Simulation of loss of uranium ions due to charge changing processes in the CSRm ring*

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Abstract: Significant beam loss caused by the charge exchange processes and ion impact-induced outgassing may restrict the maximum number of accelerated heavy ions during the high intensity operation of an accelerator. In order to control beam loss due to charge exchange processes and confine the generated desorption gas, tracking of the beam loss distribution and installation of absorber blocks with low-desorption rate material at appropriate locations in the main Cooler Storage Ring (CSRm) at the Institute of Modern Physics, Lanzhou, will be performed. The loss simulation of uranium ions with electron-loss is presented in this report and the conclusion is that most charge changed particles are lost in the second dipole of the super-period structure. The calculation of the collimation efficiency of the CSRm ring will be continued in the future.

Key words: beam loss, charge exchange, CSRm, collimation

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1 Introduction

The Cooler Storage Ring (CSR) complex consists of a main cooler storage ring (CSRm), Radioactive Ion Beam line (RIB) production and transfer line two (RIBLL2), experimental storage ring (CSRe), and several experimental stations at the Institute of Modern Physics, Lanzhou. The existing Sector Focus Cyclotron (K=69) and Separated Sector Cyclotron (K=450) of the Heavy Ion Research Facility in Lanzhou (HIRFL) are used as its injector system. The heavy ion beams from HIRFL are injected into the CSRm, then accumulated, electron cooled and accelerated, before being extracted to the CSRe and other physics experiments [1]. Until now, the HIRFL-CSR has succeeded in accumulating and accelerating particles from protons to uranium ions for different physics experiments such as the radioactive electron-capture experiment, isochronous mass spectrometer precise mass measurements in the CSRe, and particle therapy experiments.The layout of the CSRm ring can be seen in Fig. 1. $^{238}U^{32+}$ ions with an energy of 1.237 MeV/u, which were accumulated by multi-turn injection and electron cooling, are chosen as the reference ions in this paper. A sufficient beam life-time for the accumulation, electron cooling and acceleration is requisite to reach high intensity machine operation.

The interaction between the ions and the residual gas, which mainly consists of H_2, CO, CO_2 and CH_4 with the 10^{-11} mbar ultra-high vacuum (UHV), can lead to a change of the charge state of the projectiles in CSRm [2]. In the presence of dispersive ion optical elements,

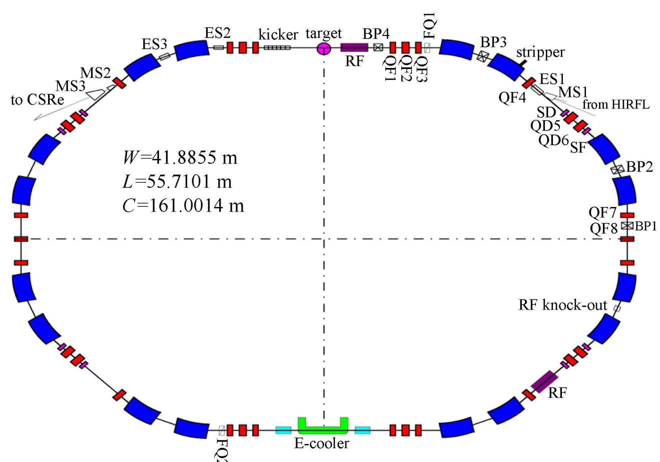

Fig. 1. (color online) CSRm ring layout.

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the trajectories of electron-loss or electron-capture particles do not match any of the reference charged states, resulting in a change of the magnetic rigidity of the particles. In consequence, the projectiles hit the vacuum chamber wall under grazing incidence, and gas which is absorbed by the wall is released [3]. Furthermore, this ion-induced desorption leads to a fast degradation of the UHV pressure during high intensity operation, which can even end up in an avalanche process and a dramatic decrease in beam life-time [4, 5].

Due to the charge change-generated beam losses and the associated produced desorption gases, a simulation of beam loss due to charge changing processes and tracking of the lost profile is indispensable in the CSRm. In Section 2, the principles of the simulation are reported. In Section 3, the simulation of the loss process is presented and discussed. In Section 4, we give our conclusions and suggest a further approach to measure the desorption rate and the dynamic vacuum to prepare for the collimation system project in the CSRm in the future.

2 Simulation principles

For the interaction between ion beams and residual gas molecules in storage rings, the cross section for electron capture dominates over the cross section for electron loss at low energy [6]. Since the collimators will in future be installed on both sides of the horizontal orientation for catching lost particles, the difference in the projectile ionization cross sections for electron-capture or electron-loss is ignored. As an example, the tracking of $^{238}U^{33+}$ with the reference charge state of $^{238}U^{32+}$ will be highlighted in this paper.

The trajectory tracking of $^{238}U^{33+}$ is simulated in the CSRm with the beta functions shown in Fig. 2 and the dispersion function shown in Fig. 3.

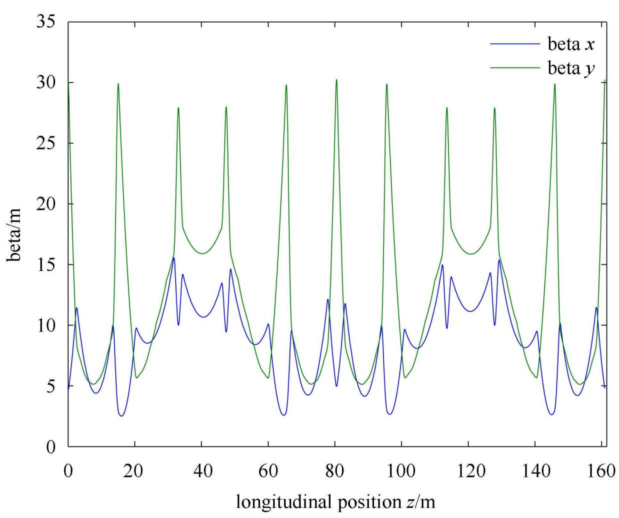

Fig. 2. (color online) Beta functions in both the horizontal and vertical plane of the CSRm ring.

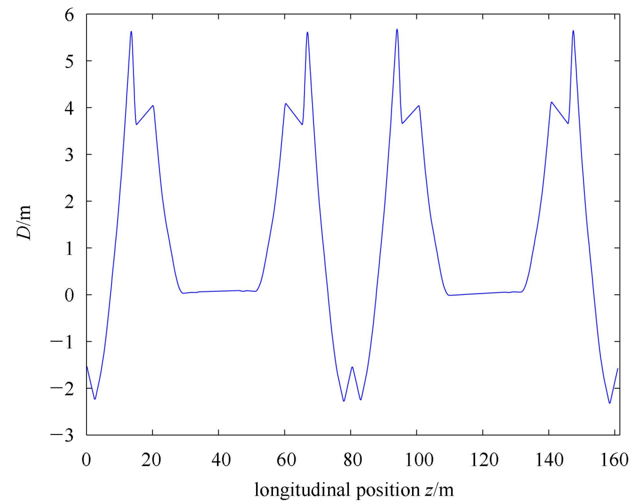

Fig. 3. (color online) Dispersion function in the horizontal plane around the CSRm ring.

The beta functions and dispersion can be calculated by a three-dimensional matrix in the transverse dimension [7]. In order to obtain more accurate beam loss positions, this program package divides each lattice element into small pieces with a certain length. For example, in this simulation, the CSRm is discretized into elements. Every element is divided into 10 parts uniformly with one $^{238}U^{33+}$ particle generated at each split point. Therefore 1200 $^{238}U^{33+}$ ions are generated at 1200 discrete locations along the whole ring. The generated particle at each point can be set in this simulation code. Each $^{238}U^{33+}$ particle is generated with random transverse coordinates and momentum offset on accurate matching to the lattice parameters in the 3σ Gaussian distribution at the generated points [8]. Specific parameters of the reference ions are listed in Table 1.

Table 1. Beam parameters adopted in the simulation.

parameter	value
circumference/m	161.0014
energy of referenced U^{32}+ions/(MeV/u)	1.237
horizontal physical admittance 4σ/(πmm·mrad)	150
horizontal physical emittance 3σ/(πmm·mrad)	84
vertical physical admittance 4σ/(πmm·mrad)	75
vacuum pressure/mbar	3.0×10^{-11}
momentum spread	0.2×10^{-3}
momentum offset	3.1×10^{-3}
tune values(Q_x/Q_y)	3.695/2.73
dipole/mm^2	140×60
quadruple/mm^2	160×100
drift/mm^2	160×100

The Gaussian distribution can be formed by the Box-Muller method. The Gaussian distribution ζ can be written as

$$\zeta=\sqrt{-2\ln\zeta_1}\sin2\pi\zeta_2. \quad (1)$$

where ζ_1 and ζ_1 represent the uniform distribution between 0 and 1. The Gaussian distribution matching the lattice parameters can be written as

$$x_\beta=\sqrt{\frac{\epsilon}{\gamma}}\zeta_1-\frac{\alpha}{\gamma}\sqrt{\frac{\epsilon}{\beta}}\zeta_2. \quad (2)$$

$$x'_\beta=\sqrt{\frac{\epsilon}{\beta}}\zeta_2. \quad (3)$$

where x_β and x'_β represent the particle's horizontal position and radian, respectively [9]. The deviation of the m/q ratio of a particle with a different charge state q compared to a reference ion with the charge state q_0 is equivalent to a momentum deviation $\Delta p/p$ of

$$\frac{\Delta p}{p}=\frac{q_0}{q}-1. \quad (4)$$

For the one electron-loss particles $^{238}U^{33+}$, transmission in the lattice is simulated by adding $\Delta p/p$=(32–33)/33 to the relative momentum offset, compared to which the initial momentum offset can be neglected [10].

Within the scope of the horizontal available aperture, all the particles are tracked from their respective generated points along the whole lattice separately according to a three-dimensional transfer matrix in transverse beam dynamics [7]. Some complicated elements such as sextupole, kicker and so on are replaced by simple horizontal ones and the vacuum pressure keeps constant in the simulation. During the simulation, the tracking of particles beyond the available rectangular aperture is stropped and the particle number is counted at the loss position. However, the simulations for ions with large vertical emittance which may go beyond the vertical acceptance of the ring during the injection are not considered in this calculation.

The trajectory of the lost particles is plotted only within the available machine apertures according to the design reports [11], which are also listed in Table 1.

The trajectories of generated $^{238}U^{33+}$ ions in the first quadrant of the CSRm ring are illustrated in Fig. 4.

The particles generated at large dispersion points will have large offsets between the initial generation point and the next transfer point, due to the large momentum offset.

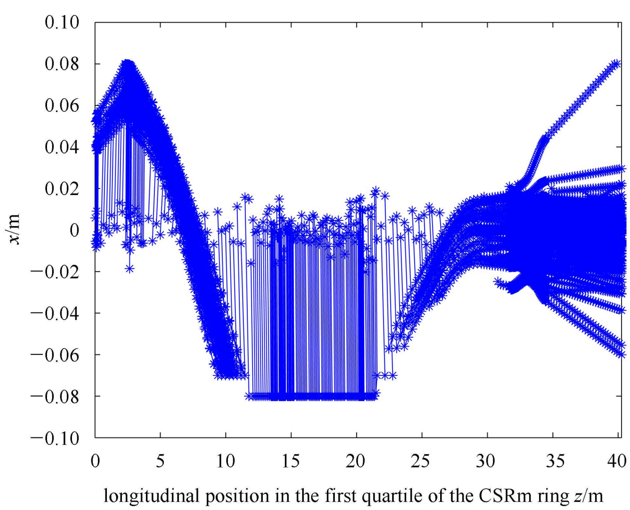

Fig. 4. (color online) $^{238}U^{33+}$ ion tracks from the points of creation until loss.

3 Calculation of beam loss distribution for $^{238}U^{33+}$ ions

The generation points and the loss position of the lost particles can be counted. Meanwhile, the trajectories of the lost particles can be tracked. Particles which are beyond the available rectangular aperture in the transverse dimension will be counted at the longitudinal position during the simulation and then the tracking is also stopped. Thus, the beam loss distribution of the $^{238}U^{33+}$ ions is calculated and shown in Fig. 5 for the first turn in the CSRm. The horizontal ordinate represents the position in CSRm, the vertical ordinate represents the number of $^{238}U^{33+}$ ions lost and the horizontal aperture of the dipole (blue) and quadruple (red), respectively. The focusing quadruples are plotted in the upper part of the plot with the defocusing ones below and the drift spaces are replaced by straight lines in the drawing of the CSRm lattice in Fig. 5.

The phenomena and results observed from the figure are summarized as follow:

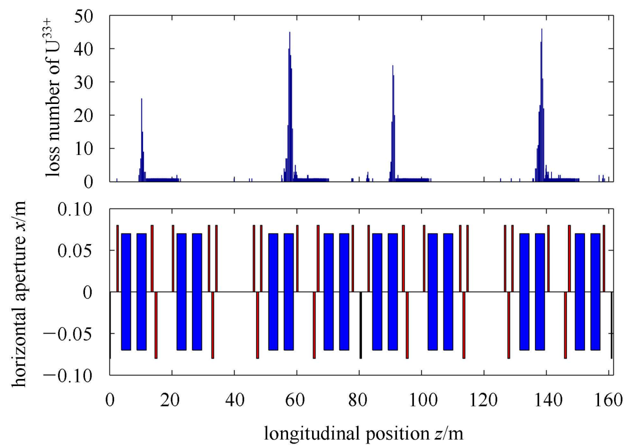

Fig. 5. (color online) Beam loss distribution of the $^{238}U^{33+}$ ions in the CSRm lattice assuming constant pressure around the ring.

1) Most charge changed particles are lost during their first loop in the ring.

2) Most charge changed particles are lost in the second dipole of the four super-period structures.

3) The charge changed particles generated in the straight drift section, with a large dispersion between the second and third dipole in every super-period structure, will mostly all be lost in the straight section before reaching the adjacent bending magnet.

4) The charge changed particles generated in the dispersion free sections are lost in the second dipole in the following super-period structure.

5) The charge changed particles generated at the last two dipoles of the super-period structure are mostly lost in the second dipole of the following super-period structure, with a few lost in the dispersion free straight section or the focusing quadruples right behind it.

6) Once the loss profile of the particles can be calculated, locations of low outgassing collimators can be made more valid and efficient by setting them in places where large numbers of particles are lost, so the collimation efficiency can also be improved [7].

4 Conclusion and future plan

The loss distribution of one electron-loss $^{238}U^{33+}$ ions with the reference $^{238}U^{32+}$ ions has been calculated around the CSRm. The corresponding randomly generated particles along the longitudinal positions are tracked. The conclusion is that most charge changed particles are lost in the second dipole of the super-period structure. The loss profile of $^{238}U^{33+}$ ions provides a possible way for the effective locations of low outgassing collimators and also provide a theoretical basis for testing and installation of the collimators in the CSRm.

This work will be continued with the probable installation of low outgassing collimators in the following calculation. The collimation efficiency can be calculated by obtaining the ratio of the number of particles hitting the collimators divided by the total number of lost particles [2]. In future, further work will continue on desorption measurements with the prototype collimator and coupling of the simulation to the dynamic vacuum problem.

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