DESIGN CONCEPT OF A HEAVY-ION STORAGE RING FOR MULTI-CHARGE-STATE BEAMS

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Abstract

Rare-event production experiments can greatly benefit from an ERIT-type heavy-ion storage ring. One of the most serious obstacles to stable circulation of heavy ions in such a ring is stochastic charge-state conversion caused by collisions between the ion beam and the internal target. Since this process randomly changes the ionic charge state, it leads to rapid emittance growth. To address this issue, we have developed a method based on a scaling FFA lattice that matches the closed orbits of beams with different charge states at the production target. Using a proof-of-principle lattice with modulated field index, six-dimensional beam-tracking simulations were performed. The results demonstrate that long-term beam circulation over nearly 3000 turns is achievable.

INTRODUCTION

Heavy-ion storage rings have a wide range of applications, and various ring concepts have been investigated. Examples include the production of super-heavy elements (Z=119, 120, etc.) and radioisotopes such as astatine ^{211}At. Since the production cross sections in these applications are extremely small, it is necessary to increase the number of collisions between the target and beam particles in order to achieve a sufficient production yield. For this reason, storage rings equipped with internal targets, such as the FFA-based energy recovery internal target (ERIT) [1], are considered promising devices for such applications.

When a heavy-ion beam passes through the target, electromagnetic interactions with the target material cause the ionic charge state to change. For beams with relatively small atomic number Z, the ions circulate in a fully stripped state. However, for low-energy heavy-ion beams with large Z, recombination with electrons in the target material cannot be neglected.

In this process, the charge state is determined stochastically according to empirical formulas such as the one proposed by Shima [2]. If the closed-orbit radius depends on the charge state, the amplitude of betatron oscillation changes whenever a beam particle collides with the target. Depending on the betatron phase, the oscillation amplitude may either increase or decrease. However, because the process is stochastic, the oscillation amplitude gradually increases over many turns. To avoid this effect, at the target location θ_T, for beam in the charge state of $q_0 + \Delta q$, the radial coordinate of the closed orbit $\bar{r}_{q_0+\Delta q}$ must satisfy the conditions

$$\begin{aligned} \bar{r}_{q_0+\Delta q}(\theta_T) &= \bar{r}_{q_0}(\theta_T) \, , \\ \bar{r'}_{q_0+\Delta q}(\theta_T) &= \bar{r'}_{q_0}(\theta_T) \, , \end{aligned} \tag{1}$$

where q_0 is the nominal charge state and the prime denotes the derivative with respect to the azimuthal angle θ. In a perfectly scaling FFA lattice, a geometrically similar closed orbit is defined for each charge state, and therefore it is impossible to realize a straight section satisfying the above conditions.

In this study, we use a ring concept that mitigates this problem by applying azimuthal modulation to the field index k characterizing the scaling FFA lattice [3].

LATTICE CONSTRUCTION

To satisfy the conditions in Eq. (1), we introduce closed-orbit distortion (COD) using an azimuthally modulated field index defined as

$$k(\theta) = k_0 + \Delta k(\theta) \, ,$$

with this modulated $k(\theta)$, COD is expressed as

$$x_{\mathrm{cod}}(\theta) = -\frac{\Delta q}{q_0(k_0+1)} \frac{\sqrt{\beta_x(\theta)}}{2\pi B\rho} \sum_{n=-\infty}^{\infty} \frac{\nu_x^2 e^{in\phi_x(\theta)}}{\nu_x^2 - n^2} \Phi_n[\Delta k] \, ,$$

where ν_x is the horizontal tune, β_x is the horizontal betatron function, $\Phi_n[\Delta k]$ is a functional of $\Delta k(\theta)$ defined as

$$\Phi_n[\Delta k] := \oint B(\tilde{r}_{q_0}(\phi_x), \phi_x) \beta_x^{3/2}(\phi_x) \Delta k(\phi_x) e^{-in\phi_x} d\phi_x,$$

and ϕ_x is a normalized phase advance

$$\phi_x(s) = \frac{1}{\nu_x} \int_0^s \frac{ds'}{\beta_x(s')},$$

which advances 2π per turn in the ring. Closed orbits corresponding to different charge states merge into the same radial position if $\Phi_n[\Delta k]$ satisfies the condition:

$$\frac{\Delta q}{q_0(k_0+1)} \left[\tilde{r}_{q_0}(\theta_T) + \frac{\sqrt{\beta(\theta_T)}}{2\pi B\rho} \sum_n \frac{e^{in\phi_x(\theta_T)} \, \Phi_n[\Delta k]}{\nu_x^2 - n^2} \right] = 0.$$

For a further suppression of the transverse emittance growth, the betatron functions for different charge state beams should be matched at the target location as well as the closed orbits. The modulation of β_x is expressed as

$$\frac{\Delta\beta_x}{\beta_x} = -\frac{\nu_x}{2} \sum_{p_x=-\infty}^{+\infty} \frac{\tilde{g}_{p_x} e^{ip_x\phi_x}}{\nu_x^2 - \left(\frac{p_x}{2}\right)^2} \, ,$$

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where $\tilde{g}_{p_x}$ is the Fourier coefficient corresponding to harmonic number p_x, given by

$$\tilde{g}_{p_x} = \frac{\nu_x}{2\pi} \int_0^{2\pi} \Delta K_x(\phi_x) \beta_x^2(\phi_x) e^{-ip_x\phi_x} d\phi_x \, ,$$

and ΔK_x denotes the modulation of the quadrupole component of the magnetic field. The same expression applies to the vertical beta function β_y by replacing the subscript x with y.

To demonstrate the lattice construction method, we consider a test ring based on a scaling FFA lattice composed of FDF triplets for accumulation of a ^{50}Ti beam. The main parameters of the beam and ring lattice are summarized in Table 1.

Table 1: Basic Parameters of the Test Ring

Beam species	$^{50}\mathrm{Ti}^{q+}$ (q = 17–22)	
Beam Energy	5.5 MeV/u	
Lattice	Radial sector FDF triplet	
Symmetry	18	
Field index	k_0	5.8
Betatron tune	(ν_x, ν_y)	(2.89, 4.63)
$B_0(= B(r_0))$	F magnet	0.9193 T
	D magnet	−0.8496 T
reference radius r_0	F magnet	6.17 m $(= \tilde{r}_{q_0}(\theta_F))$[i]
	D magnet	6.07 m $(= \tilde{r}_{q_0}(\theta_D))$
opening angle	long straight	6.34°
	short straight	1.33°
	F magnet	3.41°
	D magnet	4.18°

In the case of $n = 3$, there are 3 nodes of closed orbits for different charge state beams as shown in Fig. 1[1]. Using the modulated $k(\theta)$ optimized as

$$k(\theta) = 5.8\Big[1 - 0.15\cos(3\phi_x(\theta)) - 0.065\cos(6\phi_x(\theta)) - 0.070\cos(9\phi_y(\theta))\Big] \, ,$$

the closed orbit distortions and beta functions have been obtained as in Fig. 2 and Fig. 3, respectively. Both the closed orbits and beta functions are well matched at the target position.

BEAM SIMULATIONS

Using the lattice obtained in the previous section, we performed six-dimensional beam-tracking simulations. As a representative application, we consider a storage ring for the production of superheavy elements, particularly element 119, through collisions between a titanium beam and a berkelium target. The following effects during beam-target interactions were taken into account: (1) energy loss and straggling, (2) transverse scattering and (3) stochastic charge state conversions (SCSC).

[1] Detailed analysis of the $n = 2$ case is available in Ref. [3].

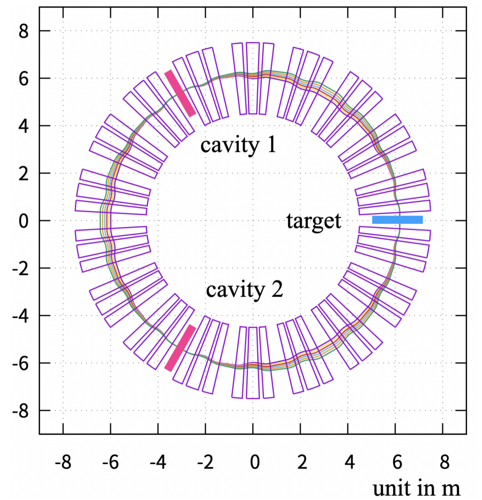

Figure 1: Footprint of closed orbits for different charge state beams.

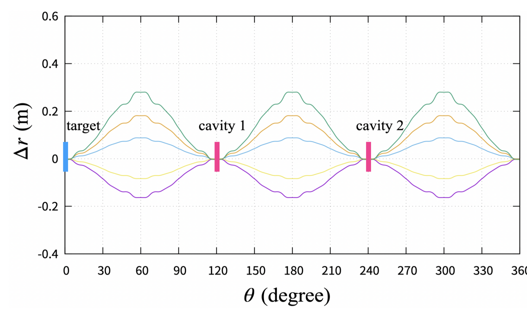

Figure 2: CODs for different charge state beams which merge into the same radius.

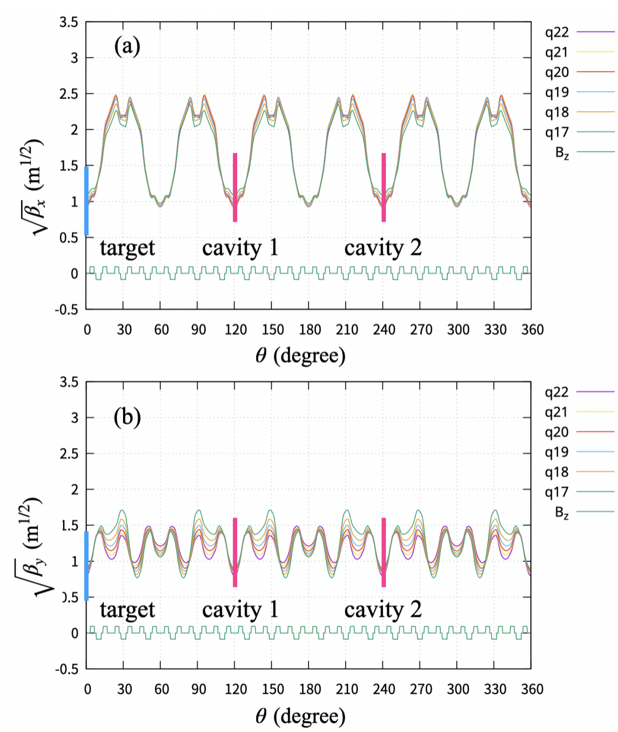

Figure 3: Square root of modulated betatron functions $\sqrt{\beta_x}$ and $\sqrt{\beta_y}$ in (a) and (b) for different charge state beams which merge into the same radius, respectively.

As the internal target, we assumed a 100 μg/cm^2-thickness ^{249}Bk target. The equilibrium ion charge distribution is obtained from Shima's formula as shown in Fig. 4-a. For the energy loss and straggling, Monte Carlo code TRIM [4] was used. The distribution of the energy loss and the scattering angle are shown in Fig. 4-b and 4-c, respectively.

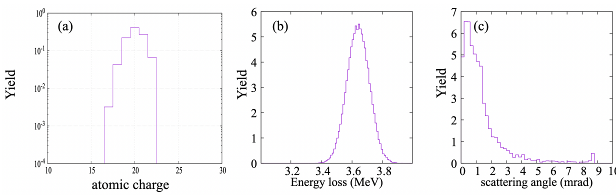

Figure 4: (a) The equilibrium ion charge distribution. (b) The energy loss distribution. (c) the scattering angle distribution. (b) and (c) were obtained from TRIM Monte Carlo.

Similar simulation studies for the n=2 case were reported in Ref. [3]. In these studies, the COD modulation of $n = 2$ was employed, while here we use $n = 3$ modulation where 3 dispersion free sections are available for a target and 2 rf cavities. One of these sections can additionally be used for a second-harmonic RF cavity. The parameters used in the beam simulations are summarized in Table 2.

Table 2: Parameters Used in the Beam Simulation

Target material	^{249}Bk
Target thickness	100 μg/cm^2
Harmonic number	1
Slippage factor	−0.841
	cavity 1 / cavity 2
RF cavity voltage	1.2 MV / 0.6 MV
RF cavity frequency	0.83 MHz / 1.66 MHz
Synchronous phase	8.7°
Injection beam duty factor	20 %
Number of macro particles	1000
Physical aperture	4.5 m $< r <$ 7.5 m −0.15 m $< y <$ 0.15 m

The emittance growth (ϵ_x, ϵ_y, and ϵ_s) and survival rate ξ obtained from the six-dimensional beam tracking are shown in Fig. 5. As shown in Fig. 6, the effective number of turns achieves almost 3000 turns. A substantial improvement was obtained compared with the $n = 2$ case, for which the effective number of turns was approximately 600.

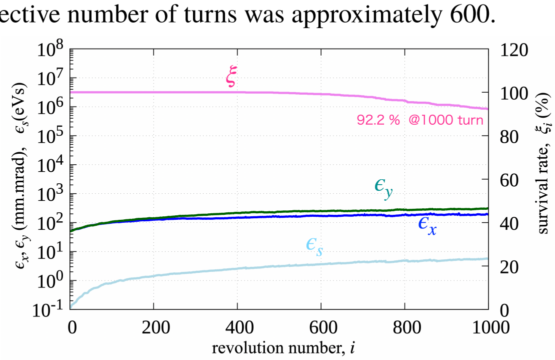

Figure 5: Emittance growth and survival rate.

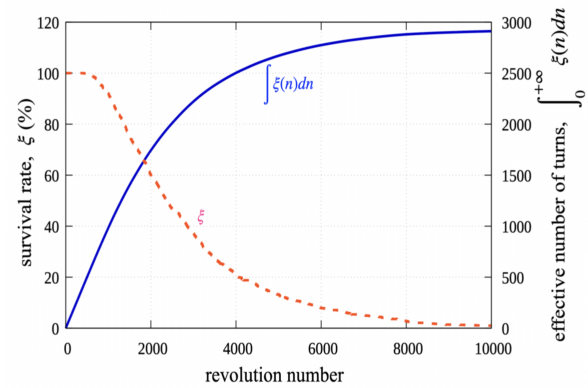

Figure 6: Survival rate and effective number of turns.

SUMMARY

An ERIT-type heavy-ion storage ring is an attractive device for efficient secondary-particle production in rare nuclear reaction processes. One of the most serious obstacles to stable circulation of heavy ions in such a ring is stochastic charge-state conversion caused by beam-target interactions, which leads to rapid emittance growth.

To address this issue, we developed a method for orbit matching and betatron-function matching at the production target for beams with different charge states by utilizing closed-orbit distortion (COD) and beta-function modulation. Based on a lattice employing this method, six-dimensional beam-tracking simulations were carried out using a proof-of-principle ring. The simulations demonstrate that beam storage for nearly 3000 turns is achievable.

The mechanism responsible for the substantial improvement observed with the $n = 3$ modulation is currently under investigation.

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