CHARGE STRIPPER RING FOR CYCLOTRON CASCADE

H. Imao, O. Kamigaito, H. Okuno, N. Fukunishi, K. Suda, N. Sakamoto, K. Yamada, Y. Yano,
RIKEN Nishina Center, Wako, Japan

Abstract

In the multi-stage acceleration of heavy ions such as the acceleration at the RIKEN RI beam factory (RIBF), the electron stripping process with charge strippers is an inevitable process for the efficient acceleration. The efficiencies, however, for the charge-state conversion of very heavy ions are not so high with common charge strippers in the acceleration up to the energy around hundreds MeV/u. The total efficiency of two charge strippers for 238U acceleration at the RIBF is only 6%. It is a bottleneck for the intensity upgrade. In the present study, we designed high-efficient charge stripper rings which have applicability to the RIBF.

INTRODUCTION

In a multi-stage acceleration of heavy ions, the electron stripping of the ions with charge strippers is an essential process for efficient acceleration. When one accelerates the very heavy ion beams, such as uranium ions, up to several hundred MeV/u, it is not possible to provide full strip beams with conventional strippers. Charge state of the beams after the stripper has a distribution following the physical law. The intensity of ions should be reduced significantly in exchange for the efficient acceleration.

In the uranium acceleration at the RIKEN RI beam factory (RIBF) [1], the charge state is converted twice and the total conversion efficiency is only 6%. The low conversion efficiency is an important bottleneck to generate a high-intensity uranium beam. Such beams are strongly desired in the world because they can provide a huge breakthrough for exploring the new domain of the nuclear chart.

The FRIB project, one of the next generation heavy ion facilities in the USA [2], is planning to use the multi-charge acceleration technique. In this scheme, the beams with five charge states are accelerated and transported at the same time in the superconducting linear accelerator. Unfortunately, this technique is not applicable for the acceleration with ring-type accelerators, such as a cyclotron.

In this paper, we propose and discuss charge stripper rings which can be available as an efficient stripper in a multi-stage accelerator complex involves circular rings such as the RIBF.

URANIUM ACCELERATION AT RIBF

The acceleration scheme of ^{238}U beams at the RIBF is shown in Fig. 1. $^{238}\mathrm{U}^{35+}$ beams extracted from the 28-GHz superconducting ECR ion source [3] is accelerated with an injector RILAC2 [4] and four ring cyclotrons (RRC, fRC, IRC, SRC) up to the energy of 345 MeV/u.

The charge state is converted twice at the energies of 10.8MeV/u and 51 MeV/u, respectively. The first stripper based on the He gas [5,6] converts the charge state from 35+ to 64+ with the conversion efficiency of about 20%. The second stripper of rotating carbon disk stripper [7] converts from 64+ to 86+ with the efficiency about 30%.

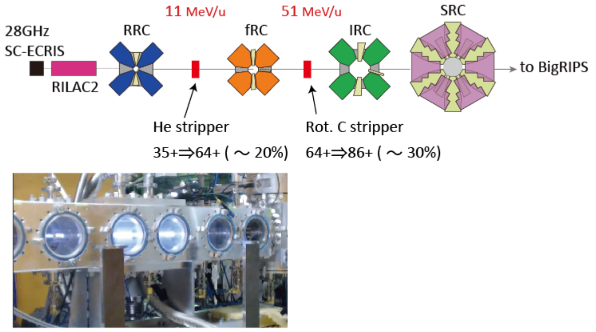

Figure 1: Acceleration scheme of ^{238}U ion beams at the RIBF.

A simple way to increase the low total conversion efficiency is to remove the first stripper and to improve the fRC to accept U^{35+} beams (K value is approximately 2200). In a design of a conventional normal conducting ring cyclotron, the new fRC should be a very huge and heavy cyclotron comparable with the SRC, the largest cyclotron in the world [8]. Although it is a sure way to improve the present intensity of uranium beams, we require further optimization of the design for the new fRC.

CONCEPT OF STRIPPER RING

We propose here the new concept of an efficient stripper ring as shown in Fig. 2. As a conventional scheme at the RIBF, $^{238}\mathrm{U}^{35+}$ beams coming at the frequency 18.25 MHz are injected to the first stripper and only $^{238}\mathrm{U}^{64+}$ beams (20% of the injected beams) are passed through the subsequent selection dipole magnet. The others are dumped inside the magnet.

On the other hand, in the new scheme, the beams other than the selected charge state are circulated recovering the energies and re-entered to the stripper. The beams with the selected charge state are extracted continuously, repeating this circulation process.

Assuming the conversion efficiency $\varepsilon_0 = 0.2$ is unchanged, the total conversion efficiency after the n-times circulation is given by $\epsilon_n = 1-(1-\epsilon_0)^n$. Ideally, the conversion efficiency becomes 3 times higher than the initial efficiency ε_0 after the 3 times circulation. The bunch structure of the extracted beams must be preserved to match to the acceleration condition of the subsequent cyclotrons.

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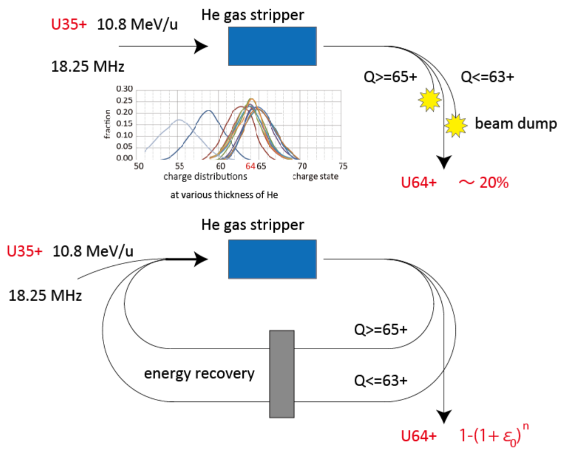

Figure 2: Concept of the charge-stripper ring.

ISOMETRIC CHARGE STRIPPER RING

Isometric ring to any magnetic rigidities of beams (momentum compaction factor α=0) is a possible ring preserving the bunch structure. Such isometric rings can be realized by using the combination of the bending and anti-bending magnets. The harmonics number of the circulating beams should be integer.

Figure 3 shows an example of the calculated orbit of such isometric ring. The initial U^{35+} beams coming from the RRC are injected with the charge-exchange injection method. The deposit energies in the stripper are recovered depending on the charge states q by the RF cavity located at the dispersive region. The beams with selected charge state (q_0=65+) are kicked out and extracted with the electrostatic septum similar to the EDC of cyclotrons.

The rings considered in this paper have the twofold symmetry. The more highly symmetric rings are also possible. Such rings would accept beams coming from many injectors at the same time,

Conditions to be satisfied by the half-cell of the isometric ring are followings.

1. The deflection angles are constant with Bρ.
2. The orbit lengths are constant with Bρ.
3. The endpoints of the orbit are collinear for all Bρ.

The trajectories for all q we want to circulate can be calculated under the three conditions above and the edge angles of the dipole magnets are automatically determined. The transfer matrix M(q) of the half-cell can be derived from the input parameters, drift lengths and field strengths of the dipole magnets for a selected charge state q_0. We also added quadrupole magnets at the first drift region for the tuning of the matrix M. We varied all input parameters to satisfy the stable circulating condition, $|\mathrm{TrM}(q)| < 2$. Because the circulating beams change the charge state at the stripper, the eigen ellipses for all q should be as uniform as possible.

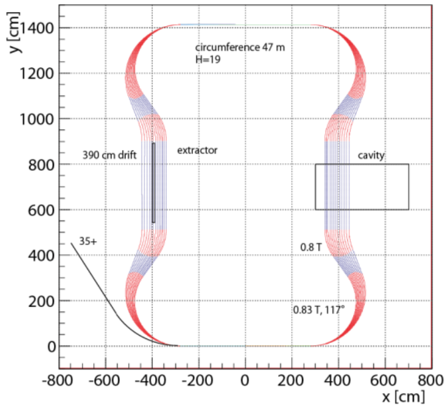

Figure 3: Schematic layout of an isometric charge-stripper ring.

Calculated orbits optimized for the first stripper at the RIBF are shown in Fig. 4. The ring with the magnetic field of 0.4 T is in about 20 m square. The orbit separation at the dispersive region for neighboring q is about 15 cm.

The calculated eigen ellipses are shown in Fig. 5. We note that vertically long ellipses are desirable to reduce the emittance growth due to the angular straggling in the stripper.

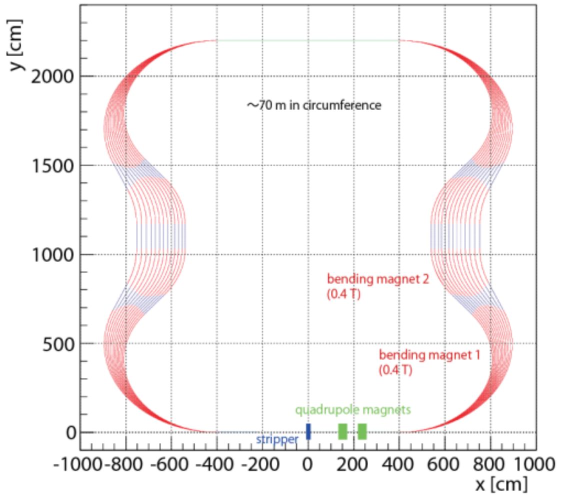

Figure 4: Equilibrium orbit for uranium beams with the charge states from 59+ to 71+.

Figure 6 is the calculated beam envelopes of x and y directions for all q. Although the tunes also depend on the charge states, the resonance would not be problematic because the charge state is not always constant in the circulation and the mean turn number is not high.

We further calculated the beam dynamics for the transverse directions in the ring by implementing the Monte-Carlo code for the charge exchange reactions. The calculation procedures are as followings:

1. Give a particle randomly on the initial ellipses matching to the intersection of the eigen ellipses.
2. Perform the Monte Carlo calculation in the stripper involving charged exchange reactions, energy loss and scattering.
3. Energy of the particle is recovered depending on q.
4. Calculate the transport matrix for the particle with the calculated q and the energy in 2 and 3 and transport the particle.
5. Repeat the calculation process between 2 and 4 until the charge state reaches at 65+.
6. Transport the particle to the extraction position and get information of extracted particle.
7. Return to 1 for the next particle.

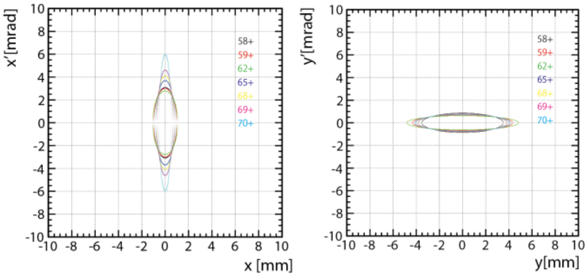

Figure 5: Eigen ellipses.

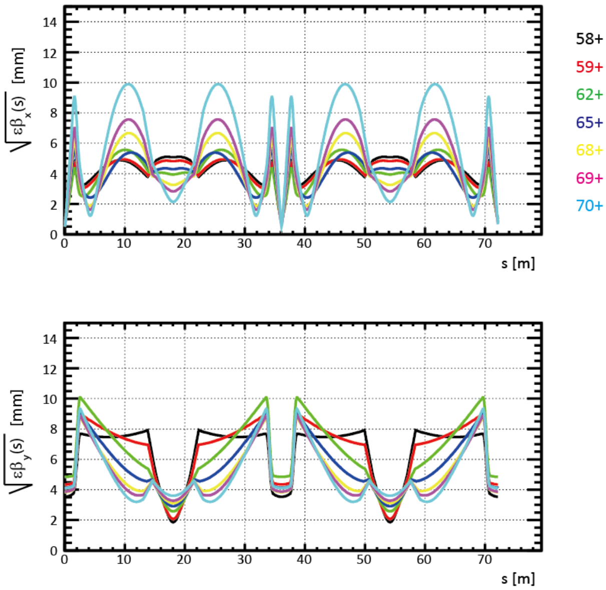

Figure 6: Horizontal and vertical betatron functions.

The He gas stripper with the thickness of 0.4 mg/cm^2 is assumed in the calculation. Figure 7 shows the calculated charge evolution and the energy degradation in the He stripper. The cross sections for the electron capture and ionization are calculated following Ref. [6].

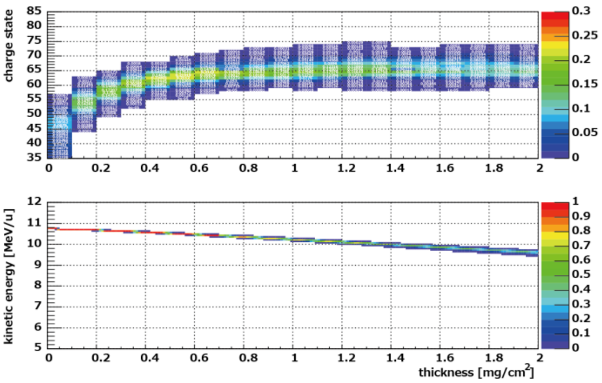

Figure 7: Charge and energy evolution in He gas.

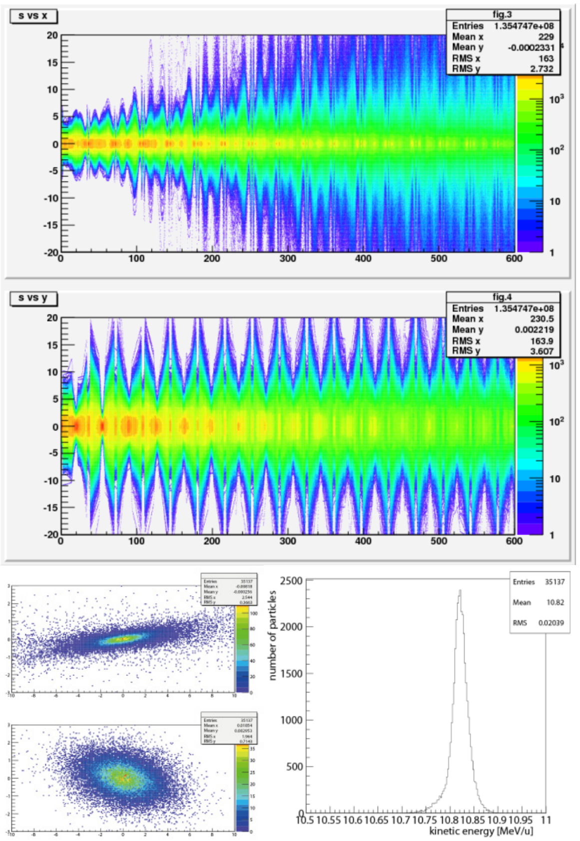

Figure 8: Figures of calculated result.

Figure 8 shows the calculated beam plots in the transverse directions. The plots in x-x' and y-y' space, and energy distribution at the ring exit are also shown. The beam with the desired charge state 65+ was extracted with the efficiency of 72% in this calculation. 9% of the beams went outside the assumed physical aperture of 10 cm square inside the ring. 14% of the beams changed the charge state outside the acceptable charge states (58-70+). The remaining 5% of beams did not reach to 65+ within the simulated 20 turns. The energy width at the exit is comparable to that after the He stripper with the thickness of 1.4 mg/cm2, which is twice of the present thickness of the first stripper at the RIBF. The calculations for further optimized lattice are continued.

ORBIT-DIFFERENCE ADJUSTING CHARGE-STRIPPER RING

As another possible ring to keep the bunch structure, a ring can be considered, in which the orbit difference by *q* is adjusted to match to the bunch spacing. In this scheme, the orbit separation among neighboring charge states become large so that some components can be placed in each orbit independently. Thus the beam extraction has no problem. The orbits for respective charge states can be treated in almost independent rings.

Figure 9 shows a schematic layout of such orbit-difference adjusting ring designed for the first stripper at the RIBF. The ring designed for circulating the beams with the charge states between 62+ and 66+ and for extracting the beams with 64+. The second and third bending magnets and quadrupole triplet are placed in each orbit, independently.

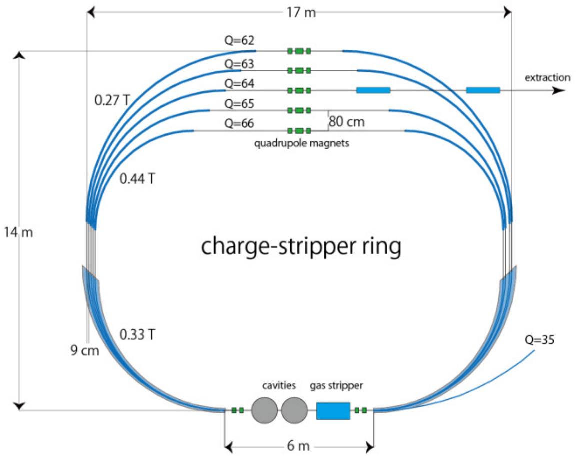

Figure 9: Orbit-difference adjusting charge-stripper ring.

As the lattice design for the isometric rings, vertically long eigen ellipses at the stripper are desirable to reduce the emittance growth due to the angular straggling. Amplitude of betatron functions and dispersion in the ring should be tolerable within realistic apertures. The achromat conditions at the position of the stripper are also desirable. In this ring, it is possible to satisfy the condition that the eigen ellipses for all *q* are nearly uniform. This is an advantage of this type of ring because some input parameters, edge angle and *n* values of magnetic channels and field values of quadrupole triplet, can be set for all *q*, respectively.

For the optimizations of the parameters, MINUIT [9] of CERN library was used. The optimized eigen ellipses for all *q* could be almost uniform with six fitting parameters for each *q* as shown in Fig. 10. Figure 11 shows the beta functions and dispersion in the ring. We also calculated the beam envelopes for transverse directions when the charge state is changed as 65+->63+->64+ with TRANSPORT [10] (Fig. 12). The result shows that the emittance growths for the transverse directions are strongly suppressed when the initial ellipse of the U^{35+} beam matches to the eigen ellipse of the ring.

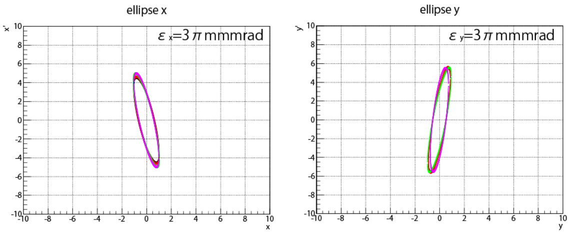

Figure 10: Optimized eigen ellipses for the beams with the charge states between 62+ and 66+.

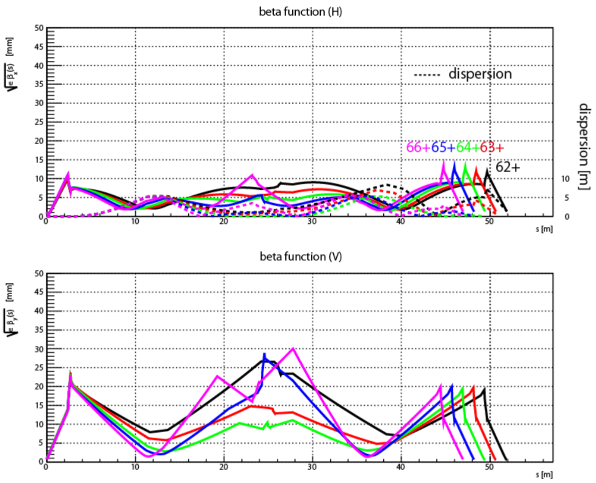

Figure 11: Beam envelopes and dispersion for horizontal and vertical directions.

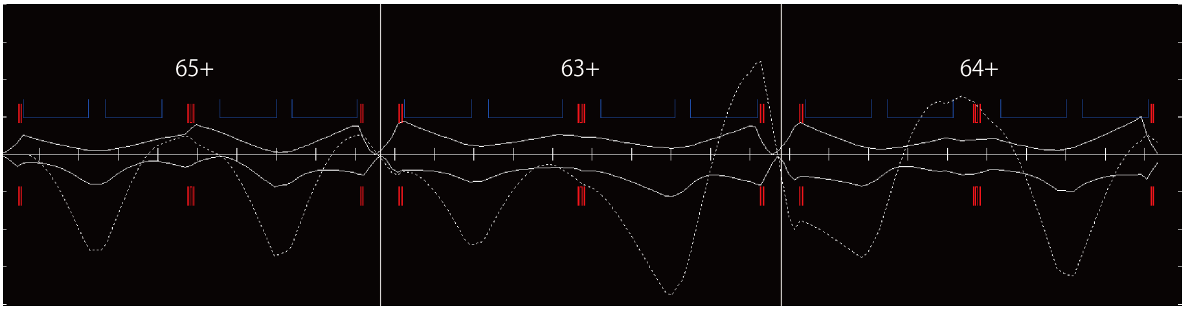

Figure 12: Beam transport calculated with TRANSPORT.

SUMMARY

Two types of high-efficient charge stripper rings which have applicability to the RIBF are proposed. Calculation methods for the lattice design are developed and demonstrated. Further optimization of lattice design and also engineering design are undergoing. Other applications, e.g., the storage ring or cooler ring, are also under consideration.

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