,"in Proceedings of the11th Int. Conf. on Cyclotrons and their Applications, 1986, pp.292-295.
5) A. Goto et al.," Study of Beam Optics for the Injector AVF Cyclotron at RIKEN," presented at this conference.
6) M. Kase et al., "Beam Diagnostic Equipments for RIKEN Ring Cyclotron and Its Beam Lines, " in Proceedings of the 11th Int. Conf. on Cyclotrons and their Applications, 1986, pp.443-446.
7) K. Hatanaka et al., "Staus of the RIKEN ECRIS," presented at this conference.
8) G. Haushahn et al., " Status Report of the Axial Injection System at the Karlsruhe Isochronous Cyclotron, " in Proceedings of 7 th Int. Conf. on Cyclotrons and their Applications, 1975, pp. 376-380.
9) T. Wada et al., "Control System of the RIKEN Ring Cyclotron," in Proceedings of the 11th Int . Conf. on Cyclotrons and their Applications, 1986, pp. 407-409.

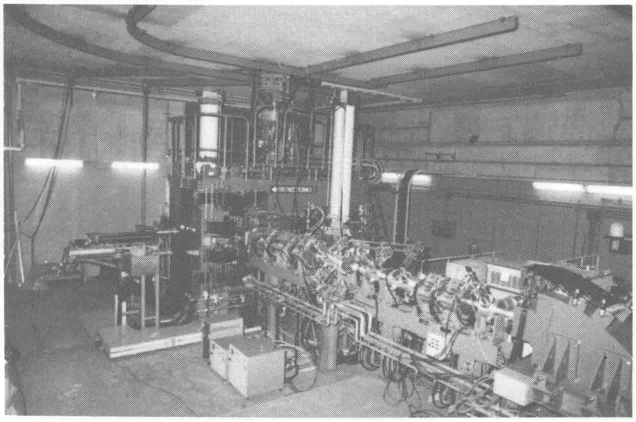
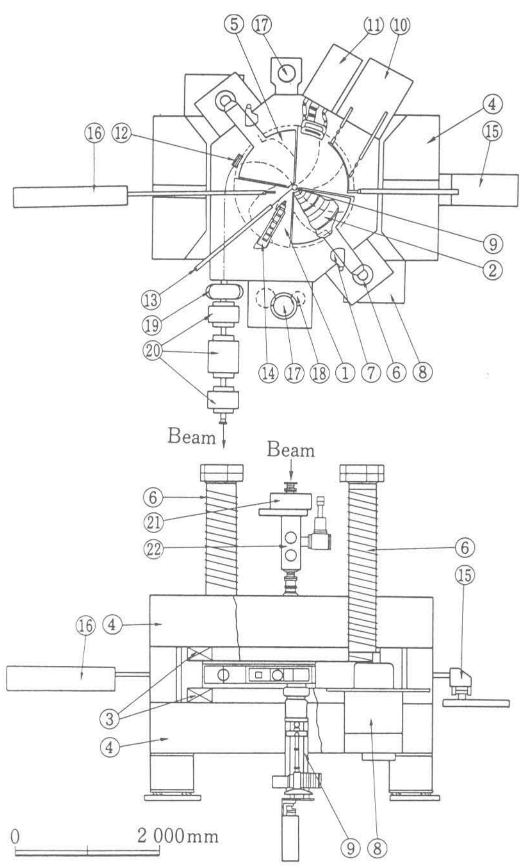


Fig. 1. Photo of the injector AVF cyclotron as viewed from the downstream od the extraction beam line.

Table 1 Characteristics of the AVF cyclotron

Number of sectors	4
Sector gap	127 mm
Pole gap	300 mm
Pole diameter	1,730 mm
Extraction radius	714 mm
Maximum magnetic field	1.7 T
Maximum main coil current	1,000 A
Maximum power	150 kW
Number of trim coils	9
Number of harmonic coils	4
Magnet size	2.1m(H)×1.9m(W)×3.9m(L)
Magnet weight	110 ton
Number of dees	2
Dee angle	85 deg
Frequency	12-24 MHz
Maximum dee voltage	50 kV
Maximum RF power	30×2 kW
Inflector	spiral type
Main evacuation system	4,000, 6,500 l/sec cryopumps 1,500 l/sec turbomolecular pump
Pressure	2×10^{-5} Pa
Control system	Computer network and CAMAC interfaces
Acceleration harmonic number	2



① Sector pole
② Trim coil
③ Main coil
④ Yoke
⑤ Dee
⑥ Resonator
⑦ Compensator
⑧ Oscillator
⑨ Infector
⑩ Deflector
⑪ Magnetic channel
⑫ Gradient corrector
⑬ Phase slit
⑭ Phase probe
⑮ Extraction profile monitor
⑯ Main radial probe
⑰ Cryopump
⑱ Turbomolecular pump
⑲ Steerer
⑳ Quadrupole magnet
㉑ Solenoid
㉒ Emittance monitor, Faraday cup, Profile monitor, Beam buncher

Fig. 2. Schematic drawing of the AVF cyclotron.

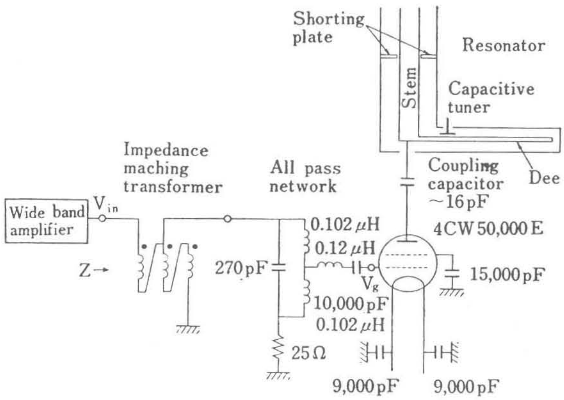


Fig. 3. Schematic diagram of the RF amplifier system.

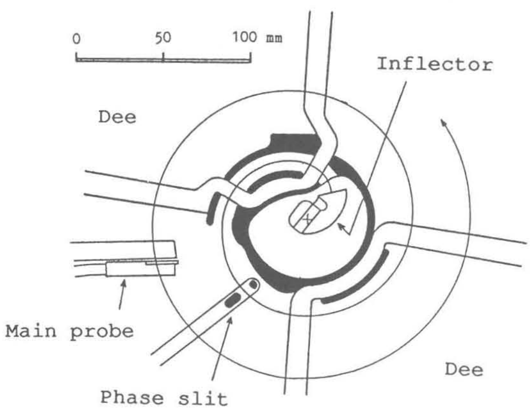


Fig. 5. Schematic drawing of the central region of the cyclotron.

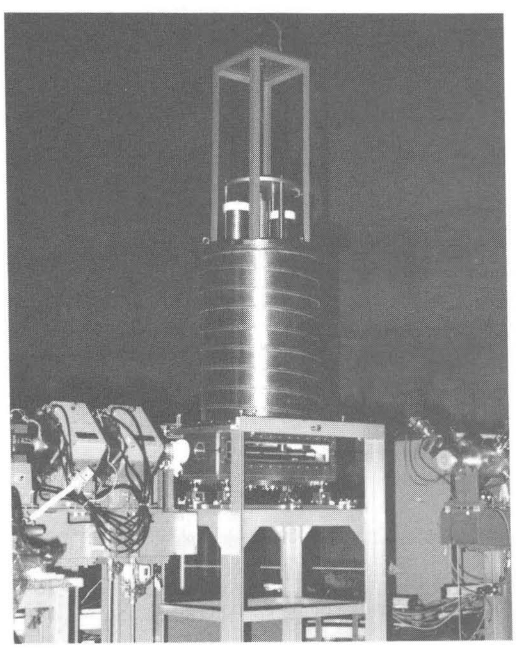


Fig. 7. Photo of the beam rebuncher being installed in the beam line from the AVF cyclotron to RRC.

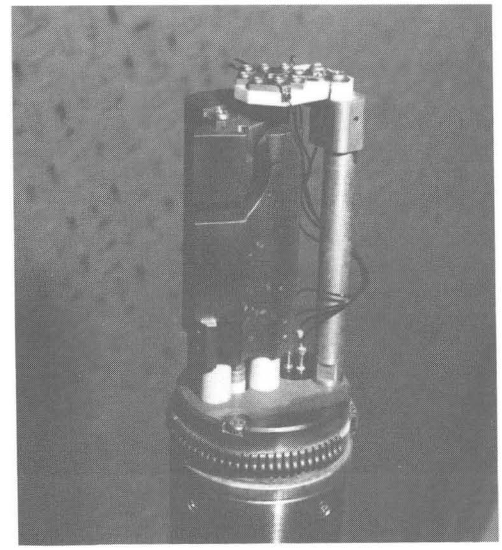


Fig. 4. Photo of the inflector.

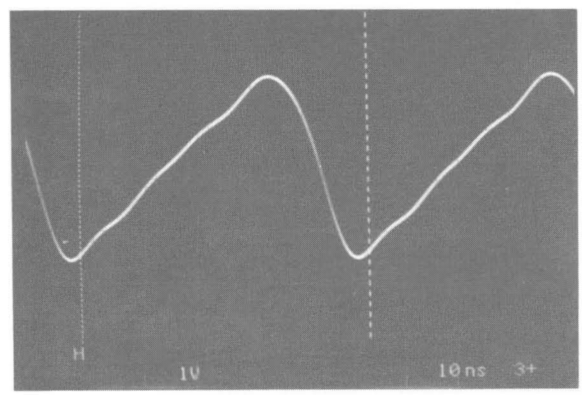


Fig. 6. Example of an oscilloscope wave-form of the sawtooth beam buncher.

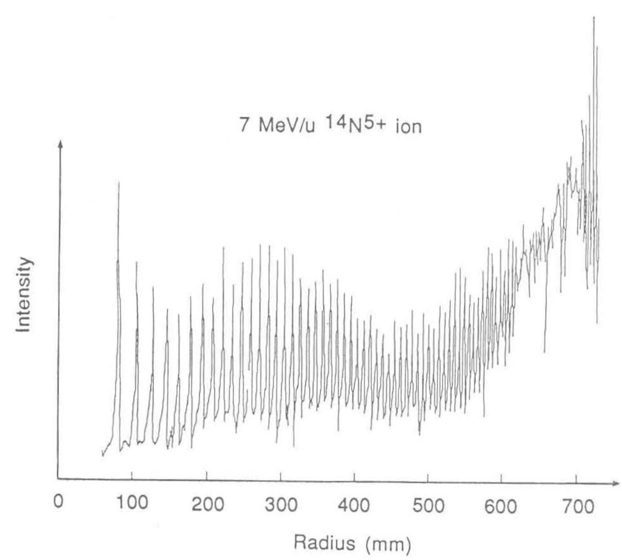


Fig. 8. Orbit pattern of 7 MeV/u $^{14}N^{5+}$ ions measured with the main radial probe.