OPERATIONAL EXPERIENCE AND UPGRADE PLANS OF THE RIBF ACCELERATOR COMPLEX

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Abstract

The Radioactive Isotope Beam Factory (RIBF) is a cyclotron-based accelerator facility for nuclear science, completed at the end of 2006. RIBF can produce the most intense RI beams using fragmentation or fission of high speed heavy ion beams. Continuous efforts since the first beam have increased the beam intensity and achieved stable operation. 49.8 pnA (3×10^{11} /s) of uranium ion beam was extracted from the final accelerator SRC with energy of 345 MeV/u in 2016, which is currently the world record. For further expansion of the scientific opportunity, an upgrade program has been proposed to increase the intensity of uranium ion beam by a factor greater than twenty. The program includes two components. The first component is increasing space charge limit of the beam intensity in the low-energy ring cyclotron (RRC) by replacing the existing resonators with newer ones to achieve higher accelerating voltage. The second component is skipping the first stripper, which requires an increase in the magnetic rigidity of the ring cyclotron just after the first stripper (FRC). The new ring cyclotron will consist of six-sector magnets with four rf-resonators to maintain approximately 15 mm of turn separation, which is similar to that in the present FRC, the K-value of which is 2200 MeV. A conceptual design of the new cyclotron is ongoing. Certain issues to realize the intensity upgrade are also under discussion.

INTRODUCTION TO RI BEAM FACTORY

The Radioactive Ion Beam Factory (RIBF) is a cyclotron-based accelerator facility that uses fragmentation or fission of heavy ion beams to produce intense RI beams over the whole atomic range [1]. The purposes of the RIBF are to explore the inaccessible region of nuclear chart, to discover the properties of nuclei far from stability, and to advance knowledge in nuclear physics, nuclear astrophysics, and applications of rare isotopes for society. The RIBF facility consists of four cyclotron rings (RRC [2], FRC [3], IRC [4], and SRC [5]) with three injectors, including two linacs (RILAC [6, 7] and RILAC2 [8]) and one AVF cyclotron (AVF) [9]. Cascades of the cyclotrons can provide heavy ion beams from H_2^+ to uranium ion at more than 70% of the speed of light to efficiently produce RI beams. Three acceleration modes are available, as shown in Fig. 1. The first mode is used mainly for mid-heavy ions, such as Ca, Ar, and Zn. The second mode is used for light ions, such as O and N. The third mode is used for very heavy ions such, as Xe and U. Table 1 lists the specifications of the four ring cyclotron of RIBF. RRC has been operating since 1986. FRC and IRC have similar structures to that of RRC. The K-value per weight is listed in the table, which clearly shows that FRC is a very compact machine compared to the other cyclotrons. We can see that SRC is the most challenging machine to obtain an acceleration voltage of 640 MV for uranium acceleration up to energy of 345 MeV/u. The design and construction of the RIBF accelerators started from 1997 and we obtained the first beam at the end of 2006.

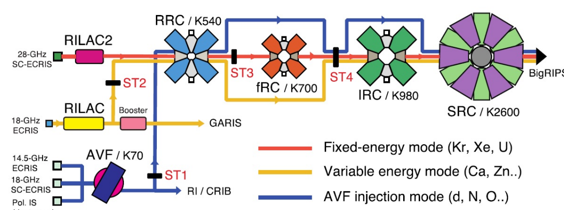

Figure 1: Acceleration modes for RIBF facility.

OPERATION FOR TEN YEARS

Operations for about ten years since the first beam have been very successful. Our continuous efforts have increased beam intensity, especially of very heavy ions, such as Xe and U, as shown in Fig. 2. The maximum beam intensity of uranium ion is 50 pnA, which is the world record. The beam availability has been significantly improved, exceeding 90% since 2014.

A 28 GHz ECR ion source using superconducting solenoids and sextuple magnets was constructed because powerful ion sources are essentially required to increase the uranium beam intensity [10, 11]. The operation of this ion source on the beam line started from 2011 with the new injector linac (RILAC2). Currently, approximately 150 eμA of U^{35+} can be stably extracted with uranium metal sputtering. A high-temperature oven for uranium ions is also under development.

Charge strippers are important devices to increase the intensity of uranium beam because they have a high risk of bottleneck problems owing to fragility against high-power

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ISBN 978-3-95450-167-0

Table 1: Specification of the RIBF Cyclotrons

	RRC	fRC	IRC	SRC
K-value (MeV)	540	700	980	2600
R_{inj} (cm)	89	156	277	356
R_{ext} (cm)	356	330	415	536
Weight (ton)	2400	1300	2900	8300
K/W	0.23	0.54	0.34	0.31
N_{sec}	4	4	4	6
rf Resonator	2	2+FT	2+F	4+FT
Frequency range (MHz)	18–38	54.75	18–38	18–38
Total Acc. Volt. (MV)	2	2+FT	2+F	640
Acc. Volt. (MV/turn)*	0.28	0.8	1.1	2.0
Δr (cm)*	0.7	1.3	1.3	1.8
I_{sc} (pμA)*	0.7	4.7	6.6	5.1

* in the table indicates that the values are shown for the case of uranium acceleration up to 345 MeV/u.

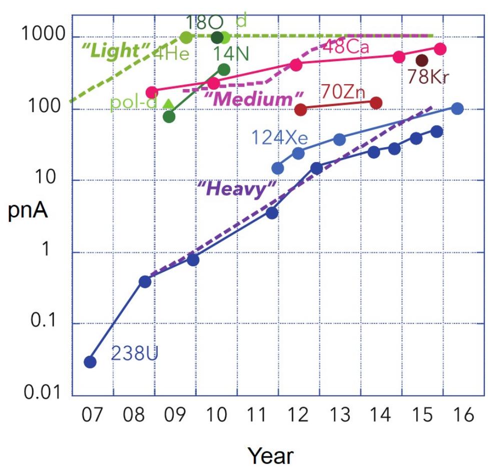

Figure 2: History of the beam intensities at the RIBF accelerator.

beams. After much research and development [12, 13], we developed a helium gas stripper [14] for the first stripper and a rotating disk stripper with a highly-oriented graphene disk for the second stripper [15]. These have been working well so far.

Here we summarize the lessons learned from the first ten years of operation. Firstly, it is a very tough business to operate an accelerator complex where four cyclotrons are connected in series, because we have to inject and extract the accelerated beams four times. Energy matching between the cyclotrons and single turn extraction requires the greatest care and effort. Secondly, multi-step charge stripping should be avoided, because charge stripping decreases beam intensity at every step owing to charge state dispersion. Furthermore, the thickness of the charge strippers at each stage should be as thin as possible because the charge strippers are always sources of emittance growth. Thirdly, the space charge effect in the low-energy cyclotron, RRC, is very severe because of low velocity and low rf voltage. Figure 3 shows the structure of the rf resonator of RRC. This resonator is frequency-tunable by the movable box from 18 to 40 MHz. Because the movable box is very close to the Dee electrode in the case of low frequencies such as 18.25 MHz, high voltage cannot be applied because of discharge between the movable box and the Dee electrode. Of course, we can get higher voltage at the frequency of 36.5 MHz (H = 18); the effective voltage for the beam is zero because the distance between the double gaps is optimized for harmonics of nine. Table 1 lists the space charge limit for the four cyclotrons in the case of uranium beam acceleration according to Baartman's paper [16]. It clearly shows that space charge limit for RRC is small compared to the required current to reach 1 pμA at the exit of SRC. The final point is that approximately 20% of the current from the ion source can reach the exit of SRC, excluding charge stripping efficiency, as shown in Fig. 4. This value is not particularly high but not so small compared to that of other accelerators. In fact, 10 mA from ion source is extracted to obtain 3 mA from the ring cyclotron in the case of the PSI machine. However, it is very important to understand the mechanisms of beam loss to improve and reduce uncontrolled beam loss.

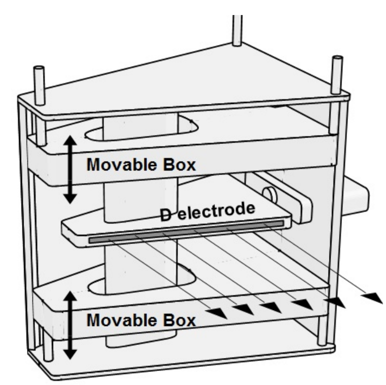

Figure 3: Structure of an rf resonator for RRC.

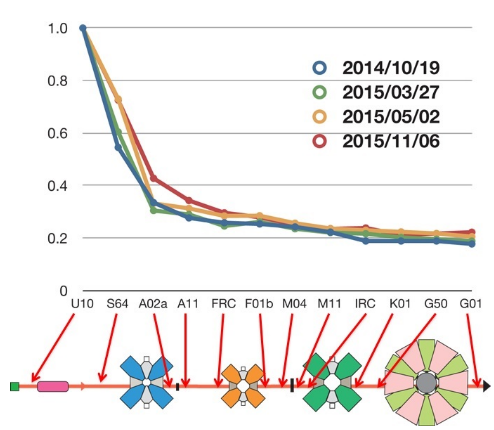

Figure 4: Transmission in the RIBF accelerator complex.

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UPGRADE PLAN

We have just started an upgrade program of the RIBF accelerator complex, mainly to increase uranium ion beam intensity. The goal intensity is approximately 1 pμA of uranium based on the potential of the accelerator complex. The program mainly consists of two components as shown in Fig. 5. Firstly, the first stripper is skipped to avoid the reduction of beam intensity due to the dispersion of the charge state after the stripper. This requires replacement of the existing fRC with a new one that can accept the same charge state, 35+, as that of the ion source. The skipping of the first stripper will improve the beam quality, especially in the longitudinal direction, because charge-exchange energy straggling in the first stripper is significant. This affects the improvement of extraction efficiency at the succeeding cyclotrons. The second component is to resolve the problems with respect to the space charge effect in the low-energy cyclotron, RRC. Our original baseline is the replacement of the RRC with the superconducting linac, as shown in Fig. 5, to eliminate these problems. The current baseline focuses on cost effectiveness. RRC is not abandoned but its resonators are remodeled to increase the space charge limit in the ring cyclotron,

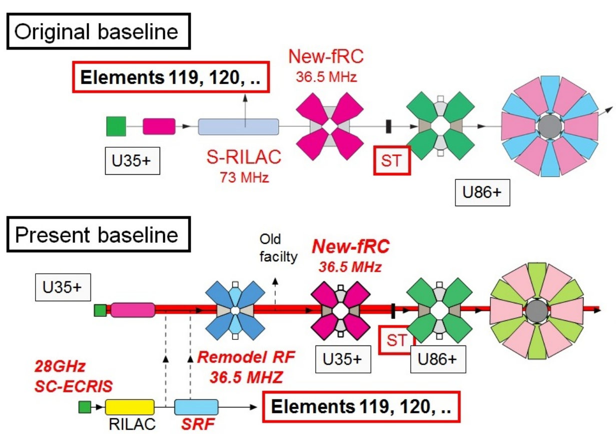

Figure 5: The original and present upgrade plans for the RIBF accelerator complex.

Remodel of RRC Rf Cavities

As mentioned in the previous section, operation of RRC at a frequency of 18.25 MHz limits the Dee voltage, which is approximately one third of that with frequency of 36.5 MHz, owing to its structure. This cavity has double gaps and the distance between the two gaps corresponds to $\beta\lambda/2$ in the case of harmonics of 9 which, which means that effective voltage is zero in the case of harmonics 18, although high voltage can be achieved with 36.5 MHz. The Dee angle was studied to optimize for the harmonics numbers of 18, 9, and 5, which are mainly used for the operation. The study shows that angles between 7.25° and 8.25° can enable sufficiently high voltage in the three studied cases. However, we should take care that operation with such large harmonics number as 18 requires high accuracy of the isochronous field because phase acceptance in the case of harmonics of 18 becomes half of that for harmonics of 9. The power supplies for the trim coils and diagnostics of the isochronous field should be also upgraded for the realization of isochronous field with high accuracy.

Conceptual Design of the New FRC

In Cyclotrons2013, a design of a superconducting ring cyclotron with four sectors and two cavities, the maximum voltage of which is around 500 kV, was presented [17]. We cannot find any problems in this design, but the turn separations are not large enough to extract the uranium beam at more than 1 pμA, which is required to achieve the goal intensity at the exit of SRC. To obtain sufficiently large turn separation, we have just started designing a cyclotron with six-sector normal conducting magnets so as to install four cavities. A preliminary design will be presented in the rest of this subsection.

Figure 6 shows a plan view of the new FRC, with the main specifications listed in Table 2. The number of sector magnets is six and the K-value is 2200. Four accelerating rf cavities and a flattop cavity are used. The acceleration rf frequency is 36.5 MHz, which is the same as that of RILAC2, to achieve wide acceptance in the longitudinal direction. The structure of the rf resonators will be similar to that used in the RIBF accelerator. We can get 15 mm of turn separation using similar rf cavities to those used in the RIBF accelerators. Betatron frequencies were calculated based on the magnetic field simulated by TOSCA [18], as shown in Fig. 7. They indicate that this design can avoid the integral resonance $\nu_z = 1$, which constitutes the most serious imperfection resonance. In the further detailed design process, however, we should take care because ν_z may easily get close to 1 as the sector angle decreases, owing to space problems.

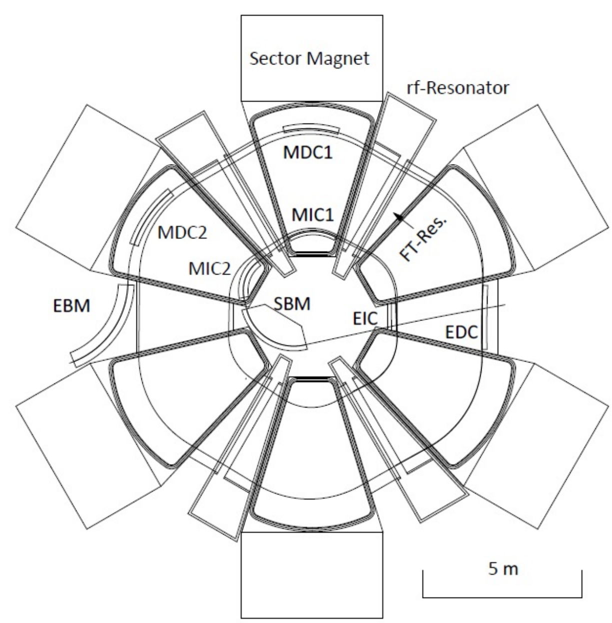

Figure 6: Plan view of new FRC.

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Table 2: Specification of the New FRC

Item	new FRC	exiting FRC
K-value (MeV)	2200	700
Sectors	6	4
rf-Cavities	4+FT	2+T
rf-Frequency (MHz)	36.5	54.75
Injection radius (m)	2.76	1.56
Extraction radius (m)	5.67	3.30
Velocity gain	2.1	2.1
Diameter (m)	19	10.8
Height (m)	6.6	3.34
Weight (ton)	8109 (7563)	1320
Δr (cm)*	1.5	1.3

The number in parentheses of the weight row is the weight estimated by cutting the edge of the yoke, where magnetic field in the iron is low.

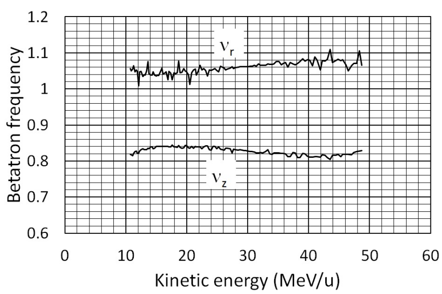

Figure 7: Betatron frequencies in the new FRC as functions of kinetic energy of U^{35+}.

A list of parameters and an illustration of the quarter-cut model of the sector magnet are given in Table 3 and Fig. 8, respectively. The sector magnets use normal-conducting main coils and trim coils, and the weight of the yokes of one sector is approximately 1350 t. The sector angle is 34°. The maximum magnetic field in the beam orbit region is 2.1 T. The excitation curve shown in Fig. 9 shows that the iron pole is almost saturated at the operation point of 180 kAT. The main coil consists of one pair of 60 turns using a conductor, the size of which measures 16×16 mm^2 with a hollow of 9 mm in diameter. The maximum current is approximately 1500 A, requiring a power consumption of 2.42 MW. Isochronous magnetic fields can be generated by optimizing the pole shape with small corrections of the trim coil current, because not only beam energy but also charge-to-mass ratio can be fixed in this cyclotron by selecting the charge from the ion source when other ions than uranium are accelerated.

The injection and extraction orbits for the new FRC are shown in Fig. 6. For beam injection, magnetic channels (SBM, MIC2, and MIC1) and an electrostatic channel (EIC) are used. For beam extraction, an electrostatic channel (EDC), two normal magnetic channels (MDC1, MDC2, and MDC3), and an extraction bending magnet (EBM) are used. Table 4 lists the parameters of these devices for injection and extraction of U^{35+} beams. Similar elements to those for the SRC can be used [5].

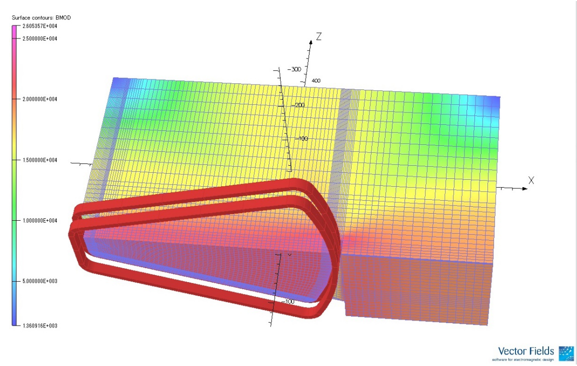

Figure 8: Quarter-cut model of the sector magnet for the new FRC.

Table 3: Specification of the New FRC Sector Magnet

Item	Value
Maximum field	2.1 T
Pole gap	50 mm
Magnetic motif forces	180 kAT
Sector angle	34°
Operational current	1450 A
Power consumption	2.4 MW/total

SOME ISSUES FOR INTENSITY UPGRADE

This section will present a discussion of three issues that should be solved to realize this upgrade program of the RIBF accelerator complex.

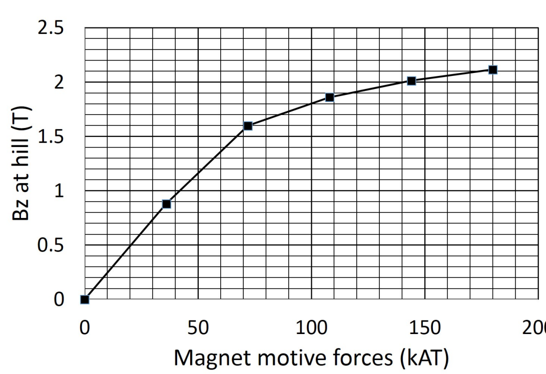

Figure 9: Excitation curve of the sector magnet for the new FRC.

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Table 4: Specifications of Injection and Extraction Elements for the New FRC

	Length (m)	Magnetic/Electric field (T)/(kV/cm)
SBM	2.43	2.1
MIC2	1.28	0.7
MIC1	1.53	0.22
EIC	0.86	90
EDC	2.02	90
MIC1	1.74	0.15
MIC2	2.05	0.25
EBM	3.13	2.5

How to Make the New FRC Smaller

As mentioned in the previous section, the upgrade program does not include a new building for the new FRC. It is supposed to be installed in a room for the secondary beam line RIPS of the existing facility. This requires that the new FRC should be as small as possible.

Increasing the charge state of the accelerated ions will help the down-sizing. We hope to achieve U^{42+} with more than 300 eμA. Some experts of the ECR ion source have already proposed the fourth generation ECR ion source, which is expected to generate such highly charged ions as more than 42+ with high current. On the other hand, they pointed out that much research and development is necessary for the realization of this goal. We hope that the proof-of-principle machine of the fourth generation will appear as soon as possible, because it will save the cost of the new building for the new FRC.

Another way to make the new FRC smaller is by recycling the existing FRC, which is to be replaced with the new FRC. Figure 10 shows an accelerator scheme in which the FRC is reused as the first cyclotron. RILAC will be upgraded for the SHE experiment, by installing SRF linacs. 3.4 MeV/u of U^{35+} from the RILAC can be injected to the reused fRC for acceleration up to 13.58 MeV/u with harmonics of 14. This means that the injection radius for the new fRC can be increased from 2.75 m to 3.14 m. The area of the pole face and the volume of the return yoke can be reduced.

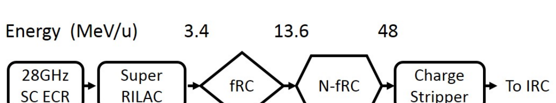

Figure 10: Acceleration scheme reusing the existing fRC.

Usage of Superconducting Wire for the Main Coil

The main coil blocks described in the previous section are made of normal conducting wires. The total power consumption exceeds 2 MW, which sufficiently high that we are studying the option of making the main coil of superconducting wires to save power. The excitation curve in Fig. 9 shows that the contribution of the iron to the magnetic field is large and the required magnet motive force is not large. This is a so-called superferric magnet.

Figure 11 shows a cross-sectional view of the main coil block in the case when a rectangular Al-stabilized superconductor is used. NbTi/Cu monolith round wires with diameter 1.6 mm are embedded in a rectangular pure Al stabilizer, the size of which is 2.9×3.6 mm^2. The ratio of Al, Cu, and NbTi in the wire is 10:2:1. The size of a section is 31×68 mm^2 and its perimeter of the main coils is 14.1 m. The operational current is set to 1000 A, which is less than 10% of the critical current at the maximum magnetic field in the main coil, 1.4 T. The coils are epoxy-impregnated with coil supports and are indirectly cooled by two-phase He flowing through a tube attached to the coil supports.

The electromagnetic forces on the coil in the radial and vertical directions are calculated to be 1.2 ton and 1.4 ton at the operational point. The expansion force on the long straight section is 0.74 ton/m. These are basic data for the design of the support structure of the coil. The solution for the support structures are easily found because they are very small. The rectangle with dotted lines indicates the coil blocks of the normal-conducting wire. It clearly shows that the necessary size for the superconducting coils does not exceed the area of the normal-conducting coil blocks.

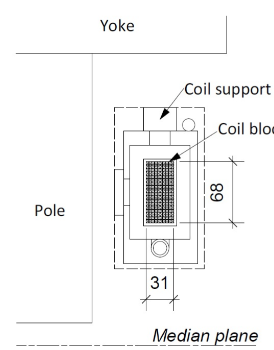

Figure 11: Structure of the main coil block using superconducting wires

Improvement of the Transmission Efficiency

As mentioned in the previous section, approximately 20% of beam from the ECR ion source can survive until the exit of the SRC. Most of the beam loss occurs at low energy until the entrance of fRC. One of the possible reasons for the beam loss comes from the beam buncher located before the RFQ entrance, where DC beam from the ion source is modified to CW beam. Figure 12 shows beam emittance in the longitudinal direction at the entrance and the exit of the RFQ in the RILAC2. Energy modulation generated by the buncher is tuned so as to focus the beam at the entrance of RFQ. The accelerated beams at the RFQ show a characteristic vortex shape, which causes the beam to have a tail. This tail causes beam loss in the succeeding linac and cyclotrons. The scale of the tail is determined by the energy

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modulation of $d\beta/\beta$. Figure 13 shows the dependence of the beam emittance in the longitudinal emittance on the initial velocity modulation. In fact, the emittance grows as the velocity modulation increases, suggesting that mono-energetic beam bunch is important for acceleration without the tail. These simulations were carried out with a zero current limit. Furthermore, space charge force distorts the beam bunch. In any case, we require a more sophisticated bunching system with phase collimation. One idea is a bunching system which consists of two bunchers and in the ring with phase collimations, as shown in Fig. 14. Negative length beam transport helps decrease the energy spread.

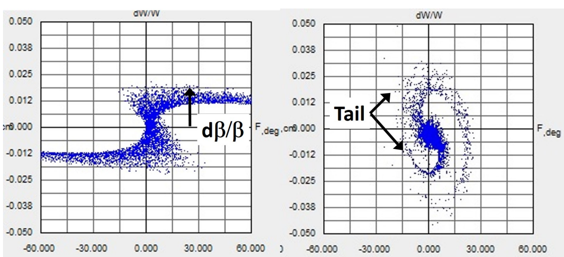

Figure 12: Typical bunch shapes in the longitudinal direction at the entrance and exit of the RFQ.

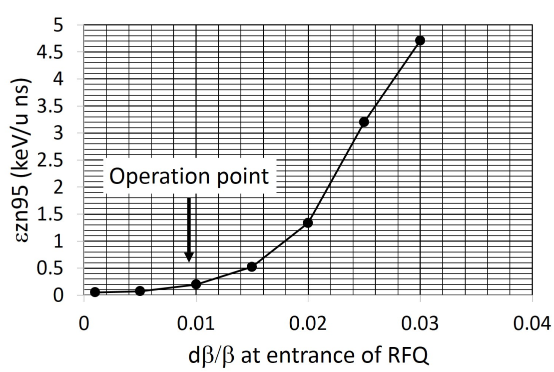

Figure 13: $d\beta/\beta$ dependence of longitudinal emittance after the RFQ.

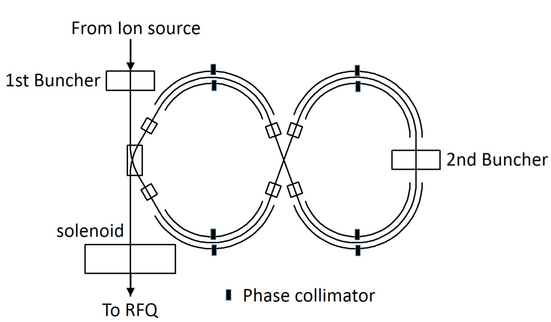

Figure 14: Low-energy ring with two bunchers.

SUMMARY AND OUTLOOK

We have just started an upgrade program to increase beam intensity, mainly of uranium ion beam, based on the successful operational experience of ten years since the first beam at the end of 2006. The program includes two components. Firstly, space charge limit in the low-energy cyclotron of RRC is increased by remodeling the rf resonators. Secondly, the existing fRC is replaced with a new one to skip the first charge stripper. Although we have to address certain issues for the realization of this program, we hope to obtain the first beam from the new, upgraded acceleration complex in 2025.

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