ACCELERATION OF INTENSE HEAVY ION BEAMS IN RIBF CASCADED-CYCLOTRONS

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Abstract

RIKEN Radioactive Isotope Beam Factory, the world's first next-generation radioactive isotope beam facility, has provided high-intensity light and medium-heavy ion beams since 2006. Our aim is to produce the world's most intense heavy-ion beams, which are essential for exploring nuclei far from the stability line. The new injector RILAC2, which was fully commissioned in 2011, has greatly improved the beam intensity for very heavy ions. As a result, stable operation of highly intense beams such as 415-pnA ^{48}Ca, 38-pnA ^{124}Xe and 15-pnA ^{238}U has been realized.

ACCELERATOR COMPLEX OF THE RIKEN RADIOACTIVE ISOTOPE BEAM FACTORY (RIBF)

The RIBF accelerator complex [1] comprises the RIKEN Ring Cyclotron (RRC) [2], three injectors and three energy-booster cyclotrons (Fig. 1). The injectors are the RIKEN heavy-ion linac complex (RILAC) [3,4], the new injector linac (RILAC2) [5,6] and the K70-MeV azimuthally varying field (AVF) cyclotron [7]. The energy boosters are the fixed-frequency Ring Cyclotron (fRC) [8], the Intermediate-stage Ring Cyclotron (IRC) [9] and the Superconducting Ring Cyclotron (SRC) [10]. The RILAC, the RRC and the AVF cyclotron started operation in 1981, 1986 and 1989, respectively. The three boosters were commissioned in 2006 and the RILAC2 was fully commissioned in 2011.

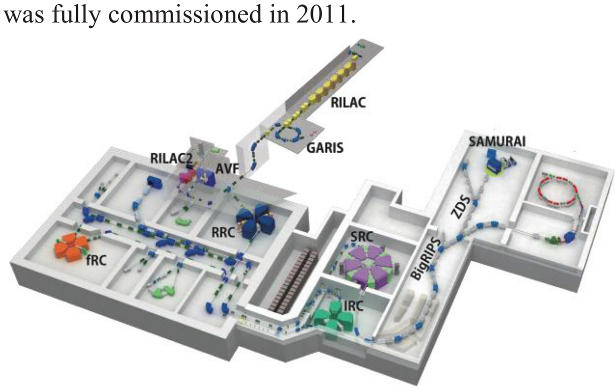

Figure 1: Layout of RIBF.

Acceleration Modes

In addition to standalone applications of the RILAC and the AVF cyclotron for low-energy experiments and direct applications of the beams accelerated by the RRC, the three acceleration modes illustrated in Fig. 2 are available at the RIBF. The variable-energy mode accelerates light and medium-heavy ions such as ^{48}Ca up to 400 MeV/nucleon, where two-step charge-state stripping is usually required. The variable-energy mode cannot accelerate ions heavier than krypton to the same velocity as lighter ions. Hence, very heavy ions, such as uranium, are accelerated further by inserting the fRC between the RRC and the IRC in fixed-energy mode. The RILAC2 replaced the RILAC for this mode in 2011. AVF injection mode is used to accelerate light ions such as oxygen by using three frequency-variable cyclotrons (AVF, RRC and SRC). A polarized ion source (PIS) produces polarized deuteron beams that range in energy from 250 to 440 MeV/nucleon.

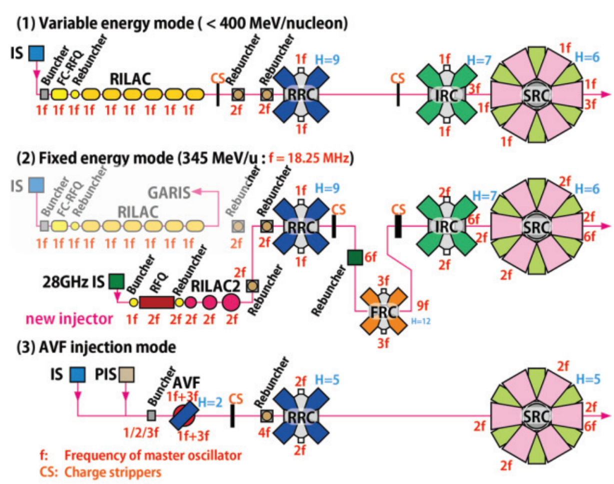

Figure 2: Acceleration modes available at the RIBF.

Ring Cyclotrons Used in the RIBF

Specifications of the four ring cyclotrons are summarized in Table 1. The SRC is the world's first superconducting (SC) ring cyclotron. The others are conventional four-sector cyclotrons. One flat-topping RF resonator is installed in each cyclotron except for the RRC to reduce the energy spread of the beam. The RRC still plays an essential role in the RIBF accelerator complex because of its large velocity gain and the greatly reduced relative energy spread of the beam during acceleration. The fRC was upgraded in 2012; its present K-number is 700 MeV. The isochronous magnetic fields of the SRC are generated by superposition of main and two types of trim coils. The main coil and the four sets of

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SC trim coils generate an approximate isochronous magnetic field with 0.2% precision, and the 22 sets of normal conducting (NC) trim coils improve precision to within 0.01%.

Table 1 Specification of the ring cyclotrons. Total acceleration voltage (V_{acc}) and typical turn separation (δR) are for uranium ions at extraction in fixed-energy mode.

	RRC	fRC	IRC	SRC
K (MeV)	540	700	980	2600
R_{inj} (cm)	89	156	278	356
R_{ext} (cm)	356	330	415	536
Weight (t)	2400	1300	2900	8300
Sectors	4	4	4	6
Trim coil number / main coil	26	10	20	4 (SC) 22 (NC)
Current (A)	600	200	600	3000 (SC) 1200 (NC)
RF system number	2	2, FT	2, FT	4, FT
Frequency (MHz)	18 - 40	54.75	18 -38	18 - 38
V_{acc} (MV)	0.28	0.8	1.1	2.0
δR (mm)	1.3	1.3	1.8	0.7

RECENT DEVELOPEMENTS

The beam intensity goal for the RIBF is 1 pμA. This goal has been achieved for light ions, such as helium and oxygen [11]. The intensity of a 345-MeV/nucleon ^{48}Ca beam reached 415 pnA in 2012. However, the uranium beam intensity was less than 1 pnA in December 2009. The primary reason for this was the low beam intensity produced by the RILAC. The RILAC was the injector for fixed-energy mode until 2009. The ion source used in the RILAC, the 18-GHz electron cyclotron resonance ion source (ECRIS) [12], was not suitable for producing highly charged (35+) uranium ions. The SC-ECRIS [13,14] and the new injector RILAC2 have been introduced to remedy this. The SC-ECRIS is designed to flexibly produce magnetic field configurations with a large ECR zone and an optimized field gradient at the ECR point; it also has a high magnetic field and high RF frequency (28 GHz), which are essential to enhancing the density and confinement time of the plasma. Dedicated to fixed-energy mode, the RILAC2 is designed to accelerate a high-intensity uranium beam up to 0.68 MeV/nucleon. It consists of an RF quadrupole linac, three drift tube linacs and three bunchers and so on. The commissioning of the RILAC2 began in 2010 and finished in 2011. It has begun stable operation [6,15].

The intensity upgrade expected for the new injector requires upgrading of the charge-state stripper used in fixed-energy mode. The serviceable of the 0.3-mg/cm^2-thick carbon foil used as the first-stage charge-state stripper was only ~12 h at 0.5 μA, which is only 1% of the requirement for the new injector. As a result of two studies [16, 17], the carbon foil stripper has been replaced with a newly developed helium gas stripper [18] that has a unique helium recirculation system. A new beam dump designed to withstand a 10-kW beam loss has been also installed in the first-stage charge-state stripping section. A rotating beryllium disk stripper has been also introduced as the second-stage charge-state stripper for uranium [19]. A high-density air stripper has been developed as the second-stage stripper for xenon [20]. These strippers have been successfully operated.

Bending-power Upgrade of fRC

The fRC is the next accelerator in sequence after first-stage charge-state stripping in fixed-energy mode. The fRC was originally designed to accelerate $^{238}U^{73+}$ ions using a 0.6-mg/cm^2-thick carbon foil at 10.8 MeV/nucleon. Beam commissioning of the fRC started in 2006, and we immediately recognized that insufficiently uniform thickness of the carbon foil produced a momentum spread outside the tolerance for the fRC. Hence, we reduced the carbon foil thickness to 0.3 mg/cm^2 and modified the injection radius of the fRC. The most probable charge state is 71+ and the operating magnetic field of the fRC is 1.69 T in this case. This modification resulted in satisfactory transmission efficiency of the uranium beam: >90%.

Table 2: Specifications of the upgraded and newly introduced devices. Values in parentheses indicate the original specifications.

	BM	MIC2	ST
Curvature radius (cm)	91	72	9 cm (pole length)
Bending angle (deg.)	100.35	80	
Pole gap / aperture (mm)	40	25 (28)	40
Hollow conductor (mm)	□9ϕ6	□8.5ϕ5 (□7ϕ4)	□7ϕ4
Number of coil windings	84 (72)	4	60
Number of cooling water channel	14 (12)	2 (1)	6
Maximum magnetic field (T)	1.95 (1.8)	0.6 (0.5)	1.1

The helium gas stripper expects that the equilibrium charge mean is 65+ [17]. The required magnetic field exceeds the capacity of the original design: the maximum rise in the cooling water temperature was 10 degrees for the main coils of the sector magnets, and the tolerance was sufficient for increasing the magnetic field up to the 1.85 T required for 65+ ions.

Design studies performed from May to early July 2011 identified the devices to be upgraded. The existing power supply system for exciting the fRC sector magnets consists of one main power supply and four currentbypassing power supplies to compensate for small differences between the four sector magnets. The maximum current of the system is 650 A, corresponding to $^{238}U^{69+}$ ions. Hence, capacity should be upgraded to the 830 A expected for $^{238}U^{65+}$. The current setting precision of the new main power supply was designed to be 1 mA, taking into account the low-magnetic-field operation during xenon acceleration.

In addition, the injection bending magnet (BM), the magnetic inflection channel 2 and its power supply, and the extraction BM (EBM) required upgrading because their maximum magnetic fields were insufficient. The specifications of the upgraded devices are summarized in Table 2. All these devices were newly built except for the EBM, for which replacement of its iron cores was sufficient to generate the required magnetic field. A drawback of the new iron cores is that magnetic field uniformity is worse than it was with the old cores, though the uniformity remains within the permissible range. Finally, two new beam steering magnets were introduced in the beam injection line to compensate for the much stronger stray magnetic fields expected for $^{238}U^{65+}$ in comparison with $^{238}U^{71+}$. The orbit correction made by the steering magnets is shown in Fig. 3.

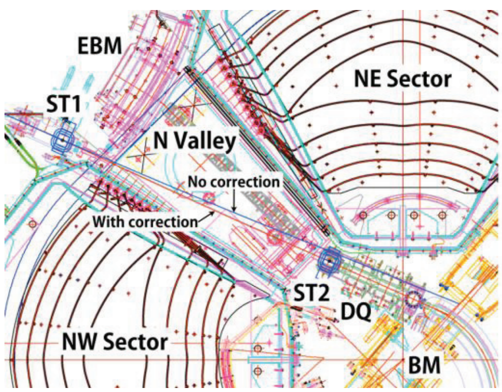

Figure 3: Injection orbits with and without correction.

The manufacture of these devices was completed in March 2012. The installation work and magnetic field measurements were performed during the first three months of FY2012 coinciding with tightly scheduled beam services for users. We measured magnetic fields for various excitation currents along the centerline of each sector magnet. It is challenging to skip the two-dimensional magnetic field mapping for large-scale ring cyclotrons such as the fRC, but we gained experience doing this during commissioning of the fRC. An acceleration test of $^{238}U^{65+}$ ions was performed in July 2012 and completed in one night. We successfully extracted a $^{238}U^{65+}$ beam from the upgraded fRC with transmission efficiency of 80%.

The newly developed helium gas stripper had stripping efficiency that was higher for $^{238}U^{64+}$ (27%) than for $^{238}U^{65+}$ (21%) with a 0.7-mg/cm^2-thick helium gas, owing to the atomic shell effect of the uranium ion [21]. The used thickness is thinner than that required for charge-state equilibrium. Thus 64+ ions were accelerated on 28 October by exploiting the design margin of the new power supply system for the fRC sector magnets. The isochronous magnetic fields obtained for the 64+ and 65+ uranium ions are shown in Fig. 4. Other quantities, such as transmission efficiency and acceleration turn pattern, exhibited no performance decline after the upgrade of the fRC.

The beam transport system from the RRC and the fRC was also upgraded to alleviate difficulty in beam tuning caused by an insufficient number of quadrupole magnets.

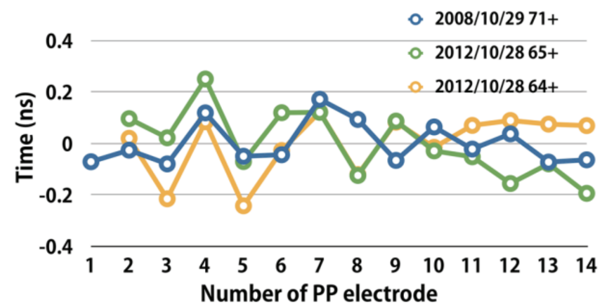

Figure 4: Isochronous magnetic fields of the fRC.

PRESENT PERFORMANCE OF RIBF

Isochronous Magnetic Fields

At the RIBF, the time difference signals of the beam passing through the phase-pickup (PP) electrodes are analyzed by using lock-in amplifiers [22]. They are used to generate precise isochronous magnetic fields. The isochronous magnetic fields recently obtained for the uranium beam are shown in Fig. 5. A time difference of 0.1 ns corresponds to 2 RF degrees for the fRC and 1.3 RF degrees for the IRC and SRC. The phase excursion of the beam during acceleration is sufficiently small, and no problems due to poor isochronous magnetic fields have been observed.

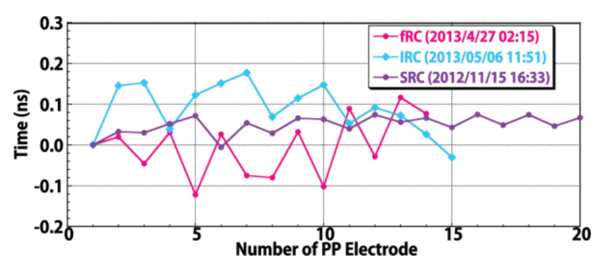

Figure 5: Isochronous magnetic fields obtained for 345-MeV/nucleon uranium beams.

Beam Intensity

The improvement of beam intensity is illustrated in Fig. 6. The uranium beam intensity was greatly improved by introducing the RILAC2. Beam intensity of 0.4 pnA was obtained in 2008 by using the RILAC and the 18-GHz ECRIS. In 2009 the SC-ECRIS was tested at the RILAC site with an 18-GHz klystron used for RF power. Next, the SC-ECRIS was installed at the front end of the RILAC2 and a 28-GHz gyrotron was introduced. The 28-

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GHz SC-ECRIS successfully produced 28-μA and 90-μA beams in 2011 and 2012, respectively. During the latter operation, a 15-pnA beam was extracted from the SRC. The beam intensity improvement from 2008 to 2012 corresponds to the beam intensity improvement of the ion source. The xenon beam intensity has also increased steadily, up to 38 pnA in June 2013.

The maximum beam intensities for 345 MeV/nucleon ^{48}Ca and ^{70}Zn are now 415 pnA and 100 pnA, respectively. For medium-heavy ions, the main limitation on beam intensity is the performance of the ion source. The 18-GHz ECRIS in use can produce a higher intensity ^{48}Ca beam than is obtained in routine operation, but the stability and consumption rate of a ^{48}Ca sample need improvement. To this end, a micro-oven system is being developed [23]. This system has already doubled the ^{48}Ca beam intensity and improved stability.

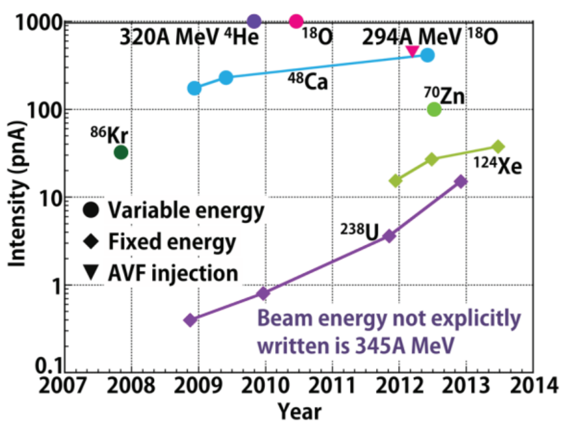

Figure 6: Beam intensity record of the RIBF.

Beam Availability

Beam availability, defined as the ratio of actual beam service time to scheduled beam service time, is summarized in Table 3 for January 2011 to August 2013. A considerable portion of the downtime recorded during 2011 was due to hardware trouble and immaturity of the upgraded system, especially in terms of stability. Time required for the exchange of carbon nanotube (CNT)-based foils mounted on the rotating cylinder [24] also contributed to the downtime. These innovative carbon foils were used in a long uranium experiment. The CNT-based foils exhibited a serviceable time 100-fold that of the fixed carbon foils previously used, but they required 8 h of beam irradiation for conditioning and a half day of parameter optimization of the accelerator complex because of fluctuations in foil thickness. Hence, expected availability was at most 80%. Upgrades of the charge-state strippers—the helium gas stripper, the rotating beryllium disk stripper and the high-density air stripper—have greatly improved availability. In addition, a main coil of the RRC was replaced in 2012 because damage to insulation between different turns of the coil made the magnetic field slightly unstable [25]. The coil replacement contributed to improving availability.

Table 3: Yearly Statistics of Beam Availability

Year	Beam service time (h)	Availability (%)
2011	1248	60.6
2012	2873	85.9
2013	1380	90.8

Transmission Efficiency

Transmission efficiencies recorded during recent operation are summarized in Fig. 7, where the data exhibiting the best performance of the cyclotron cascade are chosen for each ion species. The transmission efficiencies in variable-energy mode are within a permissible range because beam loss in the cyclotrons does not limit beam intensity. However, the best performance of the cascaded cyclotrons used in fixed-energy mode is 56%; here, beam loss at the RRC extraction actually limits beam intensity. The cause of the sizable beam losses at the RRC extraction is now under investigation. The observed low transmission efficiencies at the SRC come in part from large energy spreads produced by the thick charge-state strippers (17 mg/cm^2 for uranium and 20 mg/cm^2 for xenon) and in part from the difficulty of injecting a beam into the SRC due to its large horizontal emittance. Beam loss at the SRC extraction is non-negligible, but it is not presently a limiting factor on beam intensity.

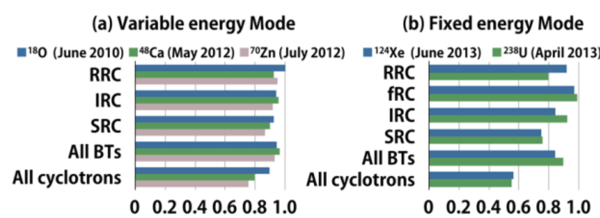

Figure 7: Transmission efficiency of the RIBF cyclotron cascade. BT means the beam transport line.

Stability

The path length of a uranium ion is 20 km in the RIBF accelerator complex and 98% of the length is covered by isochronous cyclotrons. Hence, stability of the isochronous magnetic fields and RF resonators used in the cyclotrons is essential. The stability requirement is basically fulfilled for the RF resonators. Phase and voltage stability have been improved and observed values are better than ±0.1 degree in phase and ±0.1% in voltage fluctuation, respectively [26], though improving stability of some frequency multipliers is desirable. The long-term drifts of the currents exciting the sector magnets are suppressed to a few ppm per 8 h, except for the RRC. However, the temperature stability of the sector magnets is insufficient, especially for the RRC, because of its obsolete water-cooling control system.

The beam transport system of the RIBF violates isochronism. It requires very high stability of all components. For example, the distance between the fRC and the IRC is 140 m and the ion velocity is 9 cm/ns; hence, the ion flight time is 1500 ns. A velocity fluctuation of 0.01% causes a 0.15-ns time shift, corresponding to 2 RF degrees at the IRC. This shift of the beam phase results in measurable beam loss at the SRC extraction and necessitates beam tuning.

Many instability-inducing factors have been identified from our operation experience. Some of them have been already fixed, but it is presently impossible to eliminate all sources of instability. A pragmatic solution adopted for the RIBF is introducing an integrated system that simultaneously monitors beam phases at various points in the accelerator complex and the status of relevant components [22]. By using the monitoring system, the beam intensity is maintained by the accelerator operators. An example is shown in Fig. 8 where the strength of the beam bunch signal measured by the PP electrode installed downstream of the SRC is plotted. When the beam bunch shape does not change, the signal is proportional to the intensity. For 14 days of operation, the beam intensity was maintained with a fluctuation of approximately 20%. This is tolerable for the present beam power (1–4 kW) but it should be improved as operation progresses toward 10-kW beams in the near future.

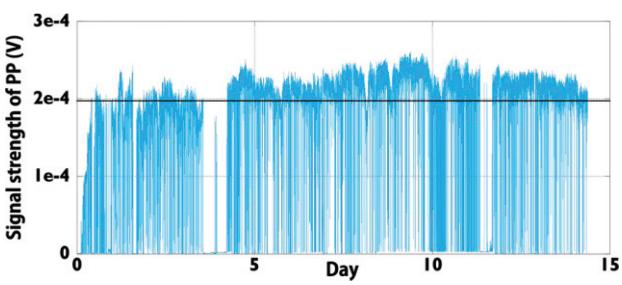

Figure 8: Stability of the beam bunch signal after the SRC for the 345 MeV/nucleon ^{124}Xe beam recorded from 17 June to 1 July 2013.

Resonance-crossing Acceleration in SRC

The vertical tune of the SRC covers a wide range from 0.4 to 1.0 (Fig. 9). In addition to the usual dependence of energy on the vertical tune, a strong stray magnetic field from the SC sector magnet to the valley region modifies the azimuthal distribution of the magnetic field. In other words, the stray magnetic field changes the flutter and forces us to use the resonance-crossing operation to accelerate light ions up to 400 MeV/nucleon, because the SRC design is optimized for uranium ions. Higher intensity RI beams are expected to be produced by higher energy heavy-ion beams, so the beam energy obtained in the variable-energy mode should be increased. Hence, an acceleration test of a 400-MeV/nucleon ^{40}Ar beam was performed in June 2013. We successfully extracted a 400 MeV/nucleon beam from the SRC and confirmed that harmonic fields exciting the ν_r = 3/2 and ν_z = 1/2 resonances were as small as expected from the SRC design.

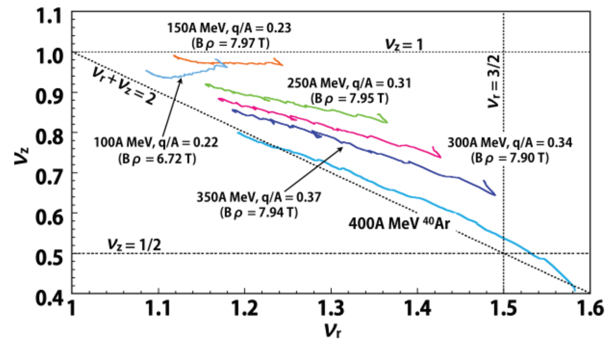

Figure 9: Tune diagram of the SRC. The difference in tune behavior in the extraction region between ^{40}Ar and the others comes from the different optimization procedures used to generate isochronous magnetic fields. Back bending can be removed by changing the combination of excitation currents of the SC and NC trim coils.

TOWARD FURTHER PERFORMANCE UPGRADES

The RIBF has been established as the facility for producing the world's most intense RI beams. Beam availability has been improved by introducing the new injector RILAC2 and upgrading the charge-state stripping system used in fixed-energy mode. However, several areas still need improvement. The most important point is to increase the beam intensity of xenon and uranium ions. For these ions, only half of the beam produced by the 28-GHz SC-ECRIS can be accepted by the RRC. The other half is removed by movable slits in order to avoid beam loss, which would cause damage to the extraction apparatus of the RRC. The typical beam intensity at the RRC extraction is now 1 pμA (2.6 kW) for uranium. Nevertheless, the transmission efficiency of the cascaded cyclotrons is less than 60%. Among the possible causes of beam loss at the RRC extraction are temperature fluctuation of the water-cooling system used for the RRC and insufficient optimization of the operational parameters of the RILAC2 and the RRC under a sizable space-charge effect. The low transmission efficiency after the RRC comes from emittance growth in the horizontal and longitudinal directions. Some growth is inevitable due to the thick charge-state strippers used in fixed-energy mode. Data analysis for three recent high-intensity operations is in progress, but a quantitative and consistent understanding of the observed transmission efficiency is not yet achieved. We plan to conduct further investigation of the data and machine studies.

Further improving the stability of the system is important. Some of the aging components, such as the two RF amplifiers of the RILAC and the power supply system for exciting the RRC's sector magnets, will be replaced during FY2013. This will improve stability. However, replacement of some old infrastructure such as the water-cooling system of the RRC has not yet been

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scheduled even though the performance of these components does not meet the recent requirements of the RIBF cascaded cyclotrons and beam intensity fluctuations due to temperature variation of air and cooling water have been clearly observed. Instability caused by temperature variation will be addressed by modification of the existing infrastructure, improved sophistication of the integrated monitoring system and more cautious operation in the near future.

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