THE STUDY OF ACCEPTANCE AND THE TRANSMISSION EFFICIENCY OF SEPARATED SECTOR CYCLOTRON

by

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In this paper we present the study of the transversal and longitudinal acceptance and the transmission efficiency in the injection, acceleration, and extraction systems in the separated sector cyclotron of the heavy ion research facility in Lanzhou, China. The study of cyclotron acceptance is done for $^{238}U^{36+}$ with energy of 97 MeV/u and for $^{70}Zn^{10+}$ with energy of 5.62 MeV/u under the theoretical isochronous and real magnetic field distribution. From the simulation results it can be seen that the transmission efficiency and the acceptances of separated sector cyclotron can be improved by redesign the curvature of MSI3 deflector or by introducing the magnet shim in MSI3 deflector region to change the distribution of the inner magnetic field.

Key words: emmitance, acceptance, transmission efficiency, separated sector cyclotron

INTRODUCTION

The separated sector cyclotron (SSC) is the main accelerator of the heavy ion research facility (HIRFL) in Lanzhou [1]. Presently higher beam intensity and quality are required to perform higher level experiments. In the view of existing conditions, the accelerator system needs to be upgraded to satisfy physical requirements, where the key issue is the SSC of HIRFL. The low beam transmission efficiency of SSC and the existing beam intensity of SSC injector – the sector focused cyclotron (SFC) [2, 3] limited the beam intensity of SSC. As a result of the above reasons, the Institute of Modern Physics (IMP) of the Chinese Academy of Science (CAS) planned to build a new linear injector (SSC-LINAC) [4] to get higher intensity beam for heavier elements. Up to today only in two places in the world it is possible to study the exotic nuclei inside the storage rings, at the centre for heavy ion research (GSI) [5], Darmstadt in Germany and at IMP, Lanzhou in China which has just started operation.

So the transverse and longitudinal acceptance is calculated under the theoretical isochronous magnetic field model and the real one, and it provides important parameters for SSC-LINAC. In addition, the simulation results will help in machine commissioning and the upgrade of HIRFL.

SEPARATED SECTOR CYCLOTRON

The separated sector cyclotron is four 52° sectors [6] (fig. 1) with energy constant K = 450. It is multi-ion, variable energy machine which accelerates ions from carbon to uranium with maximum energies of about 100 MeV/u for light ions and 5 MeV/u for heavy ions. The main parameters of the SSC are presented in the tab. 1 and the layout of the SSC is shown

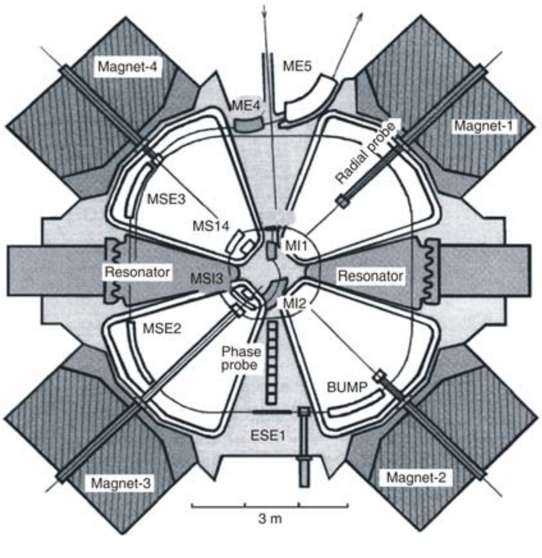

Figure 1. The overall layout of SSC

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Table 1. Main parameters of the SSC

Average injection radius	1.00 m
Average ejection radius	3.21 m
Radial betatron frequency	1.087-1.202
Vertical betatron frequency	0.742-0.864
Number of sectors	4
Angular width of sector	52 deg
Gap of the magnetic pole	10 cm
Maximal magnetic field	1.6 T
Compensation coil	36 pairs
Frequency range	6.5-14 MHz
Number of resonators	2
Angular width of resonator	30 deg
Maximal voltage	80-250 kV
RF power	2 x 120 kW
Harmonic number	2-10
Acceleration aperture	5 cm

in fig. 1. It shows four sector magnets, the injection (ESI5, MI1, MI2, MSI3, MSI4) and the extraction (ESE1, MSE2, MSE3, ME4, ME5) systems of SSC and two RF cavities.

The relations between the magnetic field and the revolution frequency at the extraction radius are shown in fig. 2.

The injection beam goes through the acceleration gap two times before injected into the first orbit. It causes an increase of magnetic rigidity and about 7° of phase shift. The perturbation field of bending magnets and stray field outside the magnetic channels are compensated by shims and trim coils, respectively.

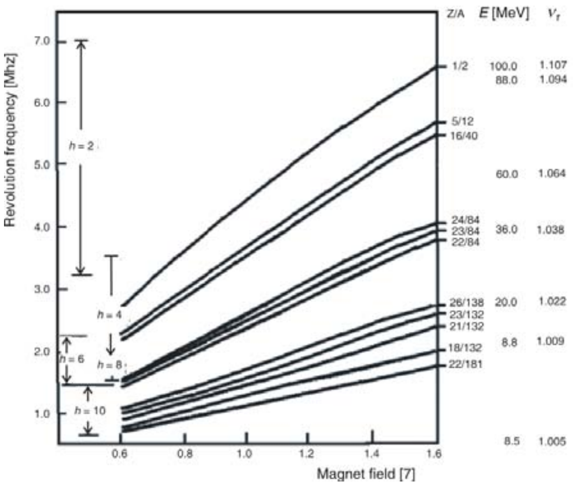

Figure 2. Relations between the magnetic field and the revolution frequency at the extraction radius; *Z, A* – the charge and mass number; *E* – beam energy in MeV/u; *h* – harmonic number

RESULTS

The study of SSC acceptance is done under the theoretical and the real magnetic field distribution. The radial and the azimuthal distributions of the theoretical and real magnetic fields are presented in fig. 3. The real magnetic field distribution is not measured directly, but it is build with the existing magnetic field parameters by using the method described in [7-9]. The theoretical isochronous magnetic fiels distribution is the hyperbolic secant function [7-10].

The study of SSC acceptance are done under the theoretical and real magnetic field distribution for $^{238}\text{U}^{36+}$ with energy of 9.7 MeV/u and for $^{70}\text{Zn}^{10+}$ with energy of 5.62 MeV/u [6]. The results are presented in figs. 4 and 5.

The radial (ε_x) and axial (ε_y) r. m. s. emittances of the beam are defined as [11]

$$\varepsilon_x \quad 4\sqrt{x^2 \qquad x^{\ 2} \qquad x\ x^{\ \ 2}} \tag{1}$$

$$\varepsilon_y \quad 4\sqrt{y^2 \qquad y^{\ 2} \qquad y\ y^{\ \ 2}} \tag{2}$$

where < > means the average value; *i. e.*:

$$x^2 \quad \frac{1}{N}\sum_{i\ 1}^{N} x_i^2 \qquad x^{\ 2} \quad \frac{1}{N}\sum_{i\ 1}^{N} x_i^{\ 2}$$

$$y^2 \quad \frac{1}{N}\sum_{i\ 1}^{N} y_i^2 \qquad y^{\ 2} \quad \frac{1}{N}\sum_{i\ 1}^{N} y_i^{\ 2} \tag{3}$$

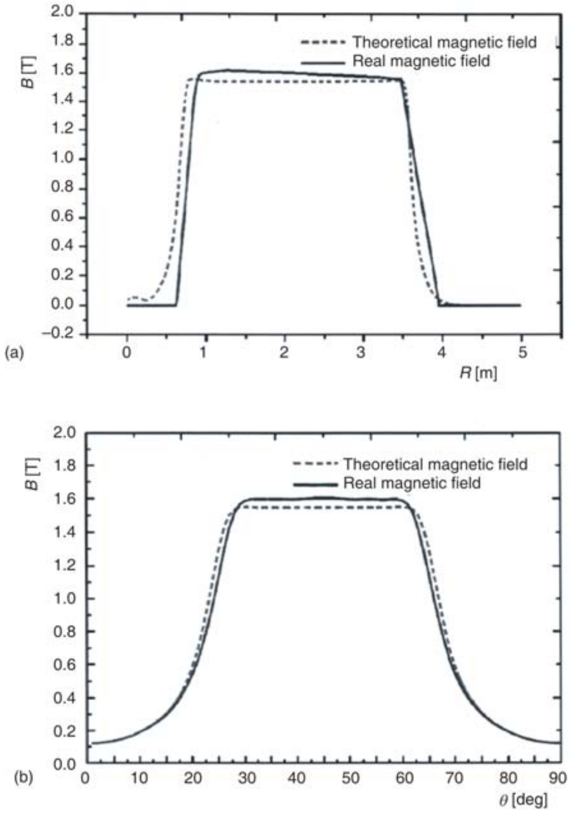

Figure 3. The radial (a) and the azimuthal (b) distributions of the theoretical and real magnetic fields

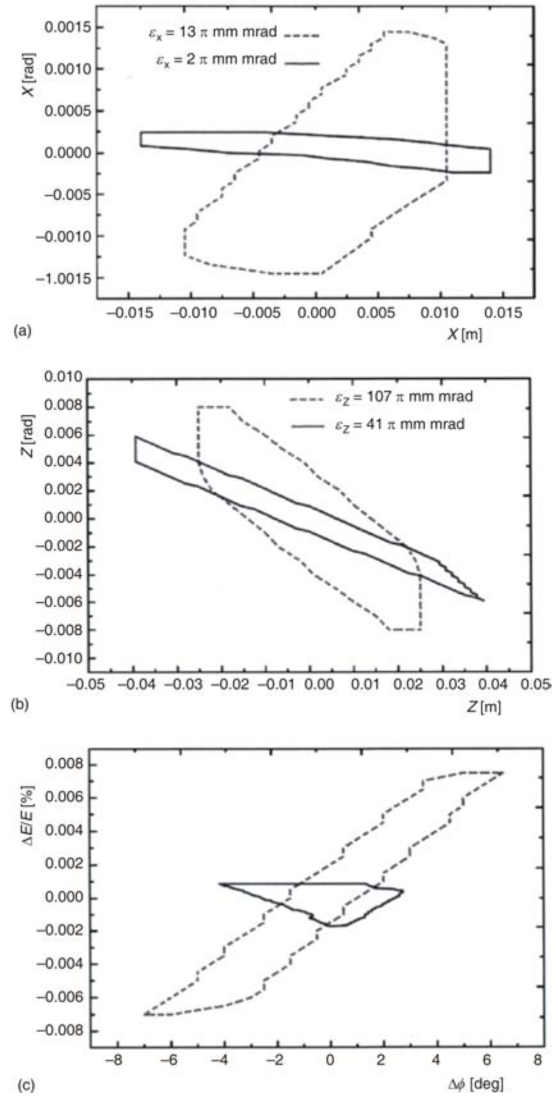

Figure 4. Phase space portraits of SSC in the theoretical (dashed line) and real (full line) magnetic field in the case of $^{238}U^{36+}$ with energy 9.7 MeV/u; radial phase space (a), axial phase space (b), and longitudinal phase space (c)

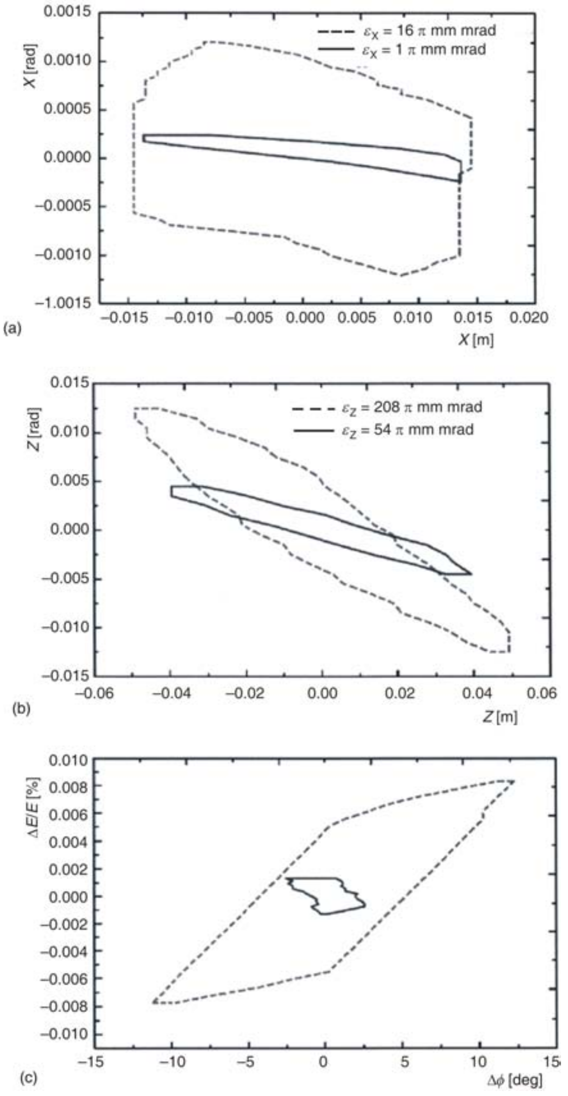

Figure. 5. Phase space portraits of SSC in the theoretical (dashed line) and the real (full line) magnetic field in the case of $^{70}Zn^{10+}$ with energy 5.62 MeV/u; radial phase space (a), axial phase space (b), and longitudinal phase space (c)

In eq. (3), N is the number of points in the phase space with co-ordinates (x_i, x'_i) and (y_i, y'_i) which represents the particles in the beam. In figs. 4 and 5 only the contour of the points in the phase space which corresponds to the transmitted particles is presented. The values of the emittances for this case, see eqs. (1) and (2), are considered then as the acceptance of the machine.

Figure 4 shows the phase space portraits of SSC in the theoretical (dashed line) and the real (full line) magnetic field in the case of $^{238}U^{36+}$ with energy 9.7 MeV/u. The upper part of fig. 4. shows the radial phase space; the middle part shows the axial phase space and the lower part of fig. 4 shows the area in the longitudinal phase space. From this figure it can be seen that the radial acceptance is 13 mm mrad (for the theoretical magnetic field) and 2 mm mrad (for the real magnetic field); the axial acceptance is 107 mm mrad (for the theoretical magnetic field) and 41 mm mrad (for the real magnetic field); the energy spread is and the phase is from –7° to +7° (for the theoretical magnetic field) and 0.002% and –4° to +3° (for the real magnetic field).

Figure 5 shows the phase space portraits of SSC in the theoretical (dashed line) and the real (full line) magnetic field in the case of $^{70}Zn^{10+}$ with energy 5.62 MeV/u. The upper part of fig. 5 shows the radial phase space; the middle part shows the axial phase space and the lower part shows the area in the longitudinal phase space. From this figure can be seen that the radial acceptance is 16 mm mrad (for the theoretical magnetic field) and 1 mm mrad (for the real magnetic field); the axial acceptance is 208 mm mrad (for the theoretical magnetic field) and 54 mm mrad (for

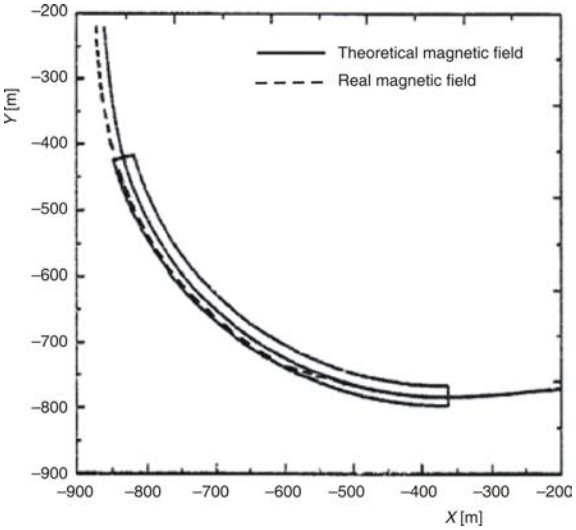

Figure 6. The central particle orbit simulation through MSI3 deflector in the case of $^{238}U^{36+}$ with energy of 97 MeV/u

the real magnetic field); the energy spread is and the phase is from –10° to +10° (for the theoretical magnetic field) and and –2° to +2° (for the real magnetic field).

From our simulation of SSC acceptance it can be seen that the acceptance under the real magnetic field distribution is much worse than in the case of the theoretical isochronous magnetic field distribution. The reason for that is the big loss of particles through MSI3 deflector (see fig. 1.). Namely, in the simulation of central particle tracking through the MSI3 deflector can be seen that the orbit of central particle is not properly centered in the case of real magnetic field distribution (fig. 6 – dashed line) as it is in the case of the theoretical isochronous magnetic field distribution (fig. 6 – full line). At the present state of SSC the transmision efficiency is very low; less than 20%. The results show that the actual efficiency and acceptances of SSC can be improved by redesign the curvature of MSI3 or by changing the distribution of the inner magnetic field (for example by shim of magnet in MSI3 deflector region). According to our calculation after improvement in the design of the curvature of MSI3 deflector the transmission efficiency is ~95%.

CONCLUSION

From the simulation results it can be seen that the orbit of central particle in MSI3 deflector in the case of the real isochronous magnetic field is not good and most particles are lost in MSI3 deflector. The transmission efficiency of SSC is less than 20%. This default of good design of MSI3 deflector is the main reason of low acceptances and transmission efficiency of SSC. The transmission efficiency and acceptances of SSC can be improved by redesign the curvature of MSI3 deflector or by shim of magnet in MSI3 deflector region to change the distribution of inner magnetic field.

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AUTHOR CONTRIBUTIONS

Calculations were carried out by X. Li and D. Toprek under supervision and guidelines of Y. Yuan and Y. He. All authors discussed the result. Manuscript was written by X. Li and D. Toprek and reviewed by Y. Yuan. Figures were prepared by X. Li and D. Toprek.

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СТУДИЈА АКСЕПТАНСЕ И ЕФИКАСНОСТИ ТРАНСПОРТА КОД ЦИКЛОТРОНА СА РАЗДВОЈЕНИМ СЕКТОРИМА

У овом раду приказана је студија трансверзалне и лонгитудиналне аксептансе и ефикасност трансмисије инјекционог, убрзавајућег и екстракционог региона циклотрона са раздвојеним секторима у Институту за тешкојонска истраживања у Ланчоу, Кина. Студија је урађена за јоне $^{238}U^{36+}$ енергије 9.7 MeV/u и $^{70}Zn^{10+}$ енергије 5.62 MeV/u у случају теоријске изохроне и стварне дистрибуције магнетског поља. Из симулационих резултата може се видети да се аксептанса и трансмисиона ефикасност циклотрона може побољшати заменом постојећег MSI3 дефлектора или шимовањем магнетског поља у региону MSI3 дефлектора како би се променила дистрибуција магнетског поља.

Кључне речи: емитанса, аксептанса, трансмисиона ефикасност, циклотрон са раздвојеним секторима