STATUS REPORT ON RIKEN RING CYCLOTRON

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ABSTRACT

RIKEN Ring Cyclotron (RRC) coupled with the injector heavy-ion linac (RILAC) was commissioned on December 16, 1986 nearly two months after the last Tokyo cyclotron conference. The routine operation of RRC began in April, 1987. So far, thirteen kinds of ion species ranging from carbon through krypton with energies of 11 - 42 MeV/u were used for experiments of nuclear physics, atomic physics and radiobiology. High quality beams with transverse emittances as small as 10 mm.mrad, an energy spread of approximately 0.1% and a pulse width shorter than 300 psec were extracted.

A new injector, K70 AVF cyclotron was fully assembled this April, and the first beam of $^{14}N^{5+}$ with 7 MeV/u, its top energy, was successfully extracted. A 10 GHz ECR ion source for this cyclotron has

been in operation for one year and has achieved high performances, e.g. 110 μA for $^{14}N^{5+}$ and 30 μA for $^{40}Ar^{11+}$.

The initial two-year operational experiences of RRC and the future program of the facility are presented.

1. INTRODUCTION

On December 16 1986, the first beam of 21 MeV/u $^{40}Ar^{12+}$ was successfully extracted from RIKEN Ring Cyclotron (RRC) coupled with the injector heavy-ion linac (RILAC). It had taken approximately six years

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

A: Connection Building
B: Ring Cyclotron Vault
C: Injector AVF Cyclotron Vault
D: Beam Distribution System Vault
E1:   (Top)   Large Acceptance Beam Line
      (Mid.) 1m Scattering Chamber
      (Bot.) Gas-Filled Recoil Isotope Separator (GARIS) with Ion-Guided Isotope Separator On-Line (IGISOL)
E2:   (Top)   Highly Stripped Ion Spectrometer
      (Bot.) Large-Scale Scattering Chamber
E3:   (Top)   Short-Lived Isotope Production System
      (Bot.) BaF_2 Crystal Ball Spectrometer and Pion Spectrometer
E4*:   High-Resolution Charged-Particle Spectrometer and Neutron TOF Beam line
E5:   (Top)   Biological Irradiation System with Wobbler Magnets
      (Mid.) Medical Science Irradiation Line
      (Bot.) Spare
E6:   Projectile Fragment Separator (RIPS) with Incident-Angle Swinger
E7:   (Top)   Slow Beam Channel (Material Science)
      (Bot.) Large Ω Muon Channel

*) This apparatus will be installed in Sept. 1989.

F: K70 AVF Cyclotron with External ECR Ion Source
G: Rebuncher
H: Charge Stripper
I: 500 kV Injector with PIG Ion Source

since the construction of RRC started.

Through two-month machine studies in April - May 1987, the routine operation of RRC for the users began at the end of May. The year of 1987 is the 50th anniversary of completion of the Japan-first cyclotron built at RIKEN by Professor Nishina, the pioneer of nuclear physics and the 20th anniversary of the Japan-first heavy-ion acceleration by our old cyclotron.

Figure 1 recalls the general layout of RIKEN Accelerator Research Facility (RARF). The beams had been delivered only to E1-room tentative experimental set-ups consisting of a 1m scattering chamber, a pion spectrometer followed by a large acceptance beam line until the other experimental set-ups and beam distribution lines were installed at E1, E2, E3, E7 and D rooms as planned. This compelled us to make a long-term shut-down in mid March - June 1988. The beam service was restricted again at E1 since December 1988 to set RIPS at E6 and extend beam distribution lines to E4 and E5. In April 1989, every experimental apparatus, except for the E4-room big spectrometer, has been completed at each due place. This spectrometer will be installed in September 1989.

In recent one-year experiment runs, with a few exceptions, the starting up and tuning of the machine was done on Monday, and the beam was offered to one or two groups from Tuesday morning until Saturday morning without changing the particle and its energy. The extensive overhauls were done in summer and winter for about one month each year.

A new injector, K70 AVF cyclotron was installed in the ring cyclotron building in December 1988, and its assembling and tuning were finished in April 1989. The first beam of 7 MeV/u $^{14}N^{5+}$ was successfully extracted immediately after that. A 10 GHz ECR ion source for this cyclotron has been in operation for one year and has achieved high performances. At this moment, May 1989, we are waiting for the permission from the authorities to inject the AVF cyclotron beam to RRC. When we do it, a 135 MeV/u nitrogen beam will be obtained.

2. OPERATION STATUS

2.1. RILAC[1]

RILAC, a variable frequency heavy-ion linac, consists of an injector (DC max. 500 kV) and six acceleration tanks of the Wideröe type. The frequency tunability was required for a coupled operation with the post accelerator RRC. Its range covers 17 - 45 MHz, while the lowest frequency used in an injector mode to RRC is 20 MHz, corresponding to the RRC frequency range of 20 - 45 MHz. In this injector mode RILAC is able to accelerate particles having a charge to mass ratio over 1/20; the maximum effective acceleration voltage is 16 MV.

One of the advantages of this linac is that in fixing a frequency, the output beam energy can be decreased continuously from the nominal (sychronous) value by shifting an rf voltage and adjusting a phase of the last acceleration tank used, and by switching off some acceleration tanks when a large energy decrease is demanded. In use of this technique the output beam energy from RRC at a given rf frequency can also be decreased from the nominal value, but discretely in this case, by increasing an acceleration harmonics of RRC from the normal number of 9. As seen later, the last tank of RILAC was switched off when the h=10 mode operation was done in RRC. Some of the user groups demand that the lower limit of the RRC beam energy decreases to around 5 MeV/u while the nominal value is 13 MeV/u in the h=9 mode. This low energy beam can be obtained in a 20 MHz, h=14 mode. The present rebuncher placed between RILAC and RRC, however, has a drift-tube structure suited to a h=9 operational mode, and cannot give enough bunching power to such a beam; a double buncher system in which each buncher has a drift-tube structure suited to the harmonic number is necessary to be introduced. To investigate the other crucial problems, we made a preliminary test for a $^{132}Xe^{19+}$ (after a stripper) beam of 0.33 MeV/u RILAC energy corresponding to 5.3 MeV/u RRC energy. The life times of charge-stripper carbon foils of 10 $\mu g/cm^2$ and 20 $\mu g/cm^2$ were about 2 hours and 5 hours at max., respectively. The vertical and horizontal emittances were measured to be 79 mm.mrad and 82 mm.mrad, while they were 25 mm.mrad and 28 mm.mrad wihtout the thicker foil. The energy spread of the beam was acceptable. The study of resolving these problems is under way.

It takes 3 - 6 hours to start up and tune the machine; the intensity ratio of an output beam to a charge-selected DC input beam from the ion source is about 1/30. The beam chopper placed at the injection line of RILAC creates beam pulses with a rising time of 10 μsec and a flattop width variable from 20 μsec to continuation.

At present the PIG ion source is used. For grading up the RILAC performance we have put an oder of the permanent-magnet ECR ion source, NEOMAFIOS to CEA/IRF (France); it will be shipped at the end of this year.

2.2 Injection beam transfer line

The first bending magnet on the injection line from RILAC works well in an AC mode, which creates a pulsed magnetic field having rising and falling times of 10 msec and a flattop width variable from 10 msec to continuation. It provides a time-sharing of the beam between the RILAC experiment room and the RRC experiment room; this is used for thinning out the beam as well.

The RILAC beam passes through the charge stripper (a 10 $\mu g/cm^2$ thick carbon foil) which is placed immediately after RILAC, and a single charge state of the beam is selected in the first bending section. Nikolaev's expression gives a good prediction of the charge-state distribution.

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

2.3. RRC

Detailed descriptions of RRC are given elsewhere[2].

An ion mass, its charge, an rf frequency and a harmonic number being given, the optimum currents of main and trim coils of the sector magnets for creating the isochronous field are calculated.

The currents obatined are set in a cycling mode. This procedure consists of two main processes. In the first process, the main and trim coil currents are raised up to each maximum value and after being maintained for about 20 minutes, falls down to zero amps. This process serves as the "reset of magnetization" of large mass of iron. For "quick setting" of the magnetic field the second process is executed in which the main coil current is oscillated to converge into the calculated value. After that, the trim coil currents are set. Approximately two hours are necessary for this procedure.

The beam injection is easily done by adjusting each injection element so that the beam is centered at its entrance. The position of the beam is monitored by a four-segment buffle slit placed in front of each element.

By changing only the main-coil current slightly, a preliminary adjustment of the sector field is made. This is done until all twenty pairs of non-interceptive capacitive pick-up probes covering the region from the injection to the extraction detect timing signals of the beam. The sector field thus obtained is not always the optimum isochronous field. Formation of the isochronous field distribution is performed according to the following iterative procedure: (1) measuring the beam phase excursion with the phase probes, (2) calculating a field deviation from the desired isochronous field, and (3) setting the optimum values of the main and trim coil currents recalculated. Usually a sufficient field distribution is obtained after a few trials; it is ended within an hour.

The three-probe method previously described in ref. 3 allows not only observation of betatron oscillations but also measurement of closed orbit off centering. Field unballance between four sector magnets can be corrected using data of two-dimensional orbit-center movement obtained with this method. Good orbit centering is achieved by adjusting the position and voltage of the electrostatic inflection channel (EIC), ballancing the four sector fields, and correcting trim coil currents to remove local residual field imperfection. Fig. 2 shows the two-dimensional movement of orbit center measured in this way.

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 a clear turn pattern ensuring single-turn extraction as shown in Fig. 3. The beam

extraction is done in the same way as the beam injection.

The beam transmission efficiency through RRC has been improved stepwise, finding a better tuning way. At present it is normally over 60% and typically 100% for a full RILAC-injected beam (no cutting it off).
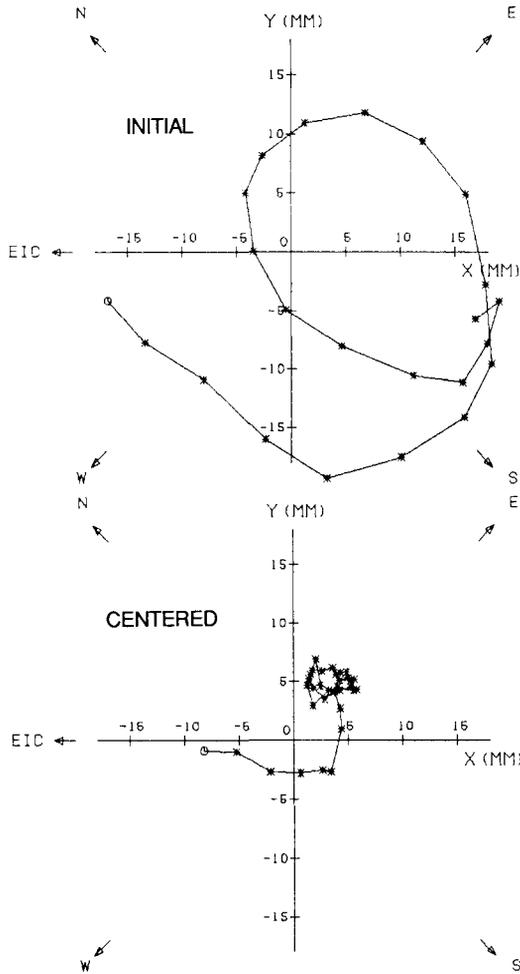
Fig. 2   An example of two-dimensional movement of orbit center measured by three radial differetial probes (the first 25 turns). Top: initial, Bottom: centered.

Fig. 3   A turn pattern in the extraction region of a 26 MeV/u Ar beam. The beam is accelerated in an off-centered way. The last peak is obtained after deflected by an electrostatic deflection channel.

Table 1. RRC beams in April 1987 - April 1989.

Particle	Charge	RF F (MHz)	h	Energy (MeV/u)	Intensity (nA)[*]
^{12}C	5	35	9	42	200
^{13}C	6	35	9	42	50
^{14}N	6	28	9	26	200
	6	35	10	34	200
	6	35	9	42	200
^{15}N	5	20.187	10	10.65	100
	6	35	10	34	50
	6	35	9	42	50
^{16}O	5	25	9	20.6	[**]
^{18}O	7	35	9	42	20
^{20}Ne	9	33	9	37	150
^{22}Ne	8	28	10	21	40
^{40}Ar	11	20	10	10.6	1500
	12	28	10	21	200
	13	28	9	26	600
^{40}Ca	14	28	9	26	10
^{64}Zn	20	25	9	20.6	10
^{65}Cu	18	25	10	17	10
^{84}Kr	18	20	10	10.6	70

[*]   Maximum beam intensity during the experimental run.
[**]   This beam was accelerated for creating the isochronous field of $^{64}Zn^{20+}$ beam (in detail see the text).

So far thirteen kinds of ion species ranging from carbon through krypton with energies of 11 - 42 MeV/u were used for experiments. The main characteristics of these beams are summerized in table 1. Among them a $^{64}Zn^{20+}$ beam was difficult to tune, because its input beam intensity to RRC was not enough. Our non-interceptive phase measuring system, the timing data from which are used for optimizing the rf-phase of the rebuncher and creating the isochronous sector field, requires at least 100 enA to obtain the clear beam-phase data. Thus, for tuning the machine, the idea of accelerating a $^{16}O^{5+}$ beam, which has enough intensity and a very close m/q-value to the $^{64}Zn^{20+}$ beam, was adopted. The isochronous field of the former beam is biased by approximately 7.7 gauss to the latter. This bias field was easily removed by adjusting a main coil current. It took nearly 17 hours since starting the sector field setting for the oxygen beam till extracting the zinc beam.

The extracted beam focuses by the size of about 4 mmϕ at the object point 3.3 m downstream from RRC. The transverse emittances were around 10 mm.mrad, and the beam spot on the target could be as small as 2 mm in diameter. From a carbon-carbon elastic scattering spectrum measured at 42 MeV/u, the energy spread of the beam was found to be approximately 0.1%. The pulse width of 26 MeV/u argon beam was measured by a PPAC at the position 30 m downstream from RRC (E1-room); it was 460 psec. This indicates that the extracted beam possessed the pulse width shorter than 300 psec.

An experiment group measured the beam energy of $^{18}O^{7+}$ by the TOF technique in use of double PPAC's placed about 7.4 m apart from each other in E1 room, and obtained 41.46±0.08 MeV/u. On the other hand, we estimated the beam energy to be 41.5 MeV/u from then-set coil current of the extraction bending magnet EBM2 whose radius of curvature and magnetic excitation curve are known. It was found that the estimation of
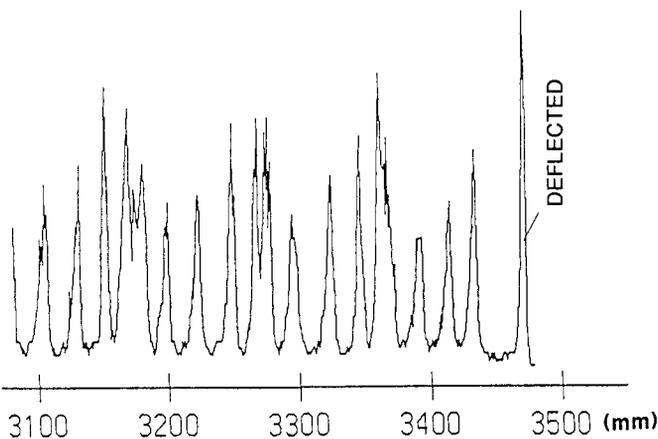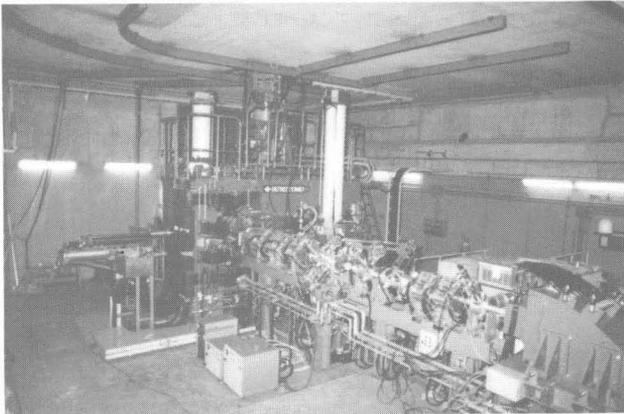
Fig. 4   The assembled injector AVF cyclotron.

the extracted beam energy from the EBM2 coil current is quite reliable.

2.4 Beam distribution line

The first bending magnet of the branch line to each experiment room except for E5 can also work in an AC mode and provide a time-sharing of the beam between two experiment rooms. The pulsed magnetic field has a time structure with rising and falling times of about 1 sec and a flattop width variable from 1 sec to continuation. We confirmed in measuring the magnetic field that it works well, but we have not yet applied it to the beam.

2.5 Injector AVF cyclotron[4]

After two-year construction period the new injector, a K70 AVF cyclotron was installed in the ring cyclotron building in December 1988. It has four sectors and two rf dees with an angle of 85 degrees, and its extraction radius and acceleration harmonics are 71.4 cm and 2, respectively. This cyclotron can accelerate particles having a m/q value smaller than 4, and serves as the injector of RRC for light ions, proton - argon. Its ECR ion source and duoplasmatron are placed on the floor above the cyclotron vault, and the beam from the source is injected axially into the cyclotron through a spiral inflector.

Immediately after finishing assembling and tuning the machine in April 1989 as shown in fig. 4, the first beam of $^{14}N^{5+}$ with 7 MeV/u, its top energy, was successfully extracted. Figure 5 shows the radial turn pattern measured with a main differential probe at that time. The transmission efficiency was not good enough (as small as 1%), but it will be improved because sufficient tuning has not yet been done.

The AVF cyclotron beam is bent down to the under-floor E7 room and

Table 2.   Output beam intensities achieved by RIKEN ECRIS for the lowest charge states of various ions to give the upper limit of RRC magnetic rigidity.

Particle	Charge	Intensity (eμA)	AVF Energy (MeV/u)	RRC Energy (MeV/u)
^{12}C	4	56	7	135
^{14}N	5	110	7	135
^{16}O	5	120	7	135
^{19}F	7	18	7	135
^{20}Ne	7	50	7	135
^{32}S	9	16	5.9	110
^{40}Ar	11	30	5.2	95
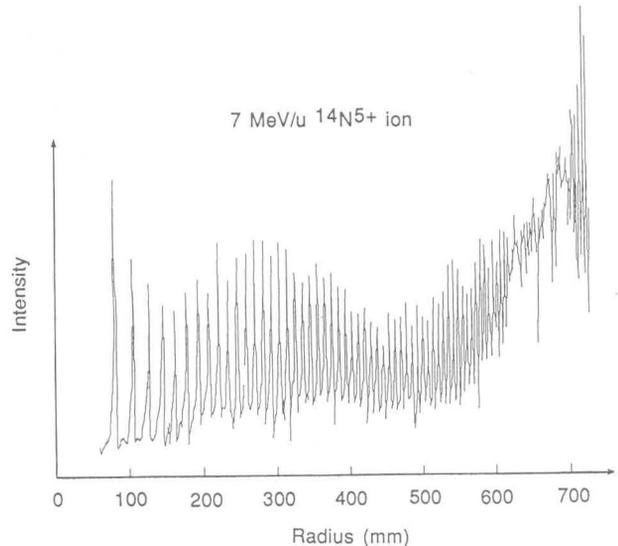
Fig. 5   The turn pattern of the first AVF cyclotron beam of 7 MeV/u $^{14}N^{5+}$ at 16.3 MHz. The extracted beam intensity was 200 enA.

is used for low-energy stage experiments as well.

The 10 GHz ECR ion source[5], which was modified from the LBL's, has been in operation for one year and has achieved high performances. Table 2 shows some of the operational results (in detail see ref. 5). Thanks to this ion source, we can push the RRC beam energy up to the bending limit. Only gaseous ions have been tested; the preparation for testing metaric ions is under way.

This source has been used for atomic physics experiments by itself, and interesting results have been obtained in this field.

3. FUTURE PROGRAM

When the AVF cyclotron beams are injected to RRC, we will obtain protons of 210 MeV and ^3He particles 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. This beam test is scheduled to start at the end of May.

At the end of this year or in the beginning of next year we will receive NEOMAFIOS, the new ion source for RILAC. Through a few-month bench testing, we will install this source on the high voltage terminal. Then, the maximum energies for Kr, Xe and Au are expected to be 56, 42 and 26 MeV/u, respectively.

The completion of the double buncher system to be placed in the injection transfer line between RILAC and RRC will extend the energy region down to nearly 5 MeV/u.

We are planning to introduce a polarized proton and deuteron source, and a polarized ^3He ion source (being developed) to the AVF cyclotron within three years.

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