RIKEN RING CYCLOTRON (RRC)

Yutaka Watanabe, Masayuki Kase, Masaki Fujimaki, Nobuhisa Fukunishi, Eiji Ikezawa,
Osamu Kamigaito, Keiko Kumagai, Takeshi Maie, Jun-ichi Ohnishi, Kazutaka Ohzeki,
Hiroki Okuno, Naruhiko Sakamoto, Kenji Suda, Shu Watanabe, Kazunari Yamada
RIKEN Nishina Center, Wako, Saitama, Japan
Seiji Fukuzawa, Makoto Hamanaka, Shigeru Ishikawa, Kiyoshi Kobayashi,
Ryo Koyama, Takeshi Nakamura, Minoru Nishida, Makoto Nishimura,
Junsho Shibata, Noritoshi Tsukiori, Kazuyoshi Yadomi
SHI Accelerator Service Ltd., Tokyo, Japan

Abstract

The RIKEN Ring Cyclotron (RRC) has operated stably for over 28 years and has supplied many types of heavy-ion beams for various experiments. The RRC has three types of injectors: the azimuthal varying field (AVF) cyclotron for comparatively light ions, the variable-frequency RIKEN heavy-ion linac (RILAC), and the RIKEN heavy-ion linac 2 (RILAC2) for high intensities of very heavy ions, such as those of U and Xe. Many accelerator combinations are possible, although the RRC should act as the first energy booster in any acceleration mode. The total operation time of the RRC is usually more than 3000 h/year. Recently, however, frequent malfunctions caused by age-related deterioration and beam loss, such as a layer short of main coils and vacuum leaks at feed-through, cooling water pipes, extraction devices, a bellows and so on, have been occurring at the RRC. The present status of the RRC is presented in this paper.

INTRODUCTION

Although the RIKEN Ring Cyclotron (RRC) began operation in 1986, it still plays an essential role as the first energy booster in the Radioactive Isotope Beam Factory (RIBF) accelerator complex. The RIBF was built by 2007 to expand the scope of research on heavier nuclei, thus building upon previous work on light unstable nuclei. The RIBF uses a combination of three injectors, RRC, three new cyclotrons (fRC, fixed-frequency Ring Cyclotron; IRC, Intermediate-stage Ring Cyclotron; and SRC, Superconducting Ring Cyclotron), and the RIKEN projectile fragment separator [1]. Using the RIBF, we aim to produce the most intense radioactive isotope beams in the world, with intensities of up to 1 pμA and including isotopes of all atomic masses. Stable operation of highly intense beams has been gradually realized at the RIBF. However, frequent malfunctions have recently occurred at the RRC due to age-related deterioration and beam loss. Some components have been repaired, and others have been replaced, but these issues remain serious and have not yet been solved. The operation of and problems with the RRC are as follows.

Table 1: RIBF Operating Statistics from August 2014 to July 2015.

Beam particle	Energy (MeV/u)	Acceleration mode	Actual beam current (pnA)	Beam tuning time (h)	Actual beam time (h)	Availability (%)
12C	70	AVF-RRC	350.0	28.4	36.0	100.0
12C	135		393.2	149.5	47.0	100.0
40Ar	95		76.5	169.5	32.0	100.0
56Fe	90		6.3	108.8	21.0	100.0
84Kr	70		5.6	72.8	121.0	100.0
86Kr	36	RILAC-RRC	8.8	41.3	12.0	100.0
48Ca	63		235.3	39.5	104.3	95.4
136Xe	10.75	RILAC2-RRC	405.0	90.3	106.0	109.4
238U	10.75		2500.0	110.2	48.0	100.0
40Ar	160	AVF-RRC-IRC	1.6	136.7	48.0	100.0
pol.d	190	AVF-RRC-SRC	290.0	77.1	123.9	105.6
48Ca	345	RILAC-RRC -IRC-SRC	530.0	175.6	492.2	96.3
78Kr	345	RILAC2-RRC -fRC-IRC-SRC	486.1	143.5	732.0	90.1
238U(1st)	345		27.9	261.8	532.1	94.2
238U(2nd)	345		31.4	214.6	553.0	91.5
238U(3rd)	345		39.5	87.2	252.0	99.5
			Total	1907	3260	

RRC OPERATION

The operation of the RRC from August 2014 to July 2015, including that of the fRC, IRC, and SRC, was published previously [2]. A list of the beams accelerated by these cyclotrons during this period is presented in Table 1. As shown, seven acceleration modes have employed the RRC, including an AVF-RRC-IRC mode for biological experiments that was first used in the winter of 2015. The actual beam service time during which the RRC was used, excluding beam tuning time, was 3260 h in the past year. The beam availability [1], defined as the ratio of actual beam service time to scheduled beam service time, was more than 90 %. Although there was downtime due to hardware trouble in 2011, this beam availability has recently increased each year [1-3]. The total yearly operation time of the RRC, including beam

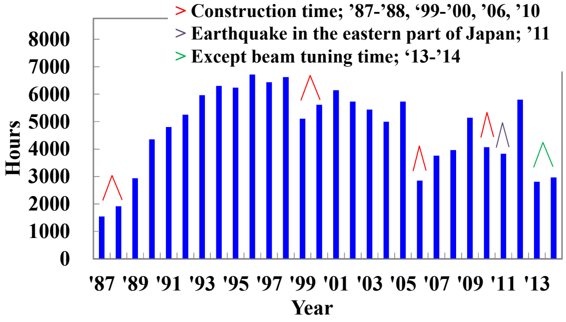

Figure 1: Total yearly operation time of RRC.

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ynabe@riken.jp

tuning time, was more than 3000 h/year during the past year, as shown in Figure 1, and recently, the RRC has operated stably without significant downtime. Furthermore, the transmission efficiency and stability of the beams have recently been improved, and a 345 MeV/nucleon ^{238}U beam with a maximum intensity of 39.5 pnA at FC-G01 (the exit of the SRC) was obtained in May 2015.

PROBLEMS

Main Coils

Two main coils of sector magnets exhibited signs of layer shorts, and an epoxy resin and glass fiber tape were carbonized throughout each layer short. Therefore, these main coils were both replaced [4-6]. In May 2011, a layer short that was causing the RRC magnetic field to fluctuate by as much as ± 20 ppm was found in the upper main coil of the RRC-E sector magnet. We found that it would be nearly impossible to repair the coil and therefore decided to fabricate a new RRC main coil, which replaced the old one in the summer of 2012. Because the RRC main coil had never before been replaced, the task was scheduled to be performed over a period of three weeks. In June 2012, the lower main coil of the RRC-W sector magnet also exhibited signs of a layer short. This layer short in the RRC-W sector magnet was identical to the short identified and repaired in 1999. We attempted to repair it using the same method that had been used in 1999, but the fluctuations of the coil voltage and magnetic fields were not fully corrected. Thus, we decided to replace the damaged lower main coil and the deteriorated upper main coil of the RRC-W sector magnet with new main coils; these were replaced in the summer of 2013. The task was scheduled to be performed over a period of eight weeks because we had never before replaced the lower main coil of the RRC during the entire 26 years of operation. Though the magnetic field of the RRC-W sector magnet before the replacement had been fluctuating over a wide range of ± 5 ppm, the field of the new magnet is stable and exhibits no fluctuation, as shown in Figure 2.

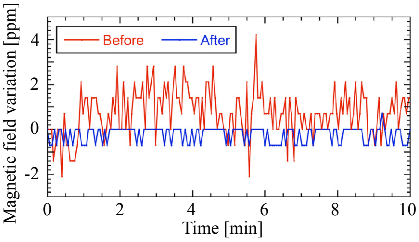

Figure 2: Fluctuation of magnetic field before and after replacement of W-sector main coils.

Vacuum Leak

The numerous vacuum leaks at the RRC have been the most serious problems in recent years. Almost all of these leaks have been caused by age-related deterioration and have been easily repaired, but the repair of a few leaks has not yet been scheduled, as the means of mending them remains unclear.

In April 2012, a vacuum leak occurred in the electric power feeder of RF resonator No. 2. This vacuum leak was attributed to a crack in the insulator and to the partial melting of the aluminium gasket. Therefore, the insulator and gasket were replaced with new ones. In the spring of 2013, a vacuum leak occurred in the inner copper cooling-water pipe for the lower dee electrode in the resonator No. 2 cavity. So, the cavity was opened in July, and the inside of the inner conductor was investigated carefully. The water leak occurred at a connection in the inner copper cooling-water pipe, as shown in Figure 3 (a), but it was impossible to repair the leak point due to the narrowness of the space surrounding the pipe. Therefore, because a new bypass line was made for the lower dee electrode, this pipe line was cut at some spot and connected with a new pipe using a sleeve and a silver braze. In October 2013, a vacuum leak occurred in a lower feed-through trim coil in the E-sector sub-chamber [2-3]. So, the E–S valley cavity, which is located next to these lower feed-through trim coils, was opened to perform these repairs in the summer of 2014. Three O-rings and plastic blocks for the feed-through had been melted, as shown in Figure 3 (b). The feed-through was cut at each melted location because there was no coupling to enable desorption of the O-rings and plastic blocks. The melted O-rings and plastic blocks were replaced with new ones, and the feed-through was again connected with coupling.

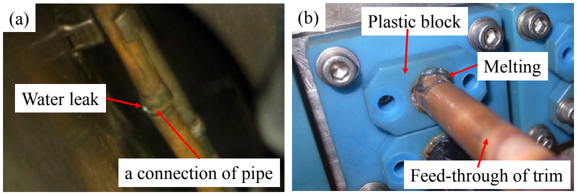

Figure 3: RRC vacuum leaks: (a) connection of the inner copper cooling-water pipe, (b) O-rings and plastic blocks for feed-through.

An investigation of the vacuum in August 2014 revealed several vacuum leaks [2]. First, a vacuum leak at a coupling of the upper copper cooling-water pipe for the dee electrode in the resonator No. 2 cavity was identified. The coupling was located at a shallow spot and was tightened, so the vacuum was improved slightly. Next, two vacuum leaks in the outer cooling-water pipe for the lower stem in the resonator No. 1 cavity were found. However, this lower stem is located in the interior and cannot be observed directly, so this vacuum leak was not investigated in detail and was not repaired. Finally, a vacuum leak occurred at a stainless bellows between the resonator No. 2 cavity and a main chamber of the S-sector magnet. This vacuum leak also was not investigated in detail, for the same reason that the lower stem leak was not further examined. Furthermore, as this bellows is long and is welded to a side-wall of the cavity, substantial work time and cost would be required to replace it.

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Though a vacuum of about 2 × 10^{-5} Pa is currently present in the two resonator cavities, beam loss is increasing more than before. Figure 4 shows the circulating beam currents of ^{78}Kr and ^{238}U that were measured by a radial probe (RP) in a 1.6 × 10^{-5} Pa vacuum in the winter of 2015 [2]. The RP position is defined as the distance from the center of the circulating orbit. Though the ^{78}Kr beam current only decreases by about 9 %, that of the ^{238}U decreases substantially, by more than 30 %. This ^{238}U beam current loss is six times greater than 5 % that measured in 2012, so it is necessary to repair the remaining leaks.

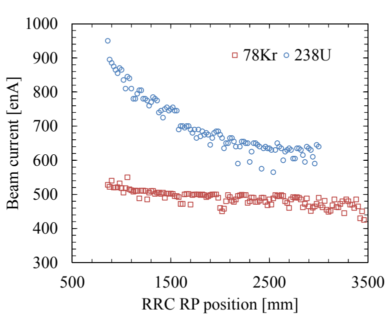

Figure 4: Circulating beam currents of ^{78}Kr and ^{238}U.

Coil Power Supplies

The capacitors of the main and trim coil magnet power supplies had exceeded their service lives, and cooling water had been leaking from pinholes in the thyristor cooling blocks. Therefore, we removed the old power supplies and installed a new main coil power supply and six trim coil power supplies in the winter of 2014 [7].

Magnetic Deflection Channels 1 and 2

Recently, a vacuum leak occurred in the RRC due to beam loss damage to its extraction device, magnetic deflection channel (MDC) 2. Though this vacuum leak is not hazardous, MDC 1 and 2 both also exhibited age-related deterioration. Therefore, we designed and produced two new MDCs in 2013 and 2014, which are usable with high-intensity heavy-ion beams, such as those of U and Xe.

Electrostatic Deflection Channel

During the U-beam service time in November 2012, a septum electrode of an electrostatic deflection channel (EDC), which deflects the circulating beam to the extraction orbit, was seriously damaged on the injection side by significant beam loss, as shown in Figure 5 [3]. After this issue arose, a beam interlock system was installed to monitor the temperature of the EDC septum electrode of the RRC and to reduce the heat load. Furthermore, a new EDC septum electrode structure was designed, in which the septum electrode forms a V-shape pointing towards the injection side.

Upgrades and Installations Around the RRC

In 2012, a new gas charge stripper system [8] with large differential pumping was installed for U-beam acceleration just after the RRC installation, and a new high-power beam dump [9] was also installed by inserting in two dipole magnets (DAA1 and DMA1) just after the gas charge stripper system. These systems were installed because the charge states of beam particles accelerated by the RRC must be multiplied before they are injected into the fRC and because the various charge states of a stripped beam must be separated. The vacuum level of the high-energy beam transport line between the RILAC2 and the RRC was also enhanced in FY2011 by mounting additional vacuum pumps, and some of the vacuum chambers in the section were modified in FY2013 to enable the use of additional beam diagnosis devices [10]. In the winter of 2012, some magnets in the injection beam transport line were rearranged, and some magnets and ducts were modified in the Magnetic Inflection Channel No. 2, Extraction Bending Magnet, and Bending Magnet of the fRC [1]. The return beam transport line from the IRC to the E5 room was installed between FY2012 and FY2014 to enable biological experiments to be conducted that require higher-energy beams of relatively heavy ions, such as Ar [2].

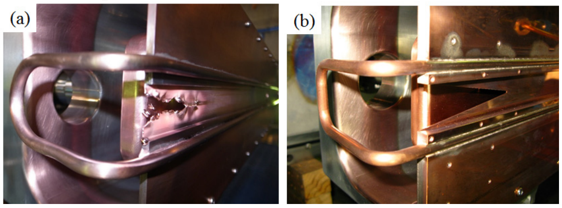

Figure 5: EDC: (a) septum electrode damaged by beam loss, (b) new V-shaped septum electrode.

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