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THE PRESENT STATUS AND FUTURE PLAN WITH CHARGE STRIPPER RING AT RIKEN RIBF

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Abstract

RIKEN RI Beam Factory (RIBF), providing the world's most intense heavy-ion beams more than 345 MeV/u, is a leading facility for generating in-flight RI beams. The RIBF has been steadily developing its performance. In particular, the beam intensity of uranium beams, which is important to produce in-flight fission RI beams, was drastically increased by a factor of 240 compared to 2008.

For further intensity upgrade of the uranium beams, a new acceleration scheme with charge stripper rings (CSRs) as a cost-effective way to enhance the charge stripping efficiency has been proposed. The CSR recycles beams other than the selected charge state. The CSR is being studied as a future plan, aiming at a 20-fold increase in the intensity of the uranium beams. We present some calculation results on the key design issues of a CSR.

INTRODUCTION

The RIKEN RI Beam Factory (RIBF) [1] is a leading facility for generating in-flight RI beams. The RIBF is a cyclotron-based heavy ion accelerator complex, operating since 2006. The RIBF uses three injectors (RILAC [2,3], RILAC2 [4], and AVF cyclotron [5]) and four ring cyclotrons (RRC, RIKEN ring cyclotron, K = 540 MeV [6]; fRC, fixed-frequency ring cyclotron, K = 700 MeV [7, 8]; IRC, intermediate-stage ring cyclotron, K = 980 MeV [9]; and SRC, superconducting ring cyclotron, K = 2600 MeV [10]), which can accelerate various heavy ions of up to 345 MeV/u or more by utilizing three different acceleration modes. In-flight RI beams produced from the primary heavy ion beam are separated using BigRIPS [11] and are applied in various experiments for nuclear physics and different applications.

For the acceleration of uranium (^{238}U) beams, which are exceptionally important for the production of rare RI beams by in-flight fission, two charge stripping processes are applied. The uranium beam intensity, which was 0.4 pnA in 2008, has been drastically enhanced to approximately 117 pnA in 2020. This is due to the continuous performance improvements of the 28-GHz super-conducting ion source [12–14], several innovations in the durability and quality of the charge strippers [15–20], the sophistication of the high-intensity beam operation, and steady improvements in other various accelerator components [21–25].

ACCELERATION SCHEME FOR ^{238}U AT RIBF

Figure 1 shows the acceleration scheme of uranium ions at RIBF. We use the He gas stripper and a rotating carbon-disk stripper in the acceleration scheme. U^{35+} ions originated from the superconducting ECR ion source is converted to U^{64+} with the stripping efficiency of ~20% at 10.8 MeV/u with the He stripper and then further converted to U^{86+} with the efficiency ~25% at the second stripper at 50.8 MeV/u. Both strippers solved lifetime problems of fixed carbon foil strippers for uranium accelerations. We briefly introduce the strippers in the followings.

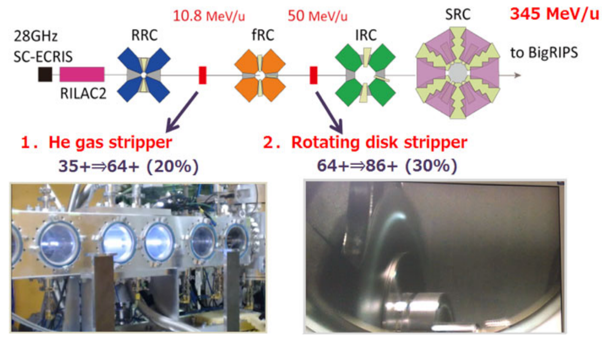

Figure 1: Acceleration scheme for ^{238}U at RIBF.

He Gas Stripper

Our group has developed a low-Z gas stripper to replace the traditional carbon-foil strippers [17–20]. The stripper is non-destructive and simultaneously provides uniform thickness and high charge state equilibrium of the low-Z gas. The high charge equilibrium is owing to the slow velocity of the 1-s electrons of low-Z gas. Such slow electrons are difficult to transfer to fast projectiles because of poor velocity matching so that the electron capture process is strongly suppressed.

One of the primary technical challenges in realizing the He gas stripper is gas confinement in a windowless vacuum because He gas is very diffusive. Figure 2 shows the actual design of the He gas stripper. The system consists of two 5-stage differential pumping systems, one on each side of the 50-cm target region. 26 pumps are used in the system. The stripper is designed to achieve vacuum reduction from the target pressure of 7 kPa to 10^{-5} Pa within a length of ~2 m while ensuring a 12-mm beam path. The He gas flow rate is about 300 m^3/day.

The stripper works well since 2012 and provide infinite lifetime for use.

Rotating Graphite Carbon Stripper

As the second stripper, we have developed rotating disk stripper [15, 16]. The module of the rotating stripper can provide the rotation speed up to ~1000 rpm. The disk diameter is 11 cm. It provides the irradiation area more

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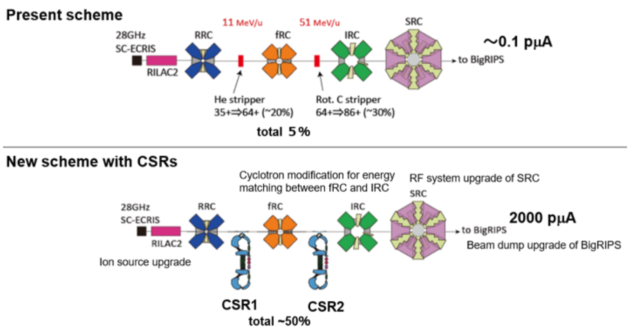

Figure 2: The present acceleration scheme of ^{238}U beam at the RIBF and new acceleration scheme to enhance the total charge stripping efficiency with CSRs.

than 60 times of the beam spots. As a material of the disk, Be was used during 2012-2014. It worked quite well. Since 2015, we used new material, which is the highly oriented graphite sheet (GS) produced by the Japanese company KANEKA Corporation [26]. The structure is like layered graphene. A prominent feature of the KANEKA GS is its very high thermal conductivity of 1500 W/mK in the planar direction. Thus, the temperature increase at the beam spot is expected to be suppressed. The other notable feature is high density and uniform thickness. In addition, the KANEKA GS is mechanically strong and can be handled easily.

The performance of the rotating GS stripper is remarkable. For the Be stripper, when it was irradiated with ~10^{18} uranium ions, we found it became cracked and heavily deformed due to the heat cycle. On the other hand, a total of ~$2\text{x}10^{18}$ uranium ions caused almost no damage to the rotating GS stripper apart from a slight deformation. The lifetime is about two weeks for the use at the present highest intensities of uranium at the RIBF.

CHARGE STRIPPER RING

Upgrade Plan with CSRs at RIBF

As described above, two charge strippers are used for uranium acceleration at RIBF. In this acceleration scheme, the total stripping efficiency is 5% at most.

We proposed an upgrade plan with the use of a charge stripper ring (CSR) as a cost-effective method for increasing the charge stripping efficiency in the ring accelerator [27, 28]. The upgrade plan also includes ion source upgrades, modification of the present cyclotrons for energy matching, RF system upgrades, and upgrade to higher power beam dumps of the BigRIPS.

Concept

A conceptual diagram of the charge stripper ring at the RIBF is shown as an example in Fig. 3. In the present scheme at the RIBF, after the $^{238}U^{35+}$ beam (11 MeV/u, 18.25 MHz) passes through the He stripper with a thickness of approximately 0.7 mg/cm^2, only the $^{238}U^{64+}$ beam

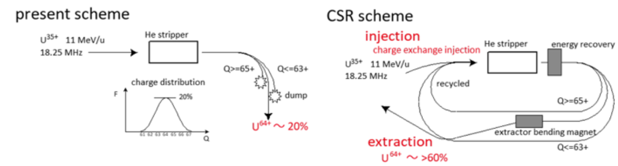

Figure 3: Present scheme of the first stripper and conceptual scheme of CSR.

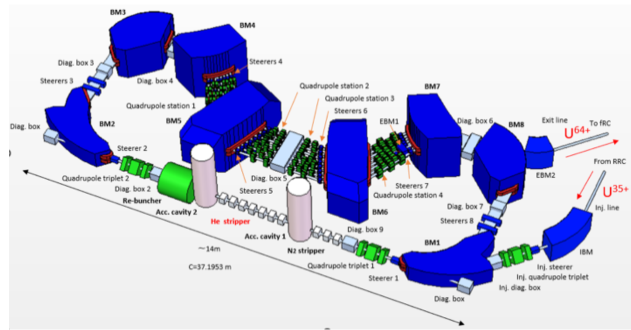

Figure 4: Design view of CSR1.

is selected by the subsequent bending magnets. The charge stripping efficiency is approximately 20%. In the charge stripper ring for the first stripper (CSR1), beams other than the selected U^{64+} beams reenter the stripper with a ring after recovering the energy lost in the stripper. The U^{35+} beams are injected simultaneously into the charge stripper ring using the charge exchange injection method. The recycling cycles are repeated, and only the U^{64+} beams are continuously extracted, using a magnetic deflector channel.

Design of Charge Stripper Ring 1

Figure 4 shows a design view of CSR1, which is a compact isometric ring with the same designed circumferences of 37.1953 m (15-times the distance interval of the beam bunches from the RRC at a frequency of 18.25 MHz) for all circulating uranium beams with eight different charge states from 59+ to 66+. The CSR1 consists of gas strippers (He and nitrogen strippers), eight main bending magnets (BM1-8), two acceleration cavities, a re-buncher, four charge-dependent quadrupole stations (QS1-4), injection magnets (IBM and injector quadrupole triplets), extractor bending magnets (EBM1 and EBM2), steerers for closed orbit distortion (COD) corrections, and diagnostic boxes involving beam diagnostics and vacuum pumps.

As a CSR, we introduce a ring with the same orbital length under all charge states (i.e., an isometric ring) to hold the bunch structure of beams to match the acceptance of the latter-stage cyclotrons. Strippers should be placed at the achromat point. In the design of the isometric ring, the main bending magnets are commonly used for all charge states.

Figure 5 shows design equilibrium orbits of CSR1 for all of our designed circulating charge states from 59+ to 66+. To place quadrupole magnets at quadrupole sections

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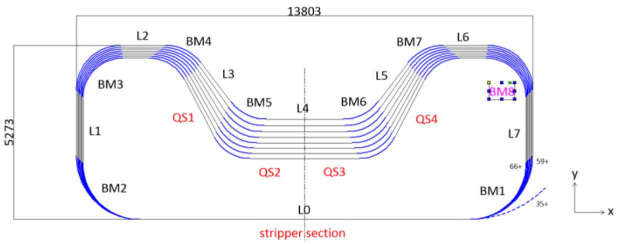


Figure 5: Equilibrium orbits of CSR1 for the charge states 59+ – 66+. CSR1 is an isometric ring with six bending magnets and two anti-bending magnets.

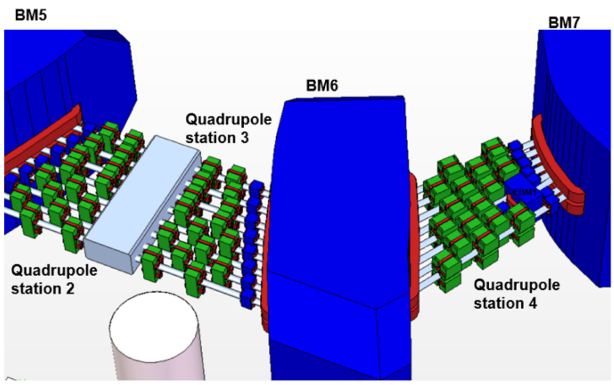


Figure 6: Close-up view of the quadrupole stations.

(QS1-4), we also require sufficient orbital spacings of more than ~10 cm among the adjacent orbits. A total of 66 quad-rupoles are placed in the sections, shown in Fig. 6.

Quadrupole Magnet

High-density quadrupole stations (QS) are equipped with a quadrupole doublet for all charge states (triplets for only 66+ in QS1 and QS4) will be used to ensure that the design optics for all charge. The line for 64+ in QS4 is equipped with a bending magnet for beam extraction (EBM1). The drift lengths of the QSs are limited owing to the overall size limitation of the CSR1. The distance be-tween adjacent orbits is quite narrow (~10 cm). Therefore, the design of a compact quadrupole magnet is a key issue. We should consider that the leakage field of the quadrupole magnets on the adjacent orbits is reduced to less than sev-eral Gauss.

Figure 7 shows the “hourglass-like” quadrupole magnet we developed. Bent poles are used, and the coils are placed in a straight neck of a pole. The shape ensures adjacent beam paths on both sides of the side yokes while making space to wind the coils, which generate the necessary mag-netomotive force (patent applied by RIKEN and HITACHI Engineering Co., Ltd., application number JP2020-056540 in Japan). The quadrupole magnet has waists on the side yokes, as shown in Fig. 8, to avoid interference with the adjacent beam ducts, making it simply an “hourglass-like” structure.

The maximum field gradient of quadrupole magnets is designed to be 16 T/m with the bore diameter of 53 mm determined by beam dynamics requirements.

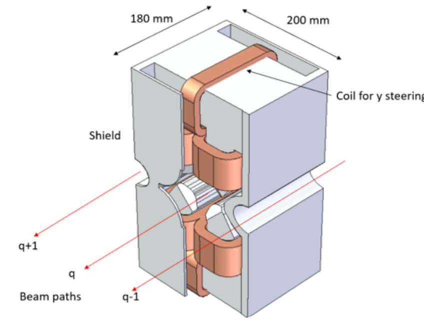


Figure 7: Close-up view of the quadrupole stations.

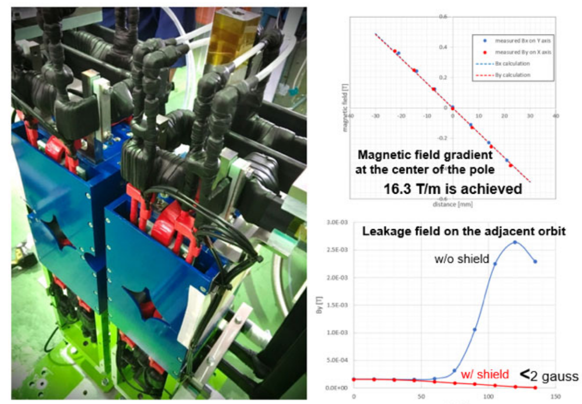


Figure 8: Picture of prototype quadrupoles and results of measurements of magnetic fields performed in HITACHI Engineering.

In the actual design, the following tasks were performed:

- Generating the required magnetic field gradient
- Maximizing uniformity and effective diameter
- Minimization of horizontal leakage field
- Minimization of magnetic field leakage to adjacent orbits through the axial direction
- Crosstalk between adjacent quadrupole magnets

We have already finished the calculations and prototypes production and measurements of the magnetic field were completed already (Fig. 8). The desired magnetic field gra-dient was obtained, more than 16 T/m at the center of the pole, and the leakage field was sufficiently small as calcu-lated.

Extraction Bending Magnet

Another important device in CSR1 is the extraction bending magnet (EBM1) to extract U^{64+} beams. Continu-ous extraction is possible with the static magnetic field of EBM1. Because the installation site of EBM1 was very crowded as shown in Fig. 6, it was a challenge to design a strong magnet to extract U^{64+} beams towards our desired direction in the very limited space.

Figure 9 is a design 3D model of the EBM1. The struc-ture has return yokes in four directions (front, back, left, and right) to generate strong magnetic field while keeping

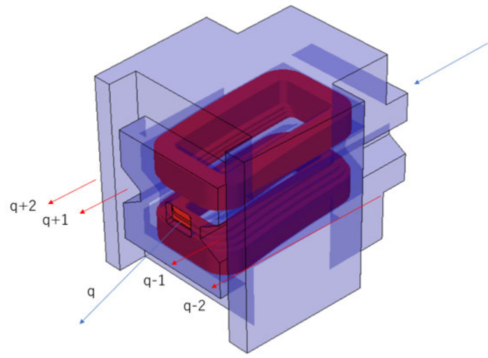


Figure 9: A design 3D model of the EBM1.

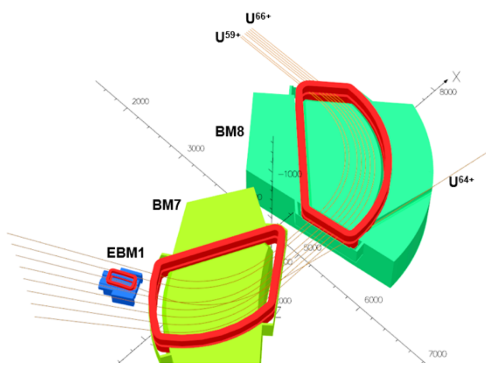


Figure 10: Calculated orbits for beam extraction with the EBM1.

the paths of adjacent charge states. The maximum magnetic field strength is 0.8 T and the poles have the length in 260 mm and the gap in 45 mm. Calculations with Opera3D show that the leakage field is less than 10 Gauss at the adjacent paths owing to this complex structure.

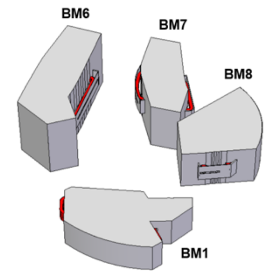
Figure 10 shows calculated trajectories for the extraction. Only the uranium 64+ beam is extracted without disturbing orbits for other charge states. Now the prototype of EBM1 is under construction.

Bending Magnet

We are also designing the bending magnets (BM1-8) as shown in Fig. 11. The parameters are listed also. The bending magnets has large pole area to bend 8-charge beams at the same time, which is similar to sector magnets of ring cyclotrons. We require fine tuning of pole edges to adjust BL products to make isometric orbits for all charge states. Such optimizations are undergoing. Calculated orbits for all charge states are shown in Fig. 12. We are also proceeding the mechanical designs of bending magnets.

2-Stage Stripper Method

A two-stage stripper with a N_2 stripper (0.1 mg/cm^2) and a He stripper (0.45 mg/cm^2) arranged in series is a good candidate for the stripper used in CSR1. By applying the He stripper after resetting the charge state distribution with the N_2 stripper, which has large charge exchange cross sections and a thin equilibrium, the charge state distribution can be fixed regardless of the number of



	BM1, 2	BM3, 8	BM4, 7	BM5, 6
magnetic field	1.0067 T	1.4261 T	1.4261 T	1.4261 T
pole gap	50 mm	45 mm	45 mm	45 mm
weight	25.5 t	32.6 t	28.5 t	56.3 t
height	930 mm	1525 mm	1285 mm	1925 mm
magnetomotive force	40200 AT	52300 AT	52300 AT	52300 AT
current	350 A	450 A	450 A	450 A
coil size	T134xH82 mm	T134xH82 mm	T134xH82 mm	T134xH82 mm
number of turns	120 turns	120 turns	120 turns	120 turns
hollow conductor	□12x ϕ 6 mm	□12x ϕ 6 mm	□12x ϕ 6 mm	□12x ϕ 6 mm

Figure 11: 3D view of designing bending magnets and design parameters for BM1-8.

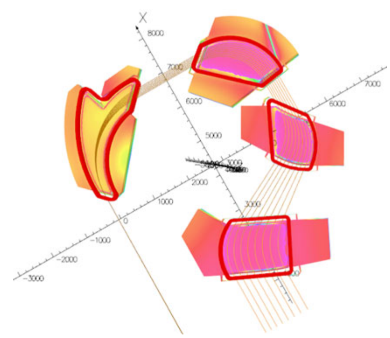


Figure 12: Calculated orbits for U59+-U66+ in the half cell of the CSR1.

Figure 13: A schematic diagram of the charge stripping cycle within the CSR1.

revolutions. Figure 13 shows a schematic diagram of the charge stripping cycle within the CSR1. The mean charge states after the N_2 and He strippers were approximately 55+ and 63+, respectively. These values have almost no dependence on the number of revolutions because the charge state distribution after the N_2 stripper is near the charge state equilibrium.

Beam Calculations with Emittance Growth

We conducted calculations to estimate the emittance growth in CSR1 using the set of 6×6 transfer matrices $M(q)$ for all eight charge states q derived from calculations considering possible sources of emittance growth, such as charge-exchange energy straggling and angular straggling at strippers.

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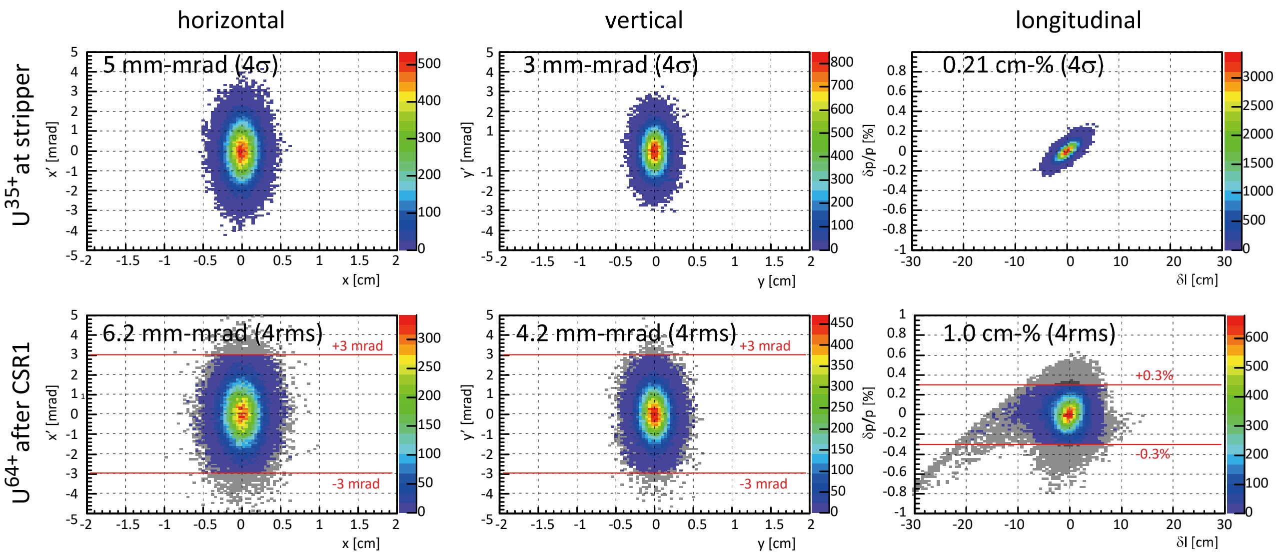

Figure 14: The initial phase ellipses of U35+ at the center of the He stripper in the CSR1 (upper) and the calculated elected ellipses of U64+ in the CSR1 (lower) for horizontal, vertical and longitudinal directions, respectively. The ellipses of grey plots indicate the calculated ones without beam losses.

Figure 14 shows the initial ellipses of U35+ at the origin and the calculated elected ellipses of U64+ in the CSR. In this calculation, U64+ can be extracted with an efficiency of approximately 74.5%. The mean number of revolutions is 3 under this condition. The uranium ions in CSR1 were assumed to be lost if |dp/p| exceeds 0.3% or the angles (|x'| or |y'|) exceed 3 mrad. The resulting beam losses were 13.5% and 2%, respectively. The remaining loss (~10%) is due to the charge state being out of range.

SUMMARY

The performance of the RIBF accelerators is improving steadily. Upgrade plan with CSRs is under consideration aiming 20-fold increase of ^{238}U intensities. Calculations, design and construction of key devices of CSR1 are undergoing so that it can be built as soon as the budget is approved. Installation site for CSR1 is being finalized and we are considering further extension of the CSR1 designs.

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