STATUS REPORT ON RIKEN RING CYCLOTRON

Yasushige Yano
RIKEN
Wako-shi, Saitama 351-01, Japan

ABSTRACT

After approximately six year construction period, RIKEN Ring Cyclotron (RRC) was successfully commissioned on December 16, 1986. The routine operation of RRC began in April, 1987, and was made until March 1988. April and May were devoted to the machine studies, and beams were delivered to the experiments from the end of May. Seven kinds of ion species from carbon to copper were used for the nuclear physics and atomic physics experiments during these one-year runs. High quality beams with transverse emittances less than 10 mm.mrad, energy spread of approximately 0.1% and pulse width less than 300 psec were extracted. Since the middle of March, 1988, RRC has been shut down for extending the beam transfer lines and installing the various experimental setups. Next experimental program will start in July, 1988. The initial operational status of RRC is described as well as the running construction program of the new injector, a K70 AVF cyclotron with an external ECR ion source.

1. INTRODUCTION

It dates back now about seven years that RILAC (RIKEN Heavy Ion Linear Accelerator), which is the world-first frequency tunable heavy-ion linac, was completed, and that the construction of the K540 four-sector ring cyclotron (RIKEN Ring Cyclotron, RRC) as its post accelerator started. A Detailed description of RIKEN Accelerator Research Facility (RARF) consisting of this accelerator complex has been given previously[1]. Figure 1 recalls the general layout of RARF which is scheduled to be fully completed in March, 1989. This facility will be the first comprehensive research center of heavy ion science in Japan.

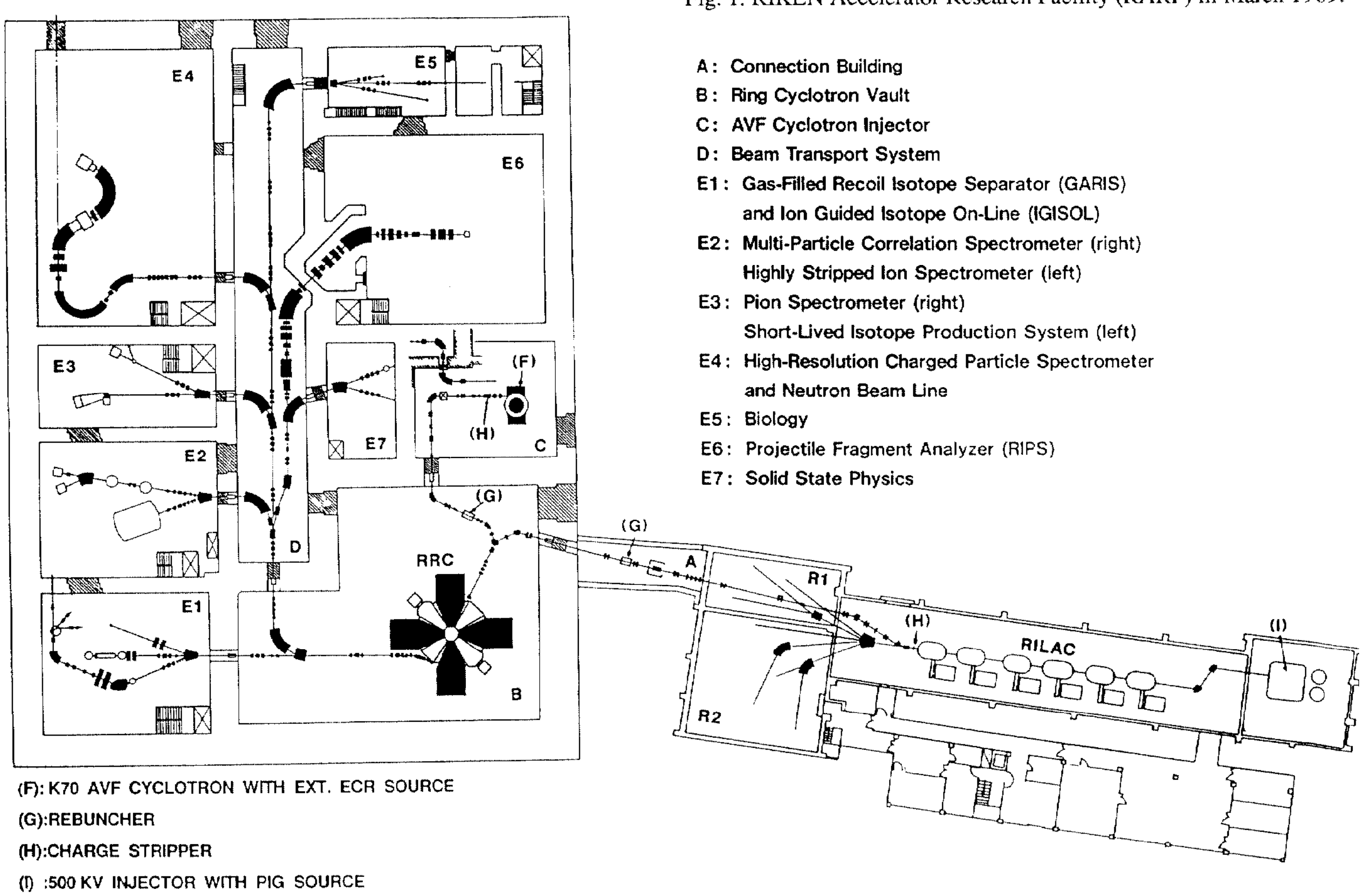
In November, 1986, RRC was fully assembled, and successfully pumped down. The injection beam transfer line from RILAC, equipped with a carbon-foil charge stripper and a rebuncher, and the extraction beam transfer line to E1 experimental hall were also completed. The experimental set-ups consisting of a 1m scattering chamber, a secondary beam analyzer and a pion spectrometer were placed at E1 tentatively.

The first operational trial of this accelerator complex was started on November 28. An $^{40}Ar^{12+}$ beam of 1.28 MeV/u from RILAC after passing through the charge stripper was injected to RRC on December 3. On December 16, the argon beam of 21 MeV/u was successfully extracted from RRC only 13 days after the beam injection. The acceleration was performed with a harmonic number of 10 insread of 9 (normal operation). This harmonic number was adopted because RILAC was operated with five resonators except the last (sixth) one, the rf amplifier of which had been disassembled for the improvements.

The routine operation of RRC began in April, 1987, and was continued until March, 1988. It was made every other week: one week for the experiments and the other for the maintenance and improvements. In the lattter week, RILAC worked for the low-energy experiments. April and May were devoted to the machine studies, and the beams were used to the nuclear-physics and atomic-physics experiments from the end of May. The extensive overhaul was done in summer (August-September), and after this overhaul, RILAC was operated with six acceleration tanks.

Since the middle of March, 1988, RRC has been shut down for extending the beam transfer lines and installing the various experimental setups. Next experimental program will start in July, 1988.

Fig. 1. RIKEN Accelerator Research Facility (RARF) in March 1989.



A K70 AVF cyclotron equipped with an external ECR ion source is under construction as the new injector. This cyclotron is sheduled to be completed at the end of March, 1989, and will be used for preacceleration of light ions from proton to argon. The initial tests of the 10 GHz ECR ion source began in April, 1988.

2. INITIAL OPERATING RESULTS

2-1. Accelerated beams

So far seven kinds of ion species were used for experiments. The main characteristics of these beams are summarized in table 1.

Table 1. RRC beams in April 1987 - March 1988.

PARTICLE	CHARGE	RF F (MHz)	h	Energy (MeV/n)	Intensity (nA typical)
^{12}C	5	35	9	42	200
^{14}N	6	28	9	26	200
		35	10	34	
			9	42	
^{15}N	6	35	10	34	50
			9	42	
^{18}O	7	35	9	42	20
^{40}Ar	12	28	10	21	200
	13		9	26	600
^{40}Ca	14	28	9	26	10
^{65}Cu	18	25	10	17	10

2-2. RILAC

RILAC consists of an injector (DC max. 500 kV) and six acceleration tanks of the Wideroe type. This is the world-first variable-frequency heavy-ion linac. The range of frequency is designed to be 17-45 MHz, and the maximum effective acceleration voltage to be 16 MV. This machine has worked well and been used for the low-energy experiments, mainly atomic physics. Recently we made some improvements on the r.f. oscillators so that the voltage of 16 MV can be achieved up to the highest frequency of 45 MHz.

2-3. Beam transfer line

The injection beam transfer line between RILAC and RRC is about 65 m long. The vacuum pressure in the line is maintained at the value of a few times 10^{-7} Torr by the turbomolecular pumps and ion pumps.

The beam from RILAC passes through the charge stripper (a 10 $\mu g/cm^2$ thick carbon foil) which is placed immediately after RILAC, and is deflected by an angle of 25.7 degrees with a couple of dipole magnets. A single charge state of the beam is selected by a slit after these magnets. In this process, the currents of the two dipoles and three quadrupoles are varied by a constant ratio, and the beam current behind the slit is monitored by a Faraday cup. The measured charge-state distribution is indicated on a graphic dispay at the control room. We use Nikolaev's expression for prediction of the charge-state distribution.

The power supplies for quadrupole magnets on the beam line are set to the currents expected from the TRANSPORT calculation based on the assumed beam emittance. On the other hand, currents for the matching-section quadrupole quartets are readjusted to make the measured beam emittance as expected to match with the transverse eigen-ellipses of RRC.

Each straight section is followed by a couple of steering magnets. This system makes the beam pass through the central axis of the magnetic field of quadrupole magnets on the line. Such steering corrections are done by changing the currents of steering magnets and a quadrupole magnet and measuring the shifts of the beam center with a beam profile monitor. This process can be automated.

Steering corrections being achieved, the buncher is switched on. Its r.f. voltage is kept at the calculated value, while its r.f. phase is carefully tuned. The correct r.f. phase is obtained when the beam central phase detected at the end of line does not change with the buncher being on or off. This buncher compresses the phase width of RILAC output beam by a factor of about 0.7 at the injection point of RRC.

The beam transfer efficiency after the charge selecting slit is typically more than 80%.

2-4. RRC

The large vacuum chamber of 30 m^3 in volume is pumped down by means of four turbomolecular pumps of 5,000 l/s and fourteen cryopumps of total evacuating speed of 120,000 l/s. It takes about three days to pump down from atmospheric pressure to the region of 10^{-8} Torr. This procedure is fully automated by the local sequencer. High vacuum is hold only by the cryopumps, and at present better than 10^{-8} Torr is achieved.

Mass and charge of ions to be accelerated, an r.f. frequency and a harmonic number being given, we calculate the optimum currents of main and trim coils of sector magnets for creating the isochronous field. Firstly, an isochronous field profile along a ridge of each sector magnet is calculated according to the GANIL's Kr-Kb formulae. Here the values of Kr and Kb are reduced from the numerous field mapping data and stored in the memory of the computer. Secondly, the optimization of currents to produce the above field profile is done with the least-square fitting method by using the trim coil field data measured along the ridge of sector magnet.

The currents obtained are set as shown in fig.2. The procedure consists of two main processes. In the first process, the main and trim coil currents are raised up to each maximum value and then falls down to zero amps. This process serves as the "reset of magnetization" of large mass of iron. For "fast setting" of the magnetic field the second process is executed. Approximately two hours are necessary for this procedure.

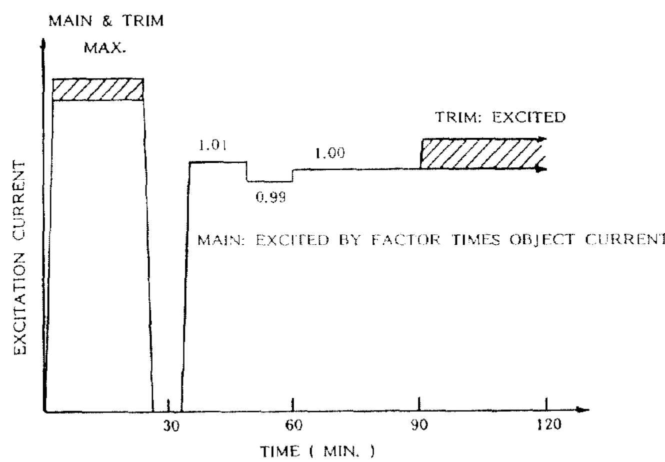


Fig. 2. Current setting of main and trim coils of sector magnets.

The power supplies for the beam injection system are adjusted so that the beam is centered at the entrance of each injection element. The position of the beam is monitered by a four-segment buffle slit placed in front of each element.

Initial settings of r.f. phases are determined to obtain maximum separation of first several turns which is measured by a 2.5 m stroke radial differential probe.

By changing only the main-coil current slightly, a preliminary adjustment of the sector field is made. This is done untill all twenty pairs of nondestructive capacitive phase pick-up probes covering the region from the injection to the extraction detect timing signals of the beam. The sector field obtained by this procedure is not always the optimum isochronous field as shown in fig.3. Formation of the isochronous field distribuiton is performed according to the following iterative procedure: (1) measuring the beam phase excursion with the phase probes, (2) calculating the field deviation from the desired isochronous field, and (3) setting the optimum values of the main and

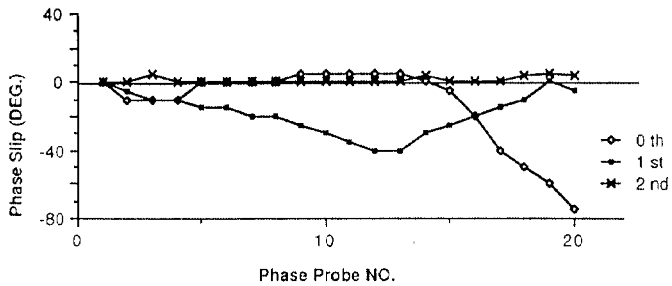


Fig. 3. An example of isochronization procesure.

trim coil currents recalculated. Usually a sufficient field distribution is obtained after three trials as shown in fig.3.

The three-probe method previously described in ref. 2 allows not only the observation of betatron oscillations but also the measurement of closed orbit off centering. Field unballance between four sector magnets can be measured and corrected according to the data of two-dimensional position of closed orbit center obtained with this method. Good orbit centering is achieved by adjusting the position and voltage of the electrostatic inflection channel, ballancing the four sector fields, and correcting trim coil currents to remove local residual field imperfections. Figure 4 shows the well-centered turn pattern measured by the main differential probe.

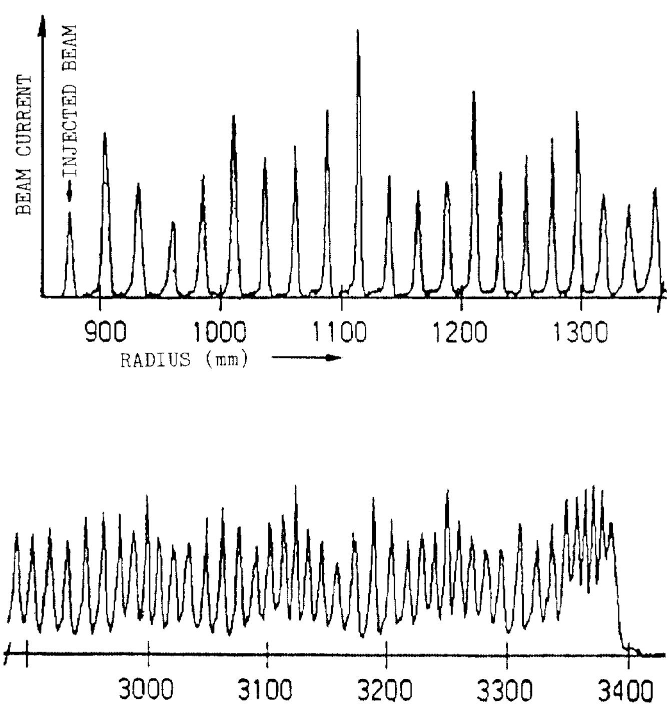


Fig. 4. Well-centered turn pattern.

In the beam-service runs for the users, well-centered orbit operation is not performed, but off-centering acceleration is made to save the beam preparation time and to expand the turn separation in the extraction region. Before the beam extraction, the RF phase is readjusted to obtain clear turn patterns in this region as shown in fig. 5. The power supplies for the beam extraction system are adjusted in the same way as the beam injection. Single turn extraction is achieved.

The beam transfer efficiency for RRC was typically 50% up to now. Most part of the beam loss in RRC takes place through the injection system.

The extracted beam focuses typically by the size of 4 mm$^{\phi}$ at the object point 3.3 m downstream from RRC. The transversal emittances were less than 10 mm.mrad, and the beam spot on the target could be smaller than 2 mm in diameter. From the carbon-carbon elastic scattering data it was found that the energy spread of the beam was approximately 0.1%. The pulse width of $^{40}Ar^{13+}$ beam of

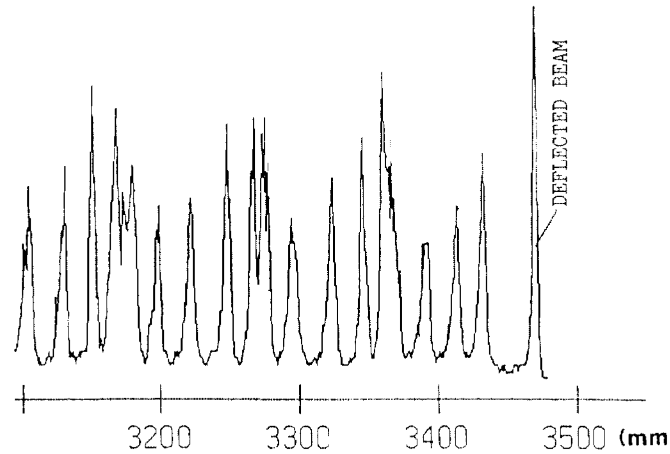


Fig. 5. Turn pattern in the extr. region in case of off-centering.

26 MeV/u was measured to be 460 psec at the position 30 m downstream from RRC. This indicates that the extracted beam posessed the pulse width shorter than 300 psec.

3. FUTURE PROGRAM

As described briefly in sect. 1, RARF construction program come into the final phase. The extention of the experimental area (E4,E5,E6) is now under way, and will be completed in February, 1989.

The AVF cyclotron[3], which is the injector of light heavy ions from proton to argon, has four sectors and two r.f. dees with an angle of 85 degrees. The extraction radius and acceleration harmonics are chosen to be 71.4 cm and 2, respectively. This cyclotron can accelerate ions whose m/q value is smaller than 4. It will be equipped with a duoplasmatron, the ECR source and a polarized ^{3}He ion source (being developed). These ion sources are placed on the floor above the AVF cyclotron vault. The beam from the sources is injected axially into the cyclotron with a spiral inflector. This cyclotron is sheduled to be installed in December, 1988 and the beam test will begin in April, 1989.

We already obtained 20 eμA of Ar^{11+} beam from the ECR source[4].

An ECR source for RILAC, one of the top candidates of which is the Grenoble's CAPRICE, is planned to be installed in winter 1989.

Our beam handling system has beam time-sharing function by pulsed magnets, and the parasite beam service will be done for two RRC experiment halls or for the RRC experiment halls and the RILAC experiment hall.

Upgrading of the RARF beam energy is scheduled as follows:

1. The effective acceleration voltage of RILAC will be increased to 16 MV for the whole frequency range of 20-45 MHz in autumn of 1988. This will allow the maximum beam energies for N, Ar, Kr and Xe ions of 60, 41, 23 and 17 MeV/u, respectively.

2. The competion of K70 injector AVF cyclotron equipped with the external ECR ion source will provide protons of 210 MeV and ^{3}He ions of 185 MeV/u. The maximum energy of 135 MeV/u corresponding to the maximum magnetic rigidity of RRC will be attained for light heavy ions up to Si, and 95 MeV/u for Ar.

3. At the end of 1989, an ECR ion source will be installed on RILAC. The final energy of heavy ions will be substantially increased. The maximum energies for Kr, Xe and Au are expected to be 56, 42 and 26 MeV/u, respectively.

REFERENCES

1) H.Kamitsubo, Proc. 11th Int. Conf. on Cyclotron and their Applications (Tokyo, 1986) p.17.

2) A.Goto et al., Proc. 10th Int. Conf. on Cyclotrons and their Applications (East Lansing, 1984) p.36.

3) A.Goto, in this conference.

4) K.Hatanaka et al., in this conference.