PROGRESS IN RIKEN RING CYCLOTRON PROJECT

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A separated sector cyclotron is being constructed as the principal accelerator for the heavy-ion research facility at RIKEN. Assembling of the cyclotron, the beam transport line from the injector, and one beam line to the experimental hall has been completed. Running test of the evacuation system and full power tests of magnets, injection and extraction elements, and the radio-frequency system are under way. Construction status and some results of measurements are reported.

INTRODUCTION

A separated sector cyclotron (RIKEN Ring Cyclotron or RRC) is the principal accelerator of the RIKEN heavy-ion accelerator complex, which is composed of two injectors and the RRC. One of the injectors is the variable-frequency heavy-ion linac(RILAC) [1] which was completed in 1980 and has been in operation since then. The other is an AVF cyclotron with K=70 MeV and construction of it will start in 1987. An outline of this facility and the layout of the accelerators were already reported [2]. In Table 1 are listed the maximum energies of ions with a charge state q_i and a mass number A_i when they are injected from the RILAC and the injector cyclotron. Here q_i is the charge state of ions accelerated at the injectors.

Construction of the RRC started in 1981 and is completed in October 1986. It will be put into operation by the end of 1986 in combination with the RILAC. The second injector, an AVF cyclotron, and most of the beam lines will be built within two years from now.

Table 1. Maximum Energy per Nucleon of RIKEN RRC

Injected from RILAC		
Ions with $A_i/q_i < 5$	70	MeV/u
Ions with $A_i/q_i \geq 5$	$(280\sim324)\times(q_i/A_i)$	MeV/u*
Injected from AVF Cyclotron		
Proton	210	MeV
^3He	185	MeV/u
Ions with $A_i/q_i = 2$	135	MeV/u
Ions with $A_i/q_i > 2$	$(1215\sim1102)\times(q_i/A_i)^2$	MeV/u*

* left and right figures correspond to values for light and heavy ions, respectively

Fig. 1 shows a bird's eye view of the RRC. The beam is injected from the far side through a canted beam line. and is extracted on this side.

The principal parameters are listed in Table 2 and a plan view of the RRC is shown in Fig.2.

SECTOR MAGNETS

Details of the design and fabrication of the sector magnets were reported previously[3] and are not explained here.

Four sector magnets were completed and assembled in

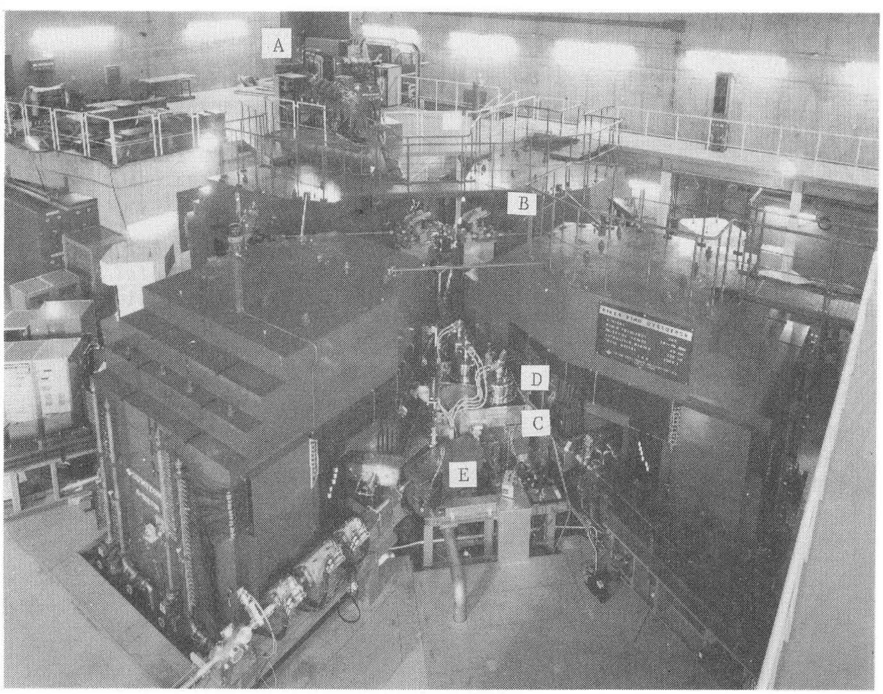


Fig.1 Bird's eye view of the RIKEN Ring Cyclotron.

A: Injection beam line
B: RF system
C: Valley chamber
D: Cryopump
E: Extraction bending magnet.

Table 2. Principal Parameters of RIKEN RRC

Number of Sector Magnets	4
Sector Angle	50°
Gap Width	8 cm
Maximum Magnetic Field	1.55 T
Maximum Magnetomotive Force	1.35×10^5 AT
Maximum Current	1050 A
Current Stability	2×10^{-6}
Maximum Power	700 kW
Total Weight	2100 ton
Number of Trim Coils	29x4 pairs
Maximum Current	500 A
Current Stability	5×10^{-5}
Total Trim Coil Power	200 kW
Number of Dees	2
Dee Angle	23.5°
RF Range	20 - 45 MHz
RF Tuning Devices	Movable Box and Triming
Maximum RF Voltage	300 kV
Maximum RF Power	600 kW
Main Evacuation System	10^4 ℓ/s x 10 Cryopumps
	5×10^3 ℓ/s x 4 Cryopanels
Pressure	$< 1 \times 10^{-7}$ Torr.
Control System	Computer Network and CAMAC Interfaces
Dimension of RRC	
Diameter	12.6 m
Height	6 m
Mean Injection Radius	0.893 m
Mean Extraction Radius	3.56 m
Orbit Frequency	1.9 - 7.37 MHz
Harmonic Number	
Coupled with RILAC	9
Coupled with AVF Cyclotron	5

the cyclotron vault in the summer of 1984. Accuracy of assembly was carefully checked out by precisely measuring the level of the lower pole of each magnet and relative distance between fixed points marked on the poles of the magnets. After assembling all the magnets, radial length of the fixed points marked on the pole flanges was remeasured from the center of the RRC. All the measured values were found to be within an accuracy of ± 0.13 mm from the designed values.

Each sector magnet has 29 pairs of trim coils which are mounted directly on the pole faces. They are flash-coated with Al_2O_3 for electrical insulation. Between pole face and the trim coils is put a Kapton sheet to ensure electrical insulation, too.

Power supplies (PS) for the main and trim coils were completed in July, 1984 and final adjustment of them was finished in December of that year.

Each main coil is divided into two, that is , a 48 turn coil (M1) and a 18 turn coil (M2). The M1 coil of four sector magnets are connected in series and one PS feeds a current. Cu-rent stability measured for eight hours was 2×10^{-6} at the maximum current of 1050A. The M2 coils of four magnets are also connected in series but a current passing through the M2 coil of each sector magnet can be varied by adjusting a current of by-pass circuit which is connected in parallel to the M2 coil. Current stability of the same amount as that of M1 PS was realized for the M2 PS [4)].

Four types of PS's were fabricated for the trim coils. Type A and B PS's feed currents to one pair trim coils connected in series over four sector magnets. Type B PS has a by-pass circuit to each trim coil pair. On the contrary, type C and D PS's feed currents only to one pair trim coil. Polarity of the output voltage can be changed for type D PS. Trim coils connected to the type C and D PS's are used to produce a harmonic field. Current stability of 1×10^{-5} was achieved for all trim coil PS's [4)].

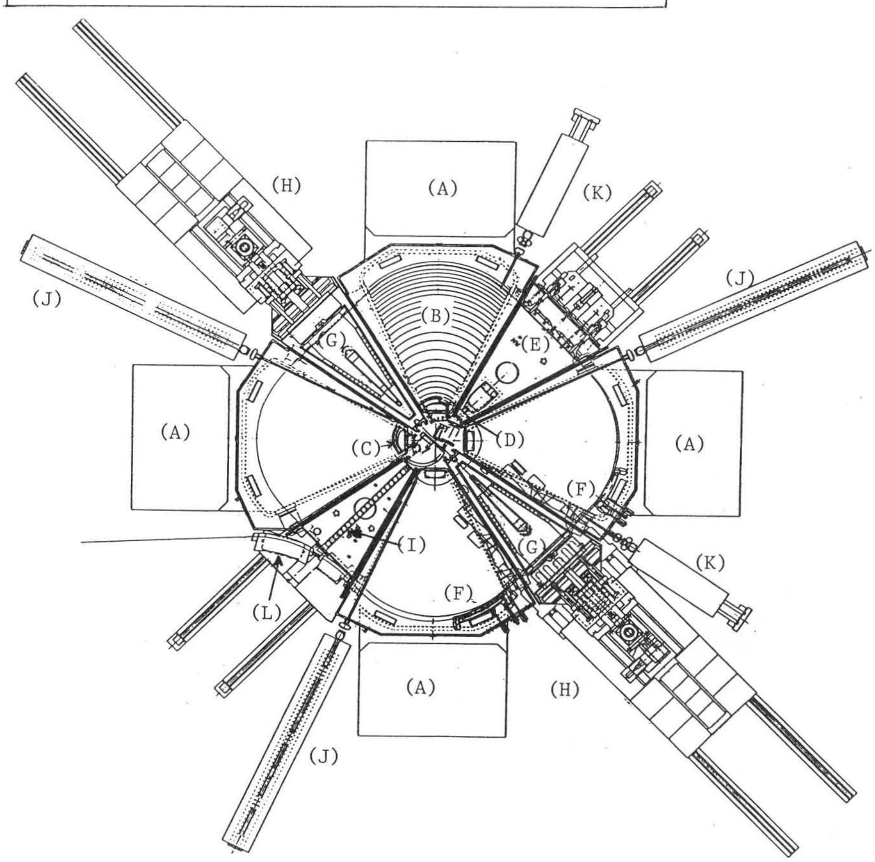


Fig. 2 Plan view of the RIKEN Ring Cyclotron.

(A) Sector Magnet
(B) Trim Coil
(C) Magnetic Inflection Channel
(D) Electric Inflector
(E) Electric Deflector
(F) Magnetic Deflection Channel
(G) RF Resonator
(H) Power Amplifier
(I) Phase Probe
(J) Main Differetial Probe
(K) Extraction Radial Probe
(L) Extraction Bending Magnet

Field measurements of the sector magnets had been carried out throughout the year of 1985. Details of the measurements was reported elsewhere[5]. It is recognized for a large scale magnet that it takes long time for the field strength to settle down to the final value, which depends on the excitation mode of the magnet. The optimum excitation procedures were investigated to ensure the fast setting and good reproducibility of the field distribution. Fig. 3 shows the excitation current of the main coil power supply operated according to the optimum procedure. Reproducibility of the field is better than 5×10^{-4} and required time for setting the field is about three hours.

Field distributions of the sector magnet (base field) were measured without exciting the trim coils for one sector magnet at field of 0.6, 1.0, 1.2, 1.3, 1.4, 1.5, and 1.55 T. Radial field distributions produced by each trim coil were measured a long the center line of the sector magnet at the same base field strength as above. The measurements were performed by passing one third of the maximum current through the trim coils one by one, then increasing the current to two thirds of the maximum value, and finally passing the maximum current through them also one by one. These measurements were performed without the injection and extraction elements.

Perturbations induced on the base field by the injection and extraction elements were measured over the azimuthal range covering four sector magnets. These measurements were performed for the magnetic channels and bending magnets by passing a current corresponding to the base field through each element. At the same time field distributions inside the magnetic channels and bending magnets were measured. The results were agreed well with the calculations.

Calculations to determine the optimum trim coil currents were carried out for 210 MeV proton, 70 MeV/u C^{6+}, 28 MeV/u Ar^{13+}, and 22 MeV/u Xe^{14+} ions by using the field data. From these calculations it was found that the maximum powers of the trim coil power supplies are slightly lower than the powers required for the formation of the isochronous fields in the center region. Soft iron shims were added in this region between the trim coils and the pole face to improve the field distribution.

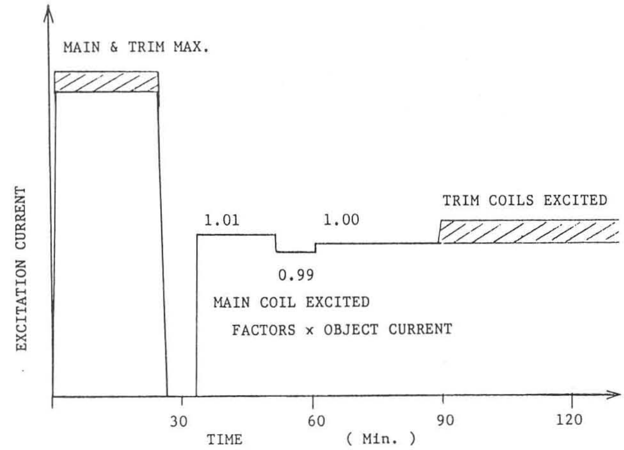


Fig. 3. Standard procedure to excite the sector magnets. The figure shows the output current of the main coil power supply which is operated according to the standard procedure.

RADIO FREQUENCY SYSTEM

New type of a variable frequency resonator was developed for the RF system of the RRC. Design principle and the results of the model study were reported[6] previously.

The resonator is of a half-wave-length coaxial type and a delta-shaped dee is supported in the median plane by vertical stems from the upper and lower sides. The frequency can be changed by moving a pair of boxes surrounding the stems. Frequency range is 20 to 45 MHz. This type of the resonator has the following merits: Firstly, the total length of the resonator can be reduced considerably. Secondly the voltage distribution along dee gap is such that the RF voltage increases with radius.

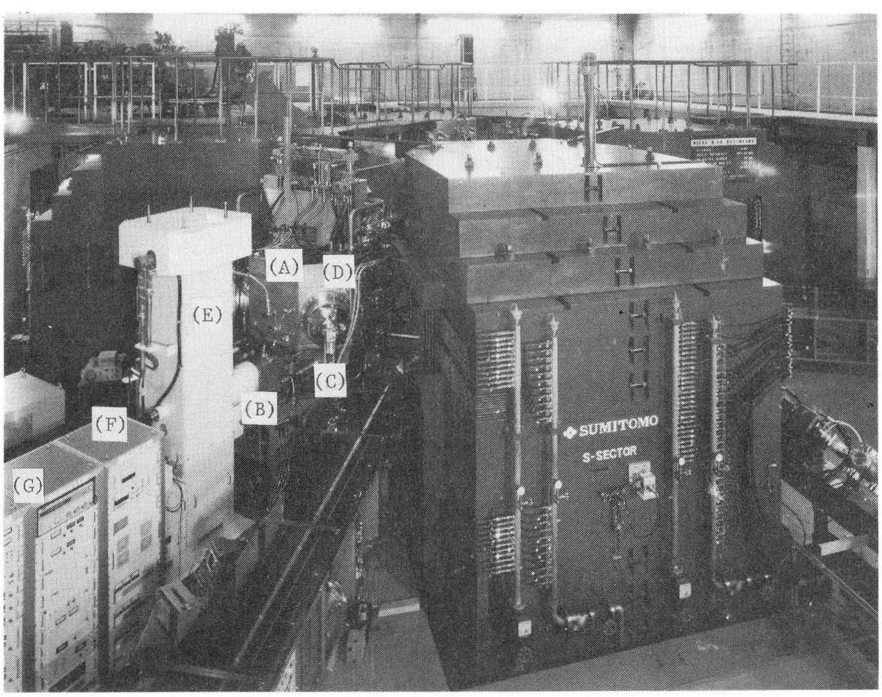


Fig.4. The RF resonator and the amplifier system of the RIKEN Ring Cyclotron.

(A) RF resonator
(B) Coupler
(C) Trimmer
(D) Cryopump
(E) Power Amplifier
(F) Low level amplifier
(G) Driving circuits

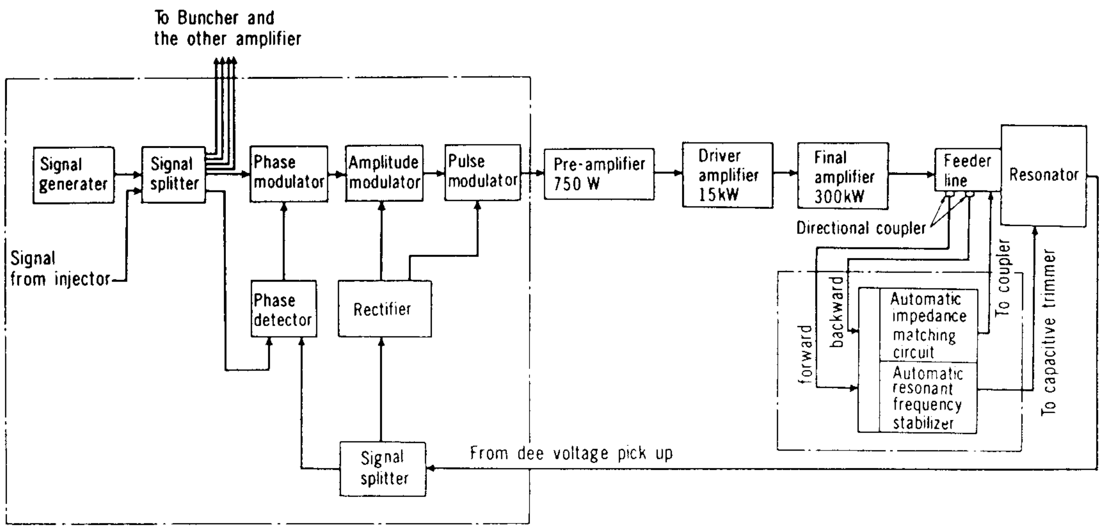


Fig. 5. Block diagram of the amplifier system for the RIKEN Ring Cyclotron.

Fabrication of the resonator started in 1984. Main parts of the resonator are made of specially fabricated copper-clad stainless steel. Before sticking together, channels for cooling water are machined on the surface of the stainless steel. Then a copper plate is sticked on the channeled surface by diffusion method. Using this copper-clad stainless steel, high cooling efficiency was realized for the resonator.

Static characteristics of the resonator such as resonance frequencies, Q-value, shunt impedance and electric field distributions along the dee gaps were measured at the factory. The same measurements were performed again in the cyclotron vault after assembled finally. The results of the measurements are reported at this Conference[7].

An RF reference signal coming from the RF system of the RILAC is amplified and fed into the resonators through feeder lines. Its imput impedance is automatically tuned to 50 Ω by detecting the incident and reflected powers on the feeder lines and at the same time by moving the coupler back and forth. The resonance frequency is also tumed automatically by moving a capacitive fine trimmer. The optimum positions of the trimmers and the couplers were investigated as a function of the resonance frequency.

Fig. 4 shows the RF resonator and the amplifier system assembled to the RRC.

Fig. 5 shows a block diagram of the amplifier and feedback system. This system can be operated both in CW and pulse modes. Siemens RS2042SK and RS2012CJ tetrodes are used for the final and driver amplifiers, respectively. Power tests of the amplifier system were done by connecting a 5o KW dummy load at the factory. The maximum RF voltage of 300 kV was obtained in the whole frequency range in the pulse operation mode.

Electrical characteristics of the resonators were measured with low level signals from a frequency synthesyzer. Power tests of the whole system was done at 28 MHz. The system works very well and the dee voltage and phase stabilities are better than 1.5×10^{-4} and 0.5 degree, respectively.

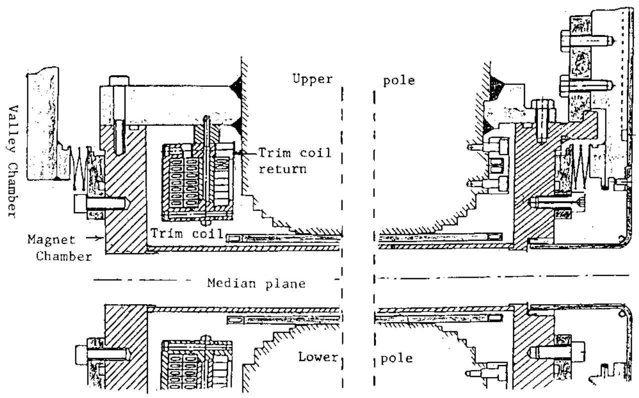
VACUUM CHAMBERS AND EVACUATION SYSTEM

The vacuum chamber of the RRC is divided into eight sections, that is, four magnet chambers, two valley chambers and two RF sections, that is, four magnet chambers, two valley chambers, and two RF resonators.

The specifications of the vacuum system is listed in Table 3. An estimated outgassing rate is 11×10^{-3} Torr•ℓ/sec. If a beam loss is kept less than 10 % for very heavy ions , the pressure inside the vacuum chamber must be lower than 10^{-7} Torr. Then pumping speed of 10^{5} ℓ/sec is needed for the evacuation system. Details of the evacuation system was reported elsewhere[8] and in the following only a brief explanation is given. As the principal vacuum pumps ten cryopumps with pumping speed of 10,000 ℓ/sec and four cryopanels of 5,000 ℓ/sec are

Table 3 Specifications of the Vacuum System

Volume of Vacuum Chambers	
Magnet chambers (Total)	1.8 m^3
Valley Chambers	5.4
RF Resonators	22.8
Total	30
Surface Area Exposed to Vacuum	
Magnet Chambers (SUS)	80 m^2
Valley Chambers (SUS)	26
RF Resonators Copper)	236
Elastomer O-Ring	3
Total	350
Estimated Outgassing Rate	11×10^{-3} (Torr•ℓ/s)
Required Vacuum Pressure	$<10^{-7}$ Torr.
Total Pumping Speed	12×10^{4} ℓ/s
10 Cryopumps	10
4 Cryopanels	2
Cleaning Methods	
Magnet Chambers	ECR Discharge Cleaning
Valley Chambers	Glow Discharge Cleaning



Rig. 6. Cross sectional view of the magnet chamber. Poles and trim coils are isolated from high vacuum part.

used in the high vacuum region. On the other hand, four turbo-molecular pumps and two mechanical booster pumps are used for rough pumping in the intermediate and low vacuum region, respectively.

As reported previously [2], the magnet poles and trim coils are put in the vacuum. However they should be completely separated from the high vacuum part because they are large sources of surface outgassing. A magnet chamber was designed to separate the low and high vacuum parts with thin walls of staless steel. A cross-sectional view of the magnet chamber is shown in Fig. 6. If the pressure of the low vacuum part becomes higher than 1 Torr, for example, and the pressure of high vacuum part is very low, then thin walls separating the low and high pressure parts should be destroyed. A special safety leak valve was developed.

An elastomer gasket is used for vacuum sealing between the magnet chamber and the RF resonator or the valley chamber.

An ECR discharge cleaning device and a glow discharge cleaning device are equipped to each magnet chamber and valley chamber, respectively, for degassing inner surfaces of the chambers [9].

Each part of the RRC was checked at the factory whether it is vacuum tight or not. All the sections of the vacuum chamber was evacuated separately to see how small the leakage of air, water leak from cooling pipes inside vacuum chambers, and outgassing from surfaces of the chambers are. Then assembling all the chambers, the injection and extraction elements, and the beam transport lines, we started evacuation of the whole system, The vacuum in the 10^{-8} Torr. region was attained very easily.

CONTROL SYSTEM

A computer-aided control system is introduced for the RRC. The details of the system is described elsewhere [10] and a short description will be given here.

The system is composed of a network of theree computers and CAMAC system. The computers are MELCOM 350-60/500 minicomputer (M-60), one is used for control of the RRC, the second for control of the RILAC and the last will be used for software development and data file. These three computers are equivalent and linked with each other with optical cables.

All the devices are controled through the CAMAC modules by the computer. To decrease necessary number of CAMAC crates, modules and cables, and to reduce the time for processing the instructions and data transfer, new CAMAC modules named CIM ICommunication Interface Module) and DIM (Device Interface Module) were developed. The DIM has a micro-processor, RAM, EPROM, and parallel and serial I?O ports, and can execute local sequence control, local surveillance, function generation, and testing independently of the central computer, M-60. The CIM has also a micro-processor, RAM, EPROM, and 12 pairs of serial I?O ports. It can be linked with twelve DIM's through pairs of plastic optical fibre cables and execute message transfer between the M-60 and the DIM's.

All analog data are digitiez in the front end of the devices or in the DIM. These data and other digital data are transfered to the M-60 and displayed on the CRT.

Application programs are written in Fortran 77 language. Operation system is a combination of a real time and a UNIX system. All the programs for the control of the RRC have been developed by us. As we decided not to use any switches, encoreders, and push buttons for the operation of the cyclotron and the beam transport lines, all the instructions should be given through the touch panel system. An example of the control program displayed on the touch panel CRT is shown in Fig. 7.

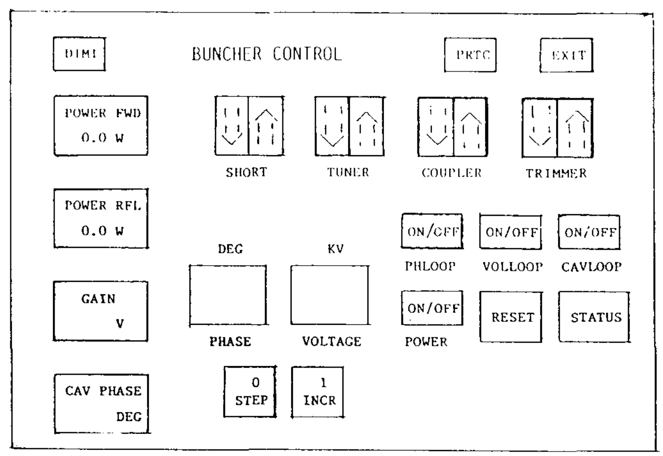


Fig. 7. Program of the buncher control displayed on the touch panel CRT. ON/OFF shows the switching instruction, arrows show instructions to increase or decrease the parameters and status of powers, gain, and so on are displayed in the rectangles.

BEAM TRANSPORT LINES

Details of the beam transport lines were already reported elsewhere [11]. As the level of the RRC median plane is twelve meters lower than the beam level of the RILAC, the beam from the RILAC is transported vertically as well as holizontally to the RRC vault and finally brought onto the median plane of the RRC through the canted beam line.

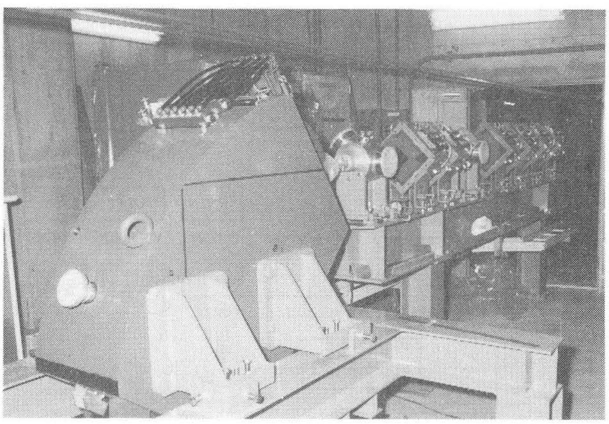
The bending magnet placed next to the RILAC in the beam transport line to the RRC is a pulse magnet and is used to switch the beam either to the RRC or to the experimental area in CW or pulse operation modes. All other bending magnets and Q magnets are DC ones and are designed as small as possible. Field distributions of them were measured and agreement between measurements and calculations are satisfactory.

Beam pipe and chambers for beam diagnostic devices are made of alminum. On the other hand, the beam diagnostic devices are mostly made of stainless steel.

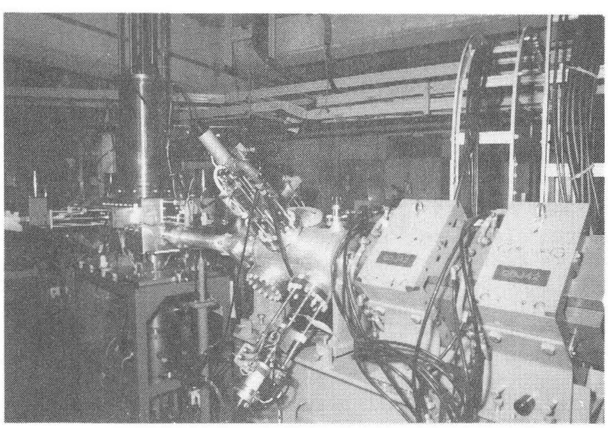
Pulse moters and air pistons are used for driving all the elements of the beam diagnostic devices. They are controled by the M-60 through the DIM-CIM system. Analog data such as positions of the elements and the measured beam currents are digitized and transfered to the M-60 through the DIM-CIM system, too.

Assembling of the beam transport lines was completed in August 1986. Then all power supplies of magnets and vacuum elements, which are also controled by the M-60 through the DIM's, were verified to work well. The first trial of the beam transport will be done at the end of November. Fig. 8 shows photographs of the beam transport line installed in the Annexe between the RILAC and The Ring Cyclotron Buildings. (A) shows a dipole magnet which bends the beam to the vertical section and Q magnets in the transverse phase space matching section. (B) shows the buncher installed in the horizontal section just after the vertical section. The beam diagnostic devices are also shown in the photograph (B).

At present only one beam line is installed for the extracted beam. A general purpose scattering chamber and a magnetic spectrometer with large solid angle for low energy particle detection will be installed at the end of the beam line.



(A)



(B)

Fig. 8. Photographs of the beam transport line between the RILAC and the RRC. (A) shows Q magnets in the phase space matching section and the bending magnet. (B) shows the beam buncher and the beam diagnostic devices in the horizontal section.

RADIATION SAFETY CONTROL SYSTEM

A computer-aided radiation safety control system was developed by Mitsubishi Electric Corporation. It consists of radiation monitoring system, gas and water monitoring system, inspection system for entrance and exit of the controlled area, and data recording system.

Four stations are built for enviromental radiation monitoring around the Ring Cyclotron Building. In each station are equipped a He^3 detector and a NaI scintillation counter for detection of enviromental neutrons and gamma rays, respectively. Counts for every ten seconds and counting rate for ten secondsare send to the center computer, M-3000, for data filing.

A BF_3counter and an ionization chamber are equiiped for area monitors in every room of the controlled area for neutron and gamma ray detection, respectively. Data from these counters are filed through the same procedure as those of the environmental radiation monitors.

Contamination of activity in the air should be monitored before some enters the experimental halls and cyclotron vault. An air suction system and a gas monitor with a NaI scintillation detector are installed. This system is also controlled by M-3000.

Standard air monitoring systems for exhaust air and waste water coming from the controlled area are equipped for continuous monitoring.

Entrance to and exit from the controlled area is continuously inspected at the gateway of the area. Every man who want to work in the area should have a card and put it in the card reader when he enters the area. The M-3000 records his name and time of entrance. When he goes out from the area he must check not to be contaminated. Then he must put the card in his card again in the card reader. He can go out when hand-foot monitor gives no alarm. There are gateways at the entrances of experimental rooms and the cyclotron vault. The M-3000 records how many people are working in the room. The M-3000 gives interupt signal to the M-60 of the control system when some one is working or the door is open, thus the beam cannot be transported to that room.

FUTURE PLAN

As described above, assembling of the Ring Cyclotron was finished and all the parts of the RRC work very well. The beam acceleration trial will start soon.

Construction of the injector AVF cyclotron will start in next fiscal year and will be completed in 1988. Construction of the beam transport lines and experimental facilities will start in the next fiscal year, too. The whole project will be finished in 1988.

Note Added in Proof

We started the acceleration trial at the end of November. A beam of Ar^{12+} was injected on Dec. 3. The beam reached up to the outermost radius on Dec. 10 and we succeeded to extract the beam on Dec. 16.

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