SHER-HIAF ring lattice design

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Abstract: The Super Heavy Experimental Ring (SHER), which is one of the rings of the next accelerator complex High Intensity Heavy Ion Accelerator Facility (HIAF) at IMP, has to be optimized for e-cooling. Its lattice is designed for two modes: the first is the isochronous mode, which is a time-of-flight mass spectrometer for short-lived secondary nuclei, the second is the storage ring mode, which is used for collecting and cooling the secondary rare isotope beams from the transport line. In order to fulfil its purpose, the ion optics can be set to different ion optical modes.

Key words: mass measurement, lattice design, dynamic aperture, isochronous mode

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1 Introduction

The properties of exotic nuclei far away from the valley of β-stability are key in modern nuclei structure physics and astrophysics research. However, the measurement of exotic nuclei is limited by their low production and short half-lives. The super heavy experimental ring (SHER) at the HIAF accelerator complex offers unique possibilities for measuring short-lived and exotic nuclides. The SHER ring is designed based on the successful operation of CSRe of HIRFL-CSR in IMP. The ring will be used for precise isochronous mass measurement and the collection of pure secondary rare isotope beam. The technique for mass measurement of exotic very short-lived nuclei is also successfully used in the ESR at GSI. A large number of exotic nuclei (with half-lives down to a few tens μs) can be measured in one experimental run. The present lattice consists of 40 identical 9° sector magnets and 9 quadrupole families (40 quadrupoles in total) in one period to fulfill the first order focusing conditions. The lattice of the SHER consists of two 180° arcs separated by two straight sections, it has four identical parts, which can decrease the errors caused by fringing field. The SHER ring is an achromatic magnetic spectrometer with a momentum acceptance of ±0.45% and a transverse acceptance of 30 πmm·mrad for the transition energy $\gamma_{\rm tr}$=1.835 within the acceptable physical aperture. Heavy-ion beams with magnetic rigidities from 3.2 T·m to 25 T·m can be analyzed by the facility. The mass-to-charge ratio m/q of the stored ions circulating in the ring can be measured from the revolution time (T) and the velocity (v) of the ions.

$$\frac{\Delta T}{T}=\frac{1}{\gamma_{\rm tr}}\cdot\frac{\Delta(m/q)}{m/q}+\left(\frac{\gamma^2}{\gamma_{\rm tr}^2}-1\right)\cdot\frac{\Delta v}{v},$$

where γ is the relativistic Lorentz factor and the $\gamma_{\rm tr}$ is the transition energy [1]. The isochronous condition is reached when $\gamma=\gamma_{\rm tr}$. The revolution time of the circulating ions is measured with the two time-of-flight detectors that are installed in the straight section of the ring. Therefore, measurements of the revolution times gives the possibility of determining the m/q ratios of circulating ions.

2 Super Heavy Experimental Ring (SHER)

2.1 Machine parameters and lattice

Due to the HIAF design target, the radius of the SHER ring should be the same as the former booster ring in order to allow it to be upgraded in the future. In contrast from the present isochronous ring CSRe in IMP, the present layout of the SHER consists of two arcs, where the envelopes in the arcs are characterized by a large dispersion function inside the central dipole magnets, in order to achieve the necessary large values of the local momentum compaction factor $\alpha_{\rm p}$ [2]. If we want to get a small energy transition $\gamma_{\rm tr}$, a large momentum compaction is needed, but a large $\alpha_{\rm p}$ means that the path length will vary by a large amount, even with

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a small momentum error. There are still many aspects that should be taken into consideration. First of all, the SHER should be operated in the isochronous mode in higher orders. Secondly the transverse and momentum acceptance will be larger than CSRe. Thirdly, the SHER will be achromatic at its straight sections, like CR (in GSI) [3], two TOF detectors will be installed in one of the straight sections. Fig. 1 shows the layout of the SHER. Table 1 lists the modified parameters of the SHER ring.

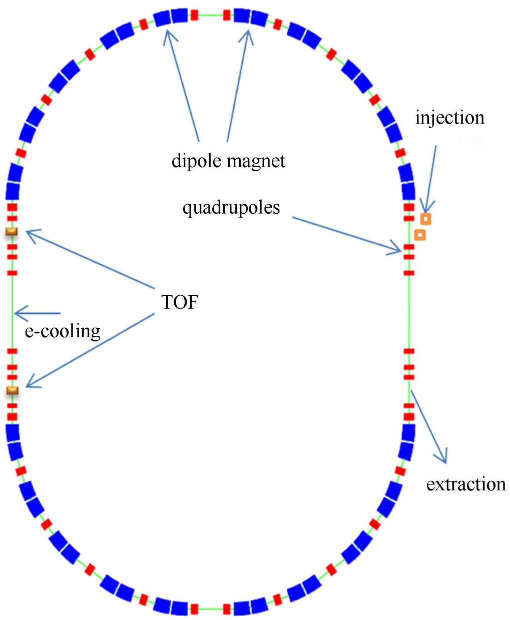

Fig. 1. (color online) Layout of the SHER.

Table 1. Modified parameters of the SHER ring.

mode	isochronous	normal
circumference/m	273.3	273.3
number of quadrupoles	40	40
γ_{tr}	1.83	3.41
tune Q_x/Q_y	2.36/2.72	4.15/2.07

Figure 2 shows the twiss function of the SHER ring with isochronous mode, and Fig. 3 shows the twiss function of normal mode.

2.2 Chromatic correction

Chromatic correction is another important part of the SHER ring design. Since the momentum spread of the particles is relatively large (3%), each individual quadrupole gives an essential contribution to the chromatic effect of the ring. The focal strength can be written as [4]

$$f^{-1}=\frac{e(G+G'D\delta)L}{P_0C(1+\delta)},$$

where f^{-1} is the focal strength of a quadrupole, G is the quadrupole field component, and G' is the sextupole component, p_0 is the momentum of the reference particle.

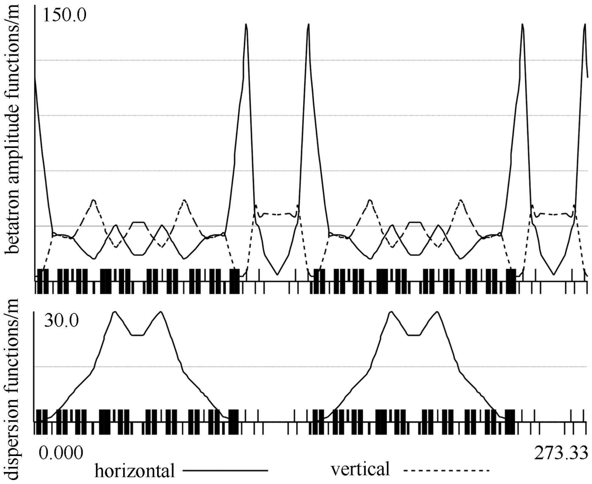

Fig. 2. Twiss function of the isochronous mode with the energy transition γ_{tr}=1.835.

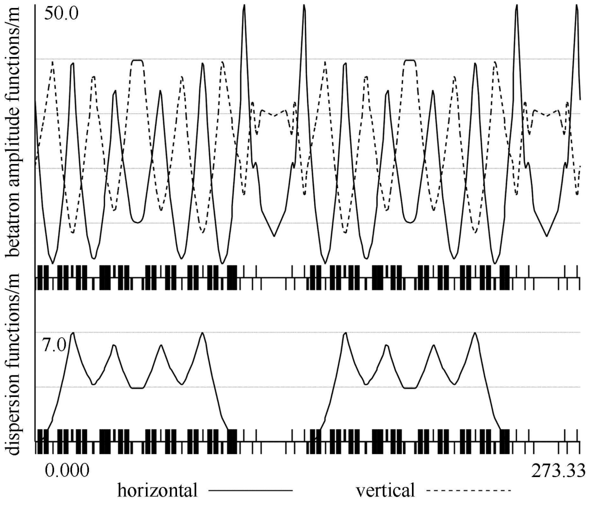

Fig. 3. The twiss function of normal.

The quadrupole is achromatic if there is a solution of

$$\frac{\mathrm{d}}{\mathrm{d}\delta}(f^{-1})=f^{-1}.$$

Usually, $\Delta P/P<1$; therefore, a quadrupole lens is almost achromatic if

$$G'/G\approx 2/D.$$

For SHER, the maximum dispersion in the arc is about 30 m, the average quadrupole strength is about 0.15 T/m^2, and so the natural chromaticity is small, which is an advantage for the dynamitic aperture.

The tune diagram for SHER is shown in Fig. 4. Due to the momentum spread, the working point is enlarged in the tune diagram and can thus cross a resonance, which can cause the loss of the beam.

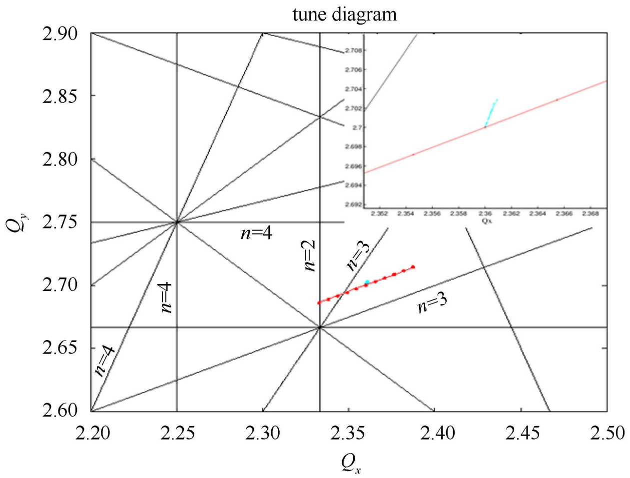

Fig. 4. (color online) The tune diagram of SHER. The resonances up to 5th order are included. Red and blue curves correspond to the working lines without and with chromaticity correction. The considered momentum spread is $\Delta p/p=\pm0.5\%$.

2.3 Dynamic aperture and tracking

The improvement of dynamic aperture starts from optimization of linear optics and chromaticity correction. In the following sections, we review the modifications, as well as all of the tracking studies that have been done by MAD-X [5] and GICOSY codes [6]. As an example, the tracking results calculated by the MAD-X code are shown in Fig. 5.

The figures show the boundary of stability in the region within which particles survived 1024 turns and the required horizontal ring acceptance of 30 πmm·mrad is much smaller than the stable region. Table 2 summarises the major parameters. Further on in the text, we will omit the word 'isochronous' because we concentrate always on the isochronous mode of the SHER ring.

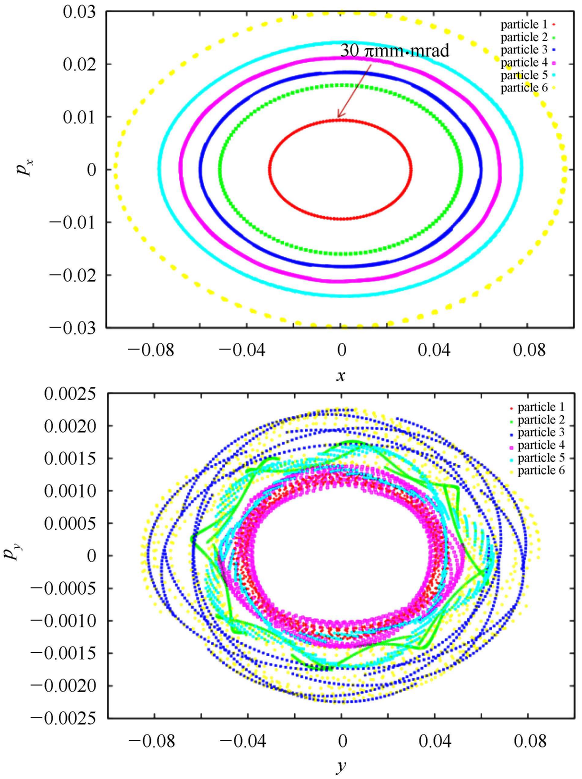

Fig. 5. Dynamic aperture of the SHER with isochronous mode.

Table 2. Summary of major parameters.

	$B\rho_{\max}$	circumference	super periodicity	x-acceptance	y-acceptance	momentum acceptance	lattice type
normal	20 Tm	273.3 m	2	70 πmm·mrad	30 πmm·mrad	3%	FODO
isochronous		273.3 m		30 πmm·mrad	30 πmm·mrad	0.9%	

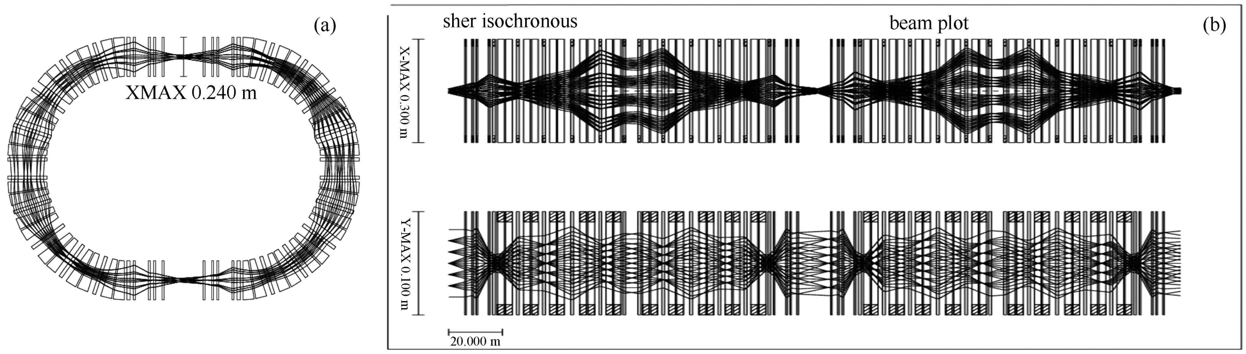

Fig. 6. Ion optical tracking simulations. The total number of starting points of trajectories is distributed equally spaced within the initially defined phase-space areas. (a) The trajectories of the beam. (b) The envelop of the beam in horizontal (up) and vertical (down) as a function of the beam path. The magnet positions are indicated along the path length.

The tracking has been done by GICOSY code in Fig. 6 with 20000 particles with the emittance 30×30 πmm·mrad. Particles started in phase space (±0.009839, ±0.003049), (±0.03267, ±0.00918), (±0.00000, ±0.00500), the number of masses is 5 and the number of energies is 5.

2.4 Injection and extraction

The SHER ring is a high acceptance ring with full aperture injection and extraction with a kickers, e-cooling system. The injection kickers should guarantee that the full ring acceptance is available for the incoming hot secondary beams, consequently the kickers are installed in the middle of the same straight section, for both injection and extraction. The trajectories of the injection beams between the first septum and the last injection kicker magnet are shown in Fig. 7. The beam envelope in the septum is 82.1 mm (for the collection mode), and 74.3 mm (for the isochronous mode), so the septum should be placed at 126.8 mm, between two quadrupoles, where the phase advance between the injection septum and the injection kicker amounts to about 90°, with COD, clearance, thickness considered. Six injection kicker modules are needed to produce a kicker angle of 12 mrad. The parameters for the septum magnet are shown in Table 3.

Table 3. Parameters for the septum magnet.

length	angle	dipole bending field	physical aperture,
1.8 m	9°	1.309 T	110 mm×60 mm

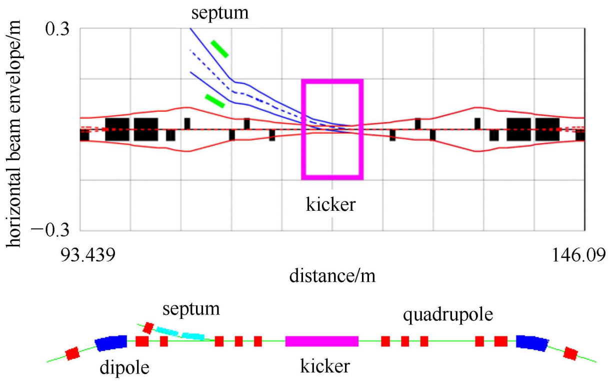

Fig. 7. (color online) Injection schemes of the beam for SHER.

3 Summary

The linear optics of the ring and the injection and extraction has been completed. By using MAD-X and GICOSY, the trace of particles is simulated and the dynamic aperture is optimized. The first order isochronous correction is completed, with precision $m/\Delta m=10^5$. However high order aberrations should be taken into consideration. There are still many aspects to be optimized; such as, the working point, which should be kept away from resonant lines for both modes. Due to the close orbit dispersion, magnetic field imperfections, and fringe fields of the magnets, the sextupole-octpole correction should be taken into consideration. In the future, further properties of the isochronous mode will be improved through the octupole corrections.

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