OPERATING EXPERIENCE WITH THE RIKEN RADIOACTIVE ISOTOPE BEAM FACTORY

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Abstract

The RIKEN Radioactive Isotope Beam Factory is pushing the limits of energy for heavy-ion cyclotrons. After our initial experiments with a 345-MeV/nucleon uranium beam in May 2007 resulted in the successful discovery of the new isotopes ^{125}Pd and ^{126}Pd, we have experienced problems of low transmission efficiency, especially for uranium beam acceleration. We have spent two years attempting to determine the source of these problems and to improve the equipment to obtain better transmission efficiency. As a result, a 345-MeV/nucleon uranium beam having an intensity of 0.4 pnA and a 345-MeV/nucleon ^{48}Ca beam having an intensity of 170 pnA have been made available for experiments.

RI BEAM FACTORY

The Radioactive Isotope Beam Factory (RIBF) [1] was built in order to expand the scope of our research into the area of heavier nuclei, thus building upon the success of our work on light unstable nuclei generated by a combination of our old K=540 MeV separate-sector cyclotron (RIKEN Ring Cyclotron, RRC) [2] and the RIKEN projectile fragment separator [3]. Using the RIBF, we aim to produce the most intense radioactive isotope (RI) beams in the world covering all atomic masses. We hope to solve various problems involving highly unstable nuclei, such as nucleosynthesis in the universe. To this end, three new cyclotrons and a new projectile fragment separator BigRIPS [4] have been constructed. The maximum beam energy of light nuclei, such as deuteron, is 440 MeV/nucleon, while it is 345 MeV/nucleon for uranium ions. Our goal is to operate a beam having an intensity of 1 pμA. The layout of RIBF is shown in Fig. 1.

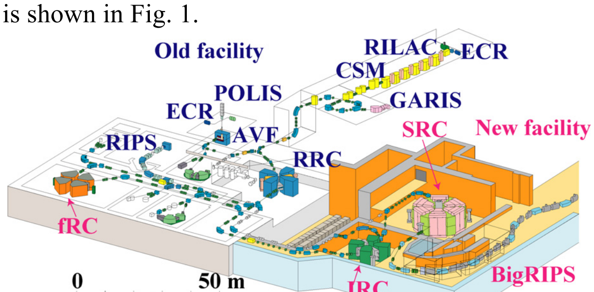

Figure 1: Layout of RIBF

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Beam commissioning for the RIBF began in July 2006, and we successfully produced a 345-MeV/nucleon aluminium beam using the new main accelerator, the superconducting ring cyclotron in December 2006. In March 2007, BigRIPS was successfully commissioned, and a 345-MeV/nucleon uranium beam was successfully produced.

RIBF ACCELERATORS AND ACCELERATION MODES

The accelerator complex of the RIBF consists mainly of the RRC, its two injectors and three newly constructed cyclotrons. One of the injectors of the RRC is a heavy-ion linear accelerator (linac) complex, which consists of the RIKEN heavy-ion linac (RILAC) [5], its pre-injector system (a buncher, a rebuncher and a folded-coaxial radio-frequency quadrupole [6]) as well as its energy-boosting linac which is denoted as the charge-state multiplier (CSM) [7]. The other injector is a K=70 MeV azimuthally-varying-field (AVF) cyclotron [8] mainly used to accelerate light ions. Two beam rebunchers are installed between the injectors and the RRC. Two of the newly constructed ring cyclotrons are conventional normal-conducting four-sector cyclotrons, one of which is a fixed-frequency ring cyclotron (fRC) [9] and the other, an intermediate-stage ring cyclotron (IRC) [10]. The remaining new cyclotron is the first superconducting ring cyclotron (SRC) [11] in the world. The specifications of the new cyclotrons are summarized in Table 1. Lastly, an additional rebuncher [12] is installed between the RRC and the fRC.

Table 1: Specifications of RIBF cyclotrons. In the bottom row, the number of acceleration cavities is shown (FT= flat-top cavity)

	fRC	IRC	SRC
K-number (MeV)	570	980	2600
Number of sectors	4	4	6
Velocity gain	2.1	1.5	1.5
Number of trim coils	10	20	4 + 22
Frequency range (MHz)	54.75	18 -38	18 - 38
RF system	2 + FT	2 + FT	4 + FT

The RIBF accelerator complex affords various modes of acceleration. The basic scheme is a variable-energy mode that uses the linac complex, RRC, IRC and SRC in a series. The variable-energy mode is able to accelerate ions such as ^{48}Ca up to at least 345 MeV/nucleon. Since the variable-energy mode cannot accelerate ions heavier than krypton to the same velocity as lighter ions, an additional cyclotron, the fRC, is inserted between the RRC and the IRC. As the fRC operates at a fixed frequency, the energy is set to 345 MeV/nucleon. The third mode, which is used to accelerate extremely light ions, such as deuteron and nitrogen, uses the AVF cyclotron as an injector and only two ring cyclotrons (RRC and SRC). This is also a variable-energy mode. Upstream of the AVF cyclotron, a polarized ion source is installed, and consequently, polarized deuteron beams are accelerated to energies of 250–440 MeV/nucleon in order to study the nuclear three-body force. In addition, the RRC and its two injectors have their own experimental beam courses. The most important project involves searching for super-heavy elements by using a standalone mode of the linac complex [13].

OPERATION STATISTICS

The operation statistics of the RIBF for the years 2007 and 2008 are summarized in Table 2. The accelerators in RIBF have been operated by RIKEN Nishina Center and Center for Nuclear Study (CNS), University of Tokyo. The yearly operation times of the RRC, which is used in the three acceleration modes mentioned above, were 3757 and 3961 hours in 2007 and 2008, respectively. The total operation time was limited by the approved budget. The full operation of the RIBF, which includes the use of the SRC, was performed five times and two times in 2007 and 2008, respectively. The corresponding operating times were 1845 hours in 2007 and 2051 hours in 2008. About 30% of this time was for experiments and the remainder was for beam tuning, machine studies and resolving technical problems.

Table 2: Operational statistics (hours) in 2007 and 2008

Year	2008	2007
RRC operation	3961	3757
RRC experiments	1165	687
RIBF operation	2051	1845
RIBF experiments	685	414

An experiment performed in May 2007 demonstrated the effectiveness of the RIBF in producing rare isotopes via projectile-fission reactions with high-energy uranium beams. Using such beams, the new isotopes ^{125}Pd and ^{126}Pd were successfully discovered [14]. We also conducted an acceleration test of a 345-MeV/nucleon krypton beam in November 2007. After this, the RIBF was not operated at full capacity for one year. This resulted from the failure of the SRC's cryogenic system to provide adequate cooling power for more than two months due to decreased liquid-helium flow to the SRC. The source of the problem (oil contamination in the SRC refrigerator from a liquid helium compressor) was resolved in February 2008. The oil that adhered to mesh filters in the refrigerator had frozen and reduced the flow of liquid helium. Troubleshooting this problem required several months and as a result, experiments using the SRC were shifted to the latter half of fiscal year 2008. The oil-contaminated apparatuses were completely cleaned and additional oil separators were installed. A series of acceleration tests without the SRC were performed in this period.

After solving the oil contamination problem, two experiments were performed using a 0.4-pnA uranium beam in November 2008 and high-intensity (0.1–0.17 pμA) ^{48}Ca beams in December 2008. Within a week, the uranium-beam experiment resulted in the discovery of more than twenty candidates of new radioactive isotopes.

In addition to the operation of the RIBF, a new beam transport line bypassing the IRC was constructed to afford the AVF+RRC+SRC mode in fiscal year 2008. The first acceleration test of this new line was performed in February 2009 with a 250 MeV/nucleon nitrogen beam and the newly constructed high-resolution spectrometer SHARAQ [15] constructed by CNS, was successfully commissioned in March 2009. The first attempt to accelerate a 250-MeV/nucleon polarized deuteron beam was also successfully completed in April 2009.

PERFORMANCE OF RIBF AND RECENT DEVELOPMENTS

The transmission efficiencies of the RIBF accelerator complex are summarized in Table 3, in which the charge stripping efficiency is not taken into account. The total charge stripping efficiency was determined experimentally as 30%, 12% and 4.4% for ^{48}Ca, ^{86}Kr and ^{238}U, respectively.

Table 3: Transmission efficiencies (%) from the ion source to each accelerator. Note that the observed currents include an error of 20–30%. The bottom row shows the maximum beam intensity during acceleration tests.

	^{238}U 07/07/03	^{86}Kr 07/11/04	^{238}U 08/11/16	^{48}Ca 08/12/21
RILAC	29	47	40	54
RRC	25	28	30	50
fRC	9	Not used	35	Not used
IRC	5	20	23	48
SRC	2	9	16	35
Max.	4 nA	1.1 μA	35 nA	3.5 μA

The allowable limit of beam loss for each cyclotron depends on beam intensity since the beam extraction apparatus (a septum electrode of the electrostatic deflector) cannot be subjected to exceedingly high heat load. The heat load limit, as determined by thermal analysis, is 300 W for the SRC extraction [16]. This corresponds to a transmission efficiency of 82% for a 100-pnA ^{48}Ca beam. In this sense, the transmission efficiency of ^{48}Ca is nearly at an acceptable level, at least for the commissioning stage. It should be noted that the design value of the transmission efficiency of the linac complex is not 100% but ~70% since the longitudinal acceptance is limited [17].

Unlike the ^{48}Ca beam, the uranium beam has suffered from low transmission efficiency. The total transmission efficiency was 2% in July 2007. After a series of acceleration tests performed during these two years, the observed low transmission efficiency was attributed mainly to poor beam tuning since the beam monitors used in the early stages of beam commissioning were not suitable for high-energy uranium ions. The low quality of the uranium beam caused by the presence of thick carbon-foil strippers and insufficient stability of the accelerator complex further complicated this problem. In the following sections, these three problems are discussed.

Charge Stripper

Variable-energy modes, such as ^{48}Ca acceleration, employ two-step charge stripping with relatively thin carbon foils. The first foil is placed below the linac complex and has a thickness of 0.04 mg/cm^2. The second is placed between the RRC and IRC (M04 position) and has a thickness of 1 mg/cm^2. On the other hand, we use extremely thick carbon foils for uranium beam acceleration. The first-stage charge stripper is placed immediately after the RRC (A01 position) and has a thickness of 0.3 mg/cm^2. The corresponding energy loss is 1.4%. The second charge stripper placed at M04 is 14 mg/cm^2 in thickness for obtaining $^{238}U^{86+}$ uranium ions. The energy loss is 9%. These large energy losses require good thickness uniformity of the carbon foils. However, this condition was not satisfied.

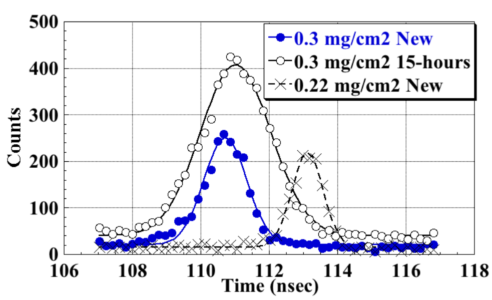

Figure 2: Longitudinal beam width measured by plastic scintillators.

Figure 2 shows longitudinal beam profiles measured with a plastic scintillator placed 38 m below the A01 stripper (0.3-mg/cm^2 commercial carbon foil strippers [18]) for obtaining $^{238}U^{71+}$ ions for fRC acceleration. The thickness uniformity was estimated by comparing the longitudinal widths of the beams generated with and without a carbon foil. The thickness uniformity was found to be about 30%. In addition, the longitudinal beam widths spread considerably after 15 hours of irradiation with a 0.6-μA uranium beam. The problem of beam quality has not yet been solved at present. We plan to use 0.2 mg/cm^2 carbon foils and to accelerate $^{238}U^{69+}$ ions with small modifications to the fRC power supplies in order to obtain better quality beams as shown in Fig. 2. To solve the lifetime problem, we tested various kinds of carbon foils including diamond-like carbon and multi-layer carbon. We also tested rotating carbon-foil strippers developed at RIKEN [19]. However, satisfactory results have not yet been obtained.

Beam Instrumentation

The beam diagnostic system of the RIBF is highly conventional. In the beam transport lines, Faraday cups, wire-scanner beam profile monitors and plastic scintillators are installed as summarized in Table 4. For the cyclotrons, we employ a series of phase-pickup electrodes to obtain a satisfactory isochronous magnetic field, as well as radial probes with integral and differential electrodes. The integral electrode measures the beam intensity and the differential probe measures the oscillation pattern of the beam during acceleration.

Table 4: Beam Monitors Installed in Beam Transport Lines

Line	Length (m)	PF	FC	Scintillator
RRC-fRC	81	12	9	3
fRC-M04	60	10	5	1
M04-IRC	59	15	5	3
IRC-SRC	64	13	6	3

The problem regarding uranium acceleration was caused by the effects of secondary electrons emitted upon bombardment with uranium ions. These electrons were not suppressed effectively for Faraday cups and differential probes. The Faraday cup originally installed had a conventional ring suppressor supplied with high voltage of 1 KV, although the voltage at the center of the cup is less than 50 V. It overestimated the beam current to be twice as large as that of the actual beam. This can be clearly seen by observing the beam intensity measured with the integral electrodes of the radial probes under strong magnetic fields (~1.5 T) working as an effective secondary electron suppressor. Hence, we decided to modify the Faraday cups and ultimately adopted a design in which the thickness of the suppressor in the beam direction is 7 cm in order to reduce the position dependence of the suppression voltage. The usage of the modified Faraday cups greatly reduced beam losses in all of the beam transport lines.

Figure 3 shows the observed turn pattern measured with one of the main differential probes of the IRC (MDP1). The effect of the secondary electrons is clearly illustrated by the sign change of the currents measured by the differential probe. This phenomenon was thought that the differential probe detected secondary electrons emitted from the sidewall of the integral electrode due to bombardment with uranium ions. Similar phenomena were observed not only in the IRC, but also in the fRC and SRC. We modified the radial probes by shifting the differential electrodes away from the integral probes. In the case of the IRC, another differential probe (MDP2) performed well since the angle of the integral probe was different from MDP1 and the uranium ions could not hit the sidewall of the integral probe.

Another problem related to the radial probes was the generation of strong electromagnetic fields by the flat-top resonators. Near the center of the cyclotrons in the radial direction, data was frequently not obtained due to the existence of strong stray fields since the frequency of the flat-topping field was beyond the cutoff frequency. To avoid this, the cylindrical covers of the radial probes were grounded by adding contact fingers to its upper half in addition to lower half and the flat-top resonators were carefully tuned to suppress stray fields. Various improvements implemented in the radial probes allowed for the precise adjustment of the phases of flat-topping RF fields by comparing turn patterns obtained for various conditions. This resulted in a drastic decrease in beam loss.

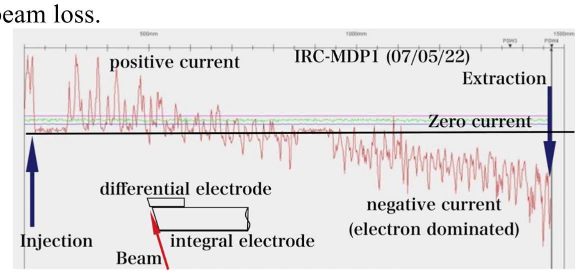

Figure 3: Effect of secondary electrons observed with IRC-MDP1.

Stabilities

We have observed two kinds of instability, one relating to the carbon-foil stripper lifetime mentioned previously and the other concerning injection-phase instability for the RRC. As shown in Table 4, the accelerators of the RIBF are away from each other, which requires that the voltages and phases of the RF system be stable, i.e., the maximal allowable fluctuations should be of the order of $< \pm 0.1$ degrees in phase and $< \pm 0.1\%$ in voltage. This condition is satisfied during standalone use of each resonator. However, it was found via the RF monitoring system recently developed using lock-in amplifiers [20] that the system was not sufficiently stable during actual use of the linac complex.

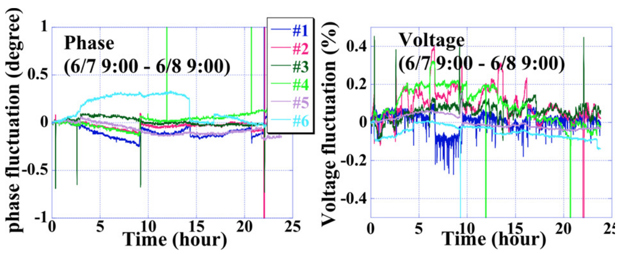

Figure 4: Results of RILAC Stability Test

Examples of RILAC stability tests are shown in Fig. 4. The correlation between the voltage instability of commercial electricity was analyzed. The results indicated that the voltage stabilities of four resonators using old low-level feedback circuits were unsatisfactory, and some of them were strongly affected by the voltage fluctuation of commercial electricity. This was verified by upgrading the low-level system of the second resonator of the RILAC. We plan to upgrade the remaining old low-level systems during this fiscal year. The problem of phase instability has not been resolved at present. It might be the result of temperature changes in the building in which the linac complex is installed. The correlation analysis between RF instability and factors such as commercial electricity, cooling water temperature and room temperature has just begun, and additional time is necessary to resolve this problem.

EMITTANCE ANALYSIS

To further improve the performance, the beam emittances were analyzed. The beam width as measured with a beam profile monitor depends on the beam emittance. Utilizing least square fitting, we determined the beam emittances of the beam transport lines. An example of least square fitting is shown in Fig. 5, where the observed data is reproduced sufficiently well.

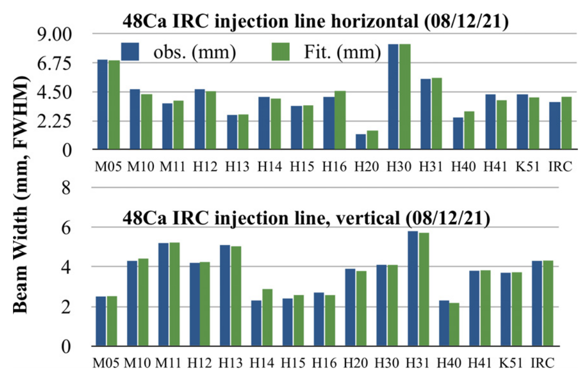

Figure 5: Result of least square fitting of beam widths on IRC injection line. A 345-MeV/nucleon ^{48}Ca beam was analyzed.

The estimated emittances (not normalized) are summarized in Table 5. The definition of emittance adopted here is within a 4σ region. Large ambiguities exist, particularly in determining the horizontal emittances, due to coupling to the longitudinal direction and an insufficient amount of observed data. In the case of ^{48}Ca, the emittance of the SRC-injected beam is about 1.7 π mm mrad in both the horizontal and vertical directions. This corresponds to a normalized RMS emittance of 0.19 π mm mrad. No notable emittance growth was found, although the present analysis might include errors of the order of 20–30%.

The vertical emittance of the uranium beam was similar to that of the ^{48}Ca beam. In the case of uranium acceleration, two thick carbon foil strippers are used and sizable emittance growth takes place. This growth should be cancelled by the fRC acceleration, which reduces the emittance by a factor of two. Our scenario was successful for the vertical direction. On the contrary, the observed horizontal emittances were three times larger than the vertical ones. The present analysis indicates that a mismatch in the emittance during the injection into fRC causes the emittance to grow by a factor of 1.7, and the rebuncher installed between the RRC and fRC, where sizable chromaticity remains, causes emittance growth by a factor of two. The former is the result of poor beam tuning, and it is possible to correct it. However, we cannot remove the latter completely without changing the layout of the beam transport system from the RRC to the fRC. The estimation of emittance growth at the rebuncher performed at the design stage yielded a value of 1.5. The energy spread at the A01 stripper was beyond our prediction. To reduce the emittance growth, we plan to use thinner carbon foils, as mentioned above.

Table 5: Emittance Estimation (not normalized, π mm mrad). H=horizontal; V=vertical.

	^{48}Ca (08/12/21)		^{238}U (08/11/07)	
	H	V	H	V
fRC injection			5	2.6
IRC injection	2.3	2.2	5 ~ 6	2.1
SRC injection	~ 1.5	1.7	4	1.4

SRC

The SRC has been working well as an isochronous cyclotron. The isochronicity obtained by normal-conducting trim coils superimposed on superconducting trim coils are within ±3 degrees. The stability of the RF system is also satisfactory. The phase stability is within ±0.1 degrees and the voltage stability is near ±0.01%. The remaining problem is the size of the errors in the magnetic field. The vertical tune of the SRC depends on the excitation level of the sector magnet. In the case of low-magnetic-field operation, the vertical tune approaches 0.5 as the energy increases. If there are large harmonic fields exciting a resonance, ions will be lost during acceleration. At present, our operating experience is limited, and we plan to perform tests regarding this point.

SUMMARY AND FUTURE PLANS

The transmission efficiencies of the RIBF accelerator complex were greatly improved by gradual modifications implemented during 2007 and 2008. The maximum transmission efficiencies of the fRC and IRC exceeded 90%, and the maximum extraction efficiency of the SRC was 82%. This is a satisfactory level for the beam commissioning stage. Several unresolved problems remain regarding uranium beam acceleration, such as the lifetime of the carbon foil and the observed emittance growth. In addition, the present beam intensity (0.4 pnA) is less than 0.1% of our goal intensity. To increase the uranium beam intensity, we have constructed a new superconducting ion source suitable for $^{238}U^{35+}$ ion production [21]. The excitation tests of its superconducting coils have already been performed successfully. This ion source was installed upstream of the RILAC, and its first acceleration test is scheduled for the summer of 2009. In addition to the new ion source, the construction of a new injector linac [22] was approved at the end of fiscal year 2008. The new injector will be capable of accelerating M/q=7 ions up to 0.7 MeV/nucleon, which is the same as the existing linac complex in fixed energy mode operation. The new ion source will be moved upstream of the new injector linac after completing performance tests using the RILAC. Fabrication of the new injector linac will be completed at the end of fiscal year 2009, and the beam commissioning is scheduled for 2010. After completion of the new linac injector, it will be possible to perform experiments aiming at the discovery of super-heavy elements simultaneously with operation of the RIBF in fixed energy mode. The beam intensity of uranium beam acceleration in the RIBF is expected to become 100 times larger than the present beam intensity with the use of the new ion source and the new injector linac.

REFERENCES

[1] Y. Yano, Nucl. Instr. Meth. B261 p. 1009 (2007), doi:10.101b/ j.nimb.2007.04.174 .
[2] Y. Yano, Proc. 13th Int. Cyclo. Conf. p. 102 (1992).
[3] T. Kubo et al., Nucl. Inst. Meth. B 70 p. 309 (1992).
[4] T. Kubo et al., Nucl. Instr. Meth. B204, p.97 (2003).
[5] M. Odera et al., Nucl. Instrum. Methods A227, p. 187 (1984).
[6] O. Kamigaito et al., Rev. Sci. Instrum. 70, p. 4523 (1999).
[7] O. Kamigaito et al., Rev. Sci. Instrum. 76 013306 (2005).
[8] A. Goto et al., Proc. 12th Int. Cyclo. Conf. p.51 and p. 439 (1989).
[9] T. Mitsumoto et al., Proc. 17th Int. Conf. on Cyclotrons and Their Applications, p. 384 (2004).
[10] J. Ohnishi et al., Proc. 17th Int. Conf. on Cyclotrons and Their Applications, p. 197 (2004).
[11] H. Okuno et al., Proc. 17th Int. Conf. on Cyclotrons and Their Applications, p. 373 (2004).
[12] T. Aoki et al., Nucl. Instr. Meth. A592, p. 171 (2008), doi:10/1016/j.nima.2008.04.004.
[13] K. Morita et al., J. Phys. Soc. Jpn Vol.73 No.10 p. 2593 (2004).
[14] T. Ohnishi et al., J. Phys. Soc. Jpn Vol.77, No. 8, p. 083201 (2008), DOI: 10.1143/JPSJ.77.083201.
[15] T. Uesaka et al., Nucl. Instr. And. Meth. In Phys. Res. B 266 p. 4218 (2008).
[16] H. Okuno, private communication.
[17] N. Fukunishi et al., RIKEN Accel. Prog. Rep. 41 p. 81 (2008).
[18] Arizona Carbon Foil Company Inc.
[19] H. Ryuto et al., Nucl. Instr. and Meth. A 569 p. 697 (2006).
[20] R. Koyama et al., Proc. EPAC08, p. 1173 (2008).
[21] T. Nakagawa et al., Rev. Sci. Instrum. 79 02A327 (2008).
[22] O. Kamigaito et al., Proc. of PASJ3-LAM31, WP78, (2006).