STATUS REPORT ON THE OPERATION OF THE RIBF RING CYCLOTRONS

K. Ozeki#, T. Dantsuka, M. Fujimaki, T. Fujinawa, N. Fukunishi, H. Hasebe, Y. Higurashi, E. Ikezawa, H. Imao, T. Kageyama, O. Kamigaito, M. Kase, M. Kidera, M. Komiyama, K. Kumagai, T. Maie, M. Nagase, T. Nagatomo, T. Nakagawa, M. Nakamura, J. Ohnishi, H. Okuno, N. Sakamoto, K. Suda, A. Uchiyama, S. Watanabe, T. Watanabe, Y. Watanabe, K. Yamada, H. Yamasawa, RIKEN Nishina Center, Wako, Japan
S. Fukuzawa, M. Hamanaka, S. Ishikawa, K. Kobayashi, R. Koyama, T. Nakamura, M. Nishida, M. Nishimura, J. Shibata, N. Tsukiori, K. Yadomi, SHI Accelerator Service Ltd., Tokyo, Japan
Y. Kotaka, CNS, University of Tokyo, Saitama, Japan

Abstract

Operating status of four ring cyclotrons (RRC, fRC, IRC, SRC) from August 2014 to July 2015 is reported. We are engaging in the improvements and adjustments for increasing beam intensities year after year, and maintenances for the stabilization of beam supply. In these contributions, we will report the past performances of accelerated beams, statistics of operational and tuning time on corresponding period, as well as failures and copings with them.

INTRODUCTION

At RIKEN Nishina Center, the Radioactive Isotope Beam Factory (RIBF) [1] consists of four ring cyclotrons and three injectors. The four ring cyclotrons are: the RIKEN ring cyclotron (RRC) [2], which was commissioned in 1986; fixed-frequency ring cyclotron (fRC) [3], which was commissioned in 2006; intermediate stage ring cyclotron (IRC) [4]; and superconducting ring cyclotron (SRC) [5]. The three injectors are: the RIKEN heavy ion linear accelerator (RILAC) [6], RILAC2 [7], and AVF cyclotron (hereafter, AVF) [8,9]. The list of nuclei accelerated in the RIBF so far is shown in Fig. 1. Several acceleration modes are available through selection of a combination of accelerators. All ions from hydrogen to uranium can be accelerated up to 345 MeV/u (400 MeV/u for A/Z~2). There are three types of acceleration modes corresponding to each injector, which use the SRC. The beam extracted from the RRC can also be used at the experimental laboratories in the old facility. In addition, high-energy light ions recently became available at the biological irradiation laboratory in the old facility (E5B), which were accelerated using AVF, RRC, and IRC and then transported back to the old facility. Figure 2 shows the examples of energy attained at each stage in multiple-stage acceleration for each acceleration mode using SRC and IRC. The solid line shows the fixed-frequency mode, in which RILAC2 is used as the injector and all the ring cyclotrons are connected in series. The dashed line represents the variable-frequency mode, in which RILAC is used as the injector. The dotted line denotes the light-ion mode, in which AVF is used as the injector [10]. The dashed-dotted line shows a mode, which utilizes the newly installed IRC-E5 beam line. In this contribution, the status of the ring cyclotron system in the RIBF from August 2014 to July 2015 is reported.

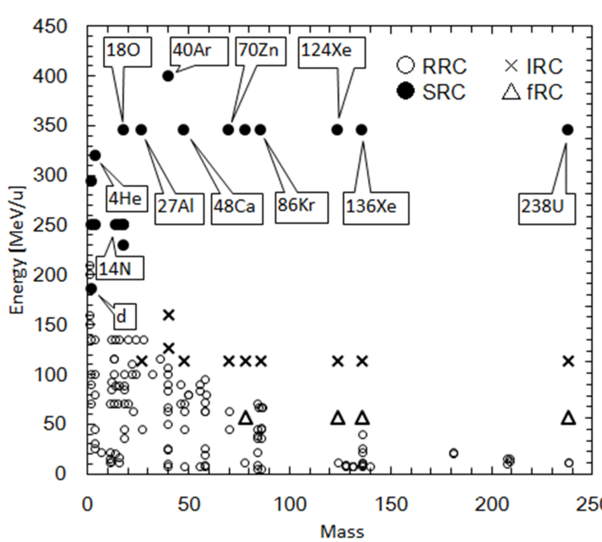

Figure 1: List of nuclei accelerated in the RIBF so far.

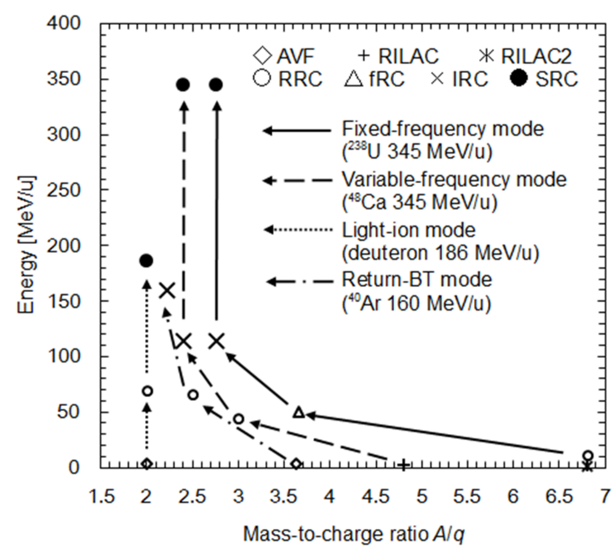

Figure 2: Transitions of energy and mass-to-charge ratio of accelerated nuclei in each acceleration mode in the RIBF.

#k_ozeki@riken.jp

ISBN 978-3-95450-131-1

OPERATING STATUS

The operating statistics of the RIBF are summarized in Table 1. Availability is defined as the ratio of the actual beam supply time to scheduled beam supply time. If the availability is greater than 100%, it denotes that actual time exceeds the scheduled time for various reasons such as shortening of beam tuning time. For the experiments in which the beam was not constantly used, such as material irradiation experiments, the availability was considered as 100% if the irradiation of the predetermined samples was completed without any delay. Multiple experiments using a similar beam are put together except for the long-term experiments using SRC; they are described separately.

The accelerations of ^{238}U using SRC were carried out three times. The total beam supply time and availability were 1,233 h and 94%, respectively. The intensity of the ^{238}U beam increased gradually, as shown in Fig. 3. In the operation on May 2015, the maximum beam intensity was 39.5 particle nA because of several factors, such as the enhancement of beam intensity supplied from the ion source, conversion of the injection buncher from the mesh type to cavity type, implementation of a new carbon material for the rotating charge stripper [11], and improvement of transit efficiency in the cyclotrons by the proficient beam tuning. On the other hand, the degradation of transit efficiency in the RRC caused by the loss of vacuum has become obvious [12].

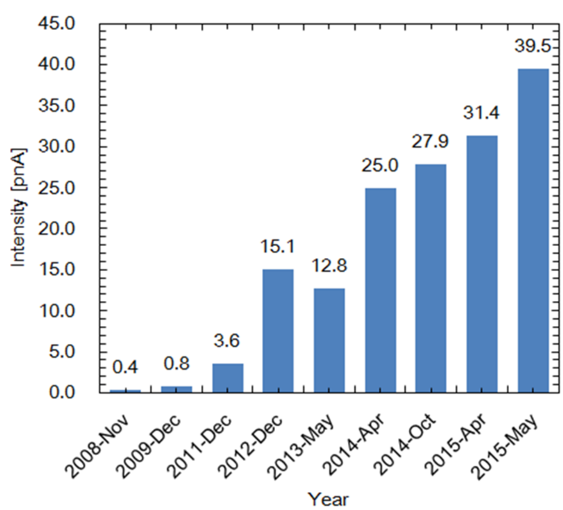

Figure 3: Beam intensity record of obtained in each ^{238}U beam service.

In the acceleration of ^{48}Ca, the beams were supplied to four experiment groups. The electrostatic deflection channel in the SRC was operated at 128 kV, the voltage of which was close to the upper limit of specification. The beam with a beam power of more than 8 kW was stably supplied.

The acceleration of polarized deuterons with the energy of 190 MeV/u was lower than the lower limit of the energy certified by the design of SRC (250 MeV/u). The acceleration test showed that a single-turn extraction was possible at this energy. In order to maintain the ratio of the half bunch to the main bunch in the beam extracted from the SRC below 1%, which was an index of the mixture of turns, beam tunings were performed frequently. Nevertheless, the availability exceeded 100% because the beam supply was started ahead of schedule because of the shortening of accelerator tunings.

Although the medium-heavy nuclei were typically accelerated using the variable-frequency mode in the RIBF, the fixed-frequency mode was adopted for the acceleration of ^{78}Kr. Adoption of this mode has several advantages: a high intensity 28-GHz superconducting ECR ion source can be used, as well as only one charge stripping is needed. However, a thick charge stripper foil must be used because of the difference between the extraction energy from the fRC and injection energy into the IRC. This mode was not adopted so far because degradation in beam quality was expected. As a result of the acceleration test, it was found that the high-intensity operation was possible in spite of the degraded beam quality. The beam with the maximum intensity of 310 particle nA was supplied to six experiments. In addition, the high-intensity beam production test was conducted using a beam dump in a projectile-fragment separator (BigRIPS), which was installed downstream of the SRC, to record a beam power of 13.1 kW (486 particle nA), which is the highest value recorded in the RIBF.

Table 1: Operation Statistics of RIBF

Beam particle	Energy (MeV/u)	Acceleration mode	Beam course	Beam current(particle nA) Requested	Beam current(particle nA) Actual	Beam time(h) Scheduled	Beam time(h) Actual	Down time (h)	Availability (%)
12C	70	AVF-RRC	E6(RIPS)	10.0	350.0	36.0	36.0	0.0	100.0
12C	135		E5B(Biology)	1.0	393.2	47.0	47.0	0.0	100.0
40Ar	95		E5B(Biology)	1.0	76.5	32.0	32.0	0.0	100.0
56Fe	90		E5B(Biology)	1.0	6.3	21.0	21.0	0.0	100.0
84Kr	70		E5A(Industry)	0.1	5.6	121.0	121.0	0.0	100.0
86Kr	36	RILAC-RRC	E3A(JAXA)	1.0	8.8	12.0	12.0	0.0	100.0
48Ca	63		E6(RIPS)	200.0	235.3	108.0	104.3	1.2	95.4
136Xe	10.75	RILAC2-RRC	E2B(KEK/KISS)	50.0	405.0	96.0	106.0	0.9	109.4
238U	10.75		A01(MS)/E5A(Material)	2.0	2500.0	48.0	48.0	0.0	100.0
40Ar	160	AVF-RRC-IRC	E5B(MS)	—	1.6	48.0	48.0	0.0	100.0
pol.d	190	AVF-RRC-SRC	BigD-pol	10.0	290.0	96.0	123.9	22.5	105.6
48Ca	345	RILAC-RRC-IRC-SRC	BigRIPS/SAMURAI	500.0	530.0	492.2	492.2	18.1	96.3
78Kr	345	RILAC2-RRC-fRC-IRC-SRC	BigRIPS/ZDS/EURICA/Rare-RI Ring	300.0	486.1	732.0	732.0	72.2	90.1
238U(1st)	345		BigRIPS/ZDS	15.0	27.9	532.1	532.1	31.1	94.2
238U(2nd)	345		BigRIPS/ZDS	15.0	31.4	552.0	553.0	47.9	91.5
238U(3rd)	345		BigRIPS/ZDS	20.0	39.5	228.0	252.0	25.3	99.5

ISBN 978-3-95450-131-1

In the old facility, biological experiments were conducted at the E5B, the industrial uses were conducted at the E5A, and nuclear experiments were conducted at the E6 (RIPS) and E2 (KISS). Stable beams were supplied as usual.

IRC-E5 BEAM LINE

In order to increase the beam energy used for biological experiments, a new beam line, which connects the IRC and an old experimental laboratory E5, was installed.

The newly installed beam line diverges from the SRC injection line at the deflection electromagnet DAKR, passes through a part of the bypass line, which connects the RRC and SRC bypassing the IRC, and joins the existing beam line at the deflection electromagnet DMA1 (See Fig. 4). The installation of each component was completed on January 2015, and a two-day commissioning was conducted. In order to obtain a high-energy beam from the IRC, a new acceleration mode that uses AVF, RRC, and IRC in series was tested. The ^{40}Ar beam was successfully accelerated up to 160 MeV/u, and transported to the old facility. In addition, a test to supply the beam to the biological irradiation device in E5B was conducted.

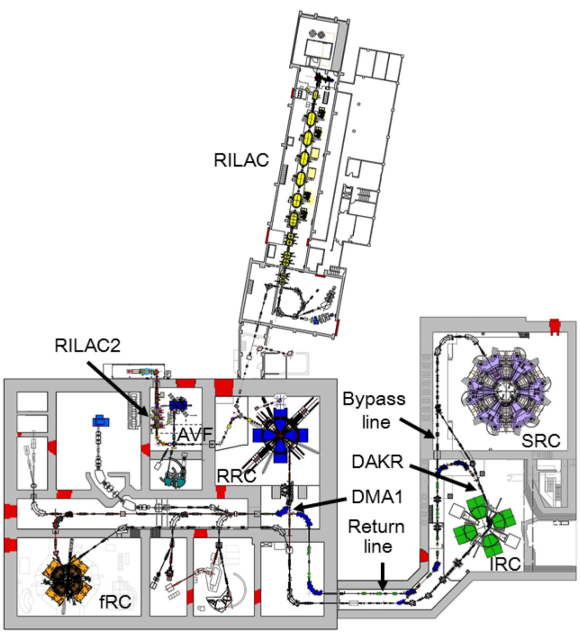

Figure 4: The layout of the accelerator facility in RIBF at RIKEN.

SUMMARY

For the duration from August 2014 to July 2015, the total beam supply time was 3,041 h. The ratio of experiments in which users use the beams directly extracted from RRC to all experiments was 19%. The total availability was 95%. The supplied beam intensities increased annually. A practical operation of the ^{48}Ca beam with the beam power of 13 kW is scheduled this autumn. Attempts for further enhancement of beam intensities and improvement of availability are made continuously.

REFERENCES

[1] Y. Yano, The RIKEN RI beam factory project: A status report, Nucl. Instrum. Methods B261 (2007) 1009-1013.

[2] H. Kamitsubo, Progress in RIKEN Ring Cyclotron Project, Cyclotrons'86, Tokyo, Oct. 1986, pp. 17-23.

[3] N. Inabe et al., Fixed-frequency ring cyclotron (fRC) in RIBF, Cyclotrons'04, Tokyo, Oct. 2004, 18P15, pp. 200-202;
T. Mitsumoto et al., Construction of the fRC sector magnet for RIKEN RI Beam Factory, ibid, 20P12, pp. 384-386.

[4] J. Ohnishi et al., Construction status of the RIKEN inter-mediate-stage ring cyclotron (IRC), Cyclotrons'04, Tokyo, Oct. 2004, 18P14, pp. 197-199.

[5] H. Okuno et al., The Superconducting Ring Cyclotron in RIKEN, IEEE Trans. Appl. Supercond. 17 (2007) 1063-1068.

[6] M. Odera et al., Variable frequency heavy-ion linac, RILAC: I. Design, construction and operation of its accelerating structure, Nucl. Instrum. & Methods 227 (1984) 187-195.

[7] K. Yamada et al., Beam commissioning and operation of new linac injector for RIKEN RI beam factory, IPAC12, New Orleans, May 2012, TUOBA02, pp. 1071-1073.

[8] A. Goto et al., Injector AVF cyclotron at RIKEN, Cyclotrons'89, Berlin, Germany, 1989, pp. 51-54.

[9] K. Suda et al., Status report of the operation of the RIKEN AVF cyclotron, in these proceedings, MOPA12.

[10] N. Sakamoto et al., High intensity heavy-ion-beam operation of RIKEN RIBF, Proceedings of PASJ9, WEPL02 (2012) 7-11.

[11] H. Hasebe, History of solid disk improvement for rotating charge stripper, in these proceedings, MOA1C01.

[12] Y. Watanabe et al., RIKEN Ring Cyclotron (RRC), in these proceedings, MOPA09.

ISBN 978-3-95450-131-1