Chinese Physics C Vol. 37, No. 3 (2013) 037001

Beam transmission efficiency of the HIRFL-SSC

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Abstract: In this paper we address the problem of the low beam transmission efficiency of the HIRFL-SSC. The influence of the SFC-SSC energy match, the SSC RF voltage, and harmonic field in the injection area of the SSC, and the SSC central trajectory on the beam transmission efficiency have been analyzed both from the theoretical side and from the actual operating data. The main reason is that the soft-edge approximation of the magnet field (the so-called theoretical field) and the simplified calculation programs were adopted when calculating the beam center trajectory and designing the injection and extraction system, and the measured magnetic field was not used to correct the calculation results. These led to large deviations of the calculated center trajectory, and then resulted in low efficiency of the SSC beam transmission. Therefore, the re-calculation of SSC beam center trajectory and injection and extraction system, as well as the measured magnet field correction are the key points required to solve the problem.

Key words: beam transmission efficiency, beam central trajectory, injection and extraction system, soft-edge approximation, measured magnet field correction

PACS: 29.20.dg **DOI:** 10.1088/1674-1137/37/3/037001

1 Discussion of several factors affecting beam transport efficiency

The maximum beam transmission efficiency of the HIRFL-SSC is less than 25% in daily operation for long time, while the efficiency of the same type of accelerators such as GANIL in France and RIKEN in Japan is often more than 90%. The reasons for the low beam transmission efficiency have been much debated. Some people thought that the SFC-SSC energy matching, the SSC RF voltage, and a harmonic field on the SSC injection areas would be the main reasons for the low beam transmission efficiency. The first harmonic field is caused by the added edge shim in sector magnet B, C near the Mi2, resulting in an over compensation of about 50–150 Gauss (corresponding to the main magnetic field 0.6–1.7 T) in the small radius (100–130 cm) of sector B and C, so causing the perturbed fields.

DING Yuan-Tao [1] used the programs adopted in the SSC injection and extraction system design to calculate the SSC energy acceptance range and SSC injection efficiency, respectively, for the typical ions of O^{8+} −100 MeV/u, Ar^{15+} −25 MeV/u, and Xe^{22+} −4.8 MeV/u. The calculation had been done in the three cases, that is the centralized trajectory at the theoretical field, centralized trajectory in the large radius at perturbed field, and non-centralized trajectory at the perturbed field at different RF voltage. The results are shown in Table 1. Data show that in addition to the O^{8+} −100 MeV/u accelerated at an RF voltage of 120 kV of the extreme cases to ensuring the injection efficiency, the energy acceptance range of the SSC is more than ±1%. For heavier ions than Ar, the energy acceptance range is between −4.6% and 2.27%. A harmonic field (perturbation field) in a small radius region causes a certain degree of beam precession; the impact on different ions is quite different. For light ions with higher energy, such as the O^{8+} −100 MeV/u, the influence is large. When giving up the beam centralized requirements, about 30% of the beam can enter into the accelerated orbit. When the RF voltage is 230 kV, the beam precession increases the acceptance range, and the efficiency can be of 70%. For the Ar^{15+} −25 MeV/u and other heavier ions, the beam orbit spacing is larger, the beam quickly turns out from the small radius area, the perturbed field has little effect, and the great energy acceptance range and high beam injection efficiency can be obtained. The SSC is an accelerator for the acceleration of C-U ions; accelerated ions heavier than Ar are the main acceleration particle species.

The test results of RF voltage and the facts found from many years running proved that the RF voltage of the SSC basically meet the design requirements. On Nov. 22, 2001, an experiment of the accelerating RF voltage influence on the beam extraction efficiency was carried out. The accelerated ion is $^{18}O^{8+}$ −65 MeV/u.

Received 10 October 2011

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Table 1. Acceptance range of energy and the injection efficiency for typical ions in different situations of the HIRFL-SSC.

typical ion	RF voltage /KV	centralized trajectory at Theoretical field		centralized trajectory in the large radius at perturbed field		non-centralized trajectory at perturbed field	
		injection energy $\Delta W/W$	injection efficiency	injection energy $\Delta W/W$	injection efficiency	injection energy $\Delta W/W$	injection efficiency
O^{8+} −100 MeV/u	230	−2.44%–4.94%	100%	−1.0%–2.8%	100%	−2.0%–4.0%	100%
	120	−1.12%–4.5%	50%	0	0	0	30%
						3.0%	70%
Ar^{15+} −25 MeV/u	120	−4.76%–3.88%	100%	−4.6%– 3.4%	100%	—	—
Xe^{22+} −4.8 MeV/u	51	−5.38%–3.53%	100%	−5.17%–2.27%	100%	—	—

The RF frequency was 10.20255 MHz. When the RF voltages were 100 kV, 110 kV, 120 kV, 130 kV, respectively and the ESi5 parameter and other injection element parameters had been adjusted carefully, the extraction beam intensity was not changed significantly.

Other research [2, 3] on IMP on the beam transmission efficiency of the SSC share the same viewpoint for most of these problems. Based on the above discussion it is clear that the energy matching, the RF voltage of the SSC, and the harmonic field in the injection area are not the main reason for the low beam transmission efficiency of the SSC. After years of deep study, the results show that the large deviation of the beam center trajectory is the main reason causing low beam transmission efficiency for the SSC.

2 Reasons for beam center trajectory deviation and the consequences

2.1 Hard-edge theory, soft-edged approximation and the measured magnet field correction

As we know, in a separated sector cyclotron, for an ion of mass A with the given energy, $\langle B\rangle = f(A, Z, f_{\text{rev}}, K_{\text{b}})$, where Z is the charge state; K_{b} is a coefficient of $K_{\text{b}}-K_{\text{r}}$ method.

Obviously, the distribution of the magnetic field has a great significance for the study and design of a cyclotron. The magnet field maps also play a decisive role for beam transmission efficiency.

In the absence of the actual magnetic field, one can easily study the beam dynamics and take accelerator design by using the hard-edge approximation theory and soft-edge approximation theory. The soft-edge approximation method could be employed to build a basic magnetic field instead of the actual magnetic field and then get the isochronous magnetic field with required accuracy.

Although the magnetic field of the soft-edge approximation is closer than one of the hard-edge approximation to the measured magnetic field, due to the limitations of the soft-edge calculation method, the results often do not fully reproduce the actual magnetic field distribution. Therefore the difference between the calculation results and the actual ones may be large. When actual magnetic field measurements are performed, the isochronous field can be built with the measured magnet field maps for the accelerated ions. It is worth emphasizing that the so-called theoretical magnet field is not a theoretical ideal target in itself but only an approximation. An isochronous field built with the measured field maps is our goal field. Therefore one needs to correct the calculations of the central trajectory and injection and extraction system by using the soft-edge approximation method with the measured magnetic field maps. This is the so-called measured magnet field correction.

2.2 SSC beam center trajectory calculation

The existing center beam trajectory calculation and the design of injection and extraction system for the SSC were carried out by using a group of GANIL initial programs in the following steps: (1) calculating the basic parameters of several typical ions by using the Abacus program; (2) using the Syn program to establish a basis field, which is the normalized field based on a soft-edge approximation method; (3) establishing an isochronous field by using the Iso program; (4) changing an isochronous field of one sector into one of the four sectors with the Cour program; (5) calculating the beam center trajectory and the relevant parameters of injection and extraction system elements, as well as others, with the Acc program.

It should be pointed out the magnetic field distribution of a separated sector cyclotron is very complicated. In this case, the results of the calculation with only the soft-edge approximation method to get the magnet field distribution will be affected by the basic mechanical parameters of the sector magnet only. So we can say that the program group is too simplified. The difference of the inhomogeneous ambient field for two types of injection and extraction elements (bending magnet and inductive septum) and the difference of the interaction between the magnet field of injection and extraction elements and the ambient field are not considered in detail. In addition, the measured magnet field correction was also not carried out. The results deviate from the optimized beam trajectory and the parameters of the injection and extraction system elements, which meets the requirements of the actual magnet field, and consequentially lead to the low beam transmission efficiency.

2.3 Magnet field calculation causing the deviation of the beam center trajectory for the SSC

The soft-edge approximation method is very easy to use in many cases. However, the result may be very different for different sector cyclotron magnet designs.

The HIRFL-SSC isochronous magnetic field is created by using the K_b-K_r method. It is defined as following:

$$K_{\mathrm{b}}(r_{\mathrm{axis}},B_0) = B_{\mathrm{axis}}/\langle B\rangle,$$

$$\text{which}\langle B\rangle = \oint_{\mathrm{E.O}} B(s)\mathrm{d}s \,/\oint_{\mathrm{E.O}} \mathrm{d}s\,,$$

$$K_{\mathrm{r}}(r_{\mathrm{axis}},B_0) = r_{\mathrm{axis}}/\langle r\rangle,\ \text{which}\langle r\rangle=1/2\pi\cdot\oint_{\mathrm{E.O}} \mathrm{d}s.$$

It can be seen that the K_{b} will affect the magnetic field distribution strongly. The shape of the main magnet edge of the HIRFL-SSC is curved, while in the designing calculation a straight-edge type was used, which has a greater difference with the actual situation.

The actual K_{b} is 1.74490 in radius of 104 cm region at the main magnet field of 14KG, which was measured in 1984 for the SSC. Unfortunately it has not been used for the correction.

We use three methods to calculate the influence of the measured K_{b} on the distribution of the real magnetic field in the injection region.

(1) K_b direct comparison method based on the existing calculation of the central trajectory for 100 MeV/u $^{16}O^{8+}$. The valley center-line R of injection equilibrium orbit is 92.628 cm, which corresponds to the location of the center-line of the sector being about 104 cm, and the K_b is 1.668635. Comparing with the actual K_b value of 1.74490 the $\Delta K_{\mathrm{b}}/K_{\mathrm{b}} \approx 4.37\%$. Because K_{b} (r_{axis}, B_0)=$B_{\mathrm{axis}}/\langle B\rangle$, if $\langle B\rangle$ is fixed, B_{axis} is proportional to the K_b value. In this case, the B_{axis} difference is about 4.37%.

(2) Magnetic angle comparison method

As we know, K_b is defined as following:

$$K_{\mathrm{b}}(r_{\mathrm{axis}},\ B_0) = B_{\mathrm{axis}}/\langle B\rangle,$$

$$\text{which } \langle B\rangle = \oint_{\mathrm{E.O}} B(s)\mathrm{d}s/\oint_{\mathrm{E.O}} \mathrm{d}s.$$

The magnetic angle is defined as following:

$$\theta_{\mathrm{m}}=\frac{1}{B(r_{\mathrm{axis}},0^\circ)}\int_{-45^\circ}^{45^\circ} B(r_{\mathrm{axis}},\theta)\mathrm{d}\theta,$$

where 0° is the sector magnet center-line. The following formula can be deduced according to the definition of K_{b}:

$$\theta_{\mathrm{m}}=90^\circ/K_{\mathrm{b}}.$$

We call this formula the effective magnetic angle discriminator.

According to this result, the magnetic angle θ_{m1}=53.936° for the use of soft-edge approximation method, and the magnet angle θ_{m2}=51.579° for the measured magnetic field, the difference between both values is 4.37%.

(3) Using the Abacus code for direct calculation

The required parameters and variables for the calculation can be obtained by careful study and derivation of the magnet field parameters of the SSC and their relationship. The typical ion is $^{16}O^{8+}$ −100 MeV/u, for example, its injection energy is 8.4698 MeV/u, $B\rho$ (in)=0.83989 Tm, f (rf)=12.7820 MHz. The calculation results use the soft-edge approximate method and by using the measured magnet field the correction can be obtained. The results show that the difference of the magnetic field values for the injection point and extraction one are of ΔB (in)=577.2 Gauss and ΔB (out)=633.4 Gauss, respectively. The difference is 4.12%.

2.4 Difference between the soft-edge approximated distribution and the measured field one

In order to provide real magnet field data, nearly a year of magnetic field measurements (including the unperturbation and the perturbation magnet field maps), trimming coil efficiency measurements, and isochronous field trimming of the SSC were done. The measured data show that the measured magnet maps are clearly different from the magnet distributions from the soft-edge approximation, especially in the central region (R is less than 1 m) where the field distribution is very complex. For example, for the R and θ direction magnet field distribution of the main magnetic field (see Fig. 1) the measured result and the calculated one by using soft-edge approximation are very different not only in a small radius and the edge area of the magnet, but also in the central part.

2.5 Consequences of the central trajectory deviation for the SSC

In heavy ion accelerators, if the ion energy is W, the magnetic rigidity G=$B\rho$, then

$$B\rho=A[W(W+2E_0)]^{1/2}/Zec.$$

Where $E_0=931.478$ MeV/u, A is atomic number, Z is the charge state.

When $v\ll c$, the above equation can be expressed as

$$W=48(B\rho)^2Z^2/A.$$

From the formula, the following relationships can be derived: $\mathrm{d}W/W=2\cdot\mathrm{d}B/B$, $\mathrm{d}W/W=2\cdot\mathrm{d}\rho/\rho$.

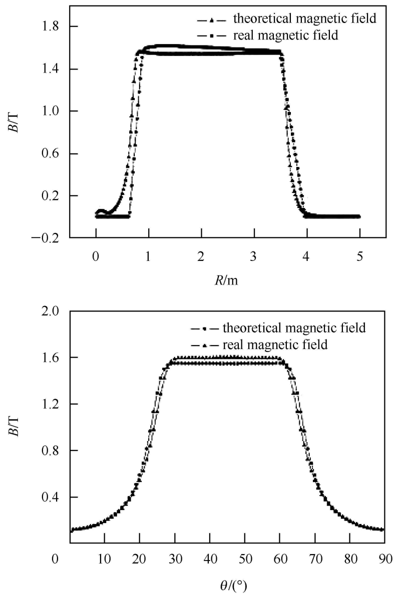

Fig. 1. R and θ direction magnet distributions of measured and soft-edge approximations.

The formula tells us that one unit variation in B or ρ will cause 2 units variation of energy W. The difference between the K_{b} value of the original calculation and the one from the measured magnetic field will produce a difference of 4.37% for the magnetic field intensity. It is obviously equivalent to cause an energy variation in the amount of 8.7%. In Table 1, one can clearly see that if the injection efficiency of 100% is requested, in the case of accelerated ions with the different energy, the maximum energy acceptance range of the SSC is not greater than ±5% (at ±1% -±5%). Thus, if $\Delta W/W$ are 8.7%, one can imagine how low the injection efficiency will be. It can be deduced that the results are applicable for the whole energy range and all accelerated ions for the SSC.

3 Deviation calculation of the central trajectory of the SSC

Several studies on the SSC beam acceptance have been carried out [2] with the theoretical isochronous field (analytical magnetic field) built by using the soft-edge approximation method and the real isochronous field established by the Kb-Kr method and the measured magnet maps, respectively. The multi-particle tracking method had been used to calculate the acceptances.

For 9.7 MeV/u $^{238}U^{36+}$ ions, the radial and axial acceptance are 13.08 π·mm·mrad and 107.27 π·mm·mrad, respectively, when the theoretical isochronous field is used. For longitudinal acceptance, the acceptance phase width is ±7° and the maximum acceptable energy range is ±0.8%. These values are consistent with the original design.

In the case of an isochronous magnet field established by using the K_b-K_r method, the radial and axial acceptances are respectively 2.33π·mm·mrad and 41.09π·mm·mrad for the 9.7 MeV/u $^{238}U^{36+}$. For the longitudinal acceptance, the phase width is ±4°, the maximum acceptable energy range is ± 0.1% only.

Second, when the 5.62 MeV/u $^{70}Zn^{10+}$ ions were accelerated in the theoretical isochronous field, their radial and axial acceptances are 16.43π·mm·mrad and 208.34π·mm·mrad, respectively. For longitudinal acceptance, the phase width is ±12° and the maximum acceptable energy region is ±0.8%. In the case of the isochronous field established by the K_{b}-K_{r} method using the measured magnet field, the corresponding values are 1.54π·mm·mrad, 54.27π·mm·mrad, ±2.5°, and ±0.13%, respectively.

From the above data it is clear that in a real isochronous magnet field built by using the K_{b}-K_{r} method, the radial acceptance is only 17% and 9.4% of the values obtained with the theoretical field, respectively. Others are far lower than the corresponding value in the case of the theoretical field.

After calculation by using single-particle tracking it was found that the beam central orbit had a great deviation from the central line in MSi3 in the case of a real isochronous field (see Fig. 2). In any case, adjusting the electromagnetic parameters of the elements could not change the facts. The results of the multi-particle tracking method show that nearly half of the beam was lost inside MSi3. Similarly the same problem occurred in MSe3. The deviation leads to low beam transmission efficiency.

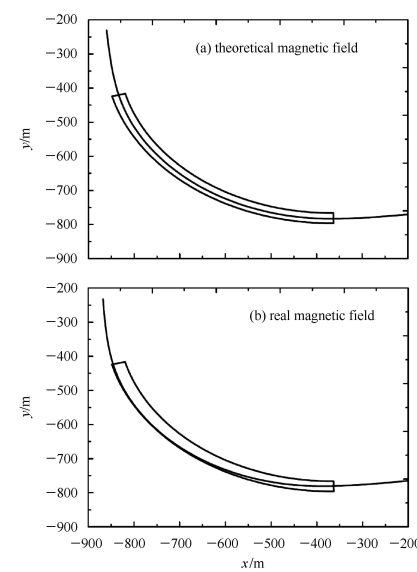

Fig. 2. Central particle orbit of MSi3 in the theoretical field and real isochronous magnet field.

Dr. HAO Huan-Feng of IMP [4] calculated the deviation of the beam central obit in injection elements MSi3 and MSi4 by using same method. In the real magnetic field the location deviations of the entry and exit end of MSi3 are 0 mm and 10.6 mm respectively, while those of MSi4 are 10.4 mm and 8.0 mm.

It should be emphasized that due to the limitating conditions the above calculations are based on Acc program. In fact, these calculations are equivalent to making a measured magnet field correction for a part of the centre trajectory calculated by Acc in a soft-edge approximate field.

These results obviously indicate that the existing beam trajectory and the injection and extraction systems do not match a real isochronous measured magnetic field, and therefore lead to a low beam transmission efficiency.

4 Discussion of several experiment issues

4.1 Relationship between the main magnetic field in the actual operation and the energy of an extraction ion

Before 2003 more than 30 different ions with different energies have been accelerated by the SSC. The operating current values of the main magnetic field power supply compared with the calculated value were about 0.8%–1.8% higher, which would lead to an increase of about 1.6%–3.6% of the accelerated ion energy, but the increase did not appear. The reason causing such a large difference is very worthy of study. The results show that the magnetic field intensity difference of injection and extraction between the values calculated by using the soft-edge approximation method and the measured magnetic field is 4.37%. In addition, if one uses the calculation method of measured magnet field correction and uses the data from the soft-edge approximation method to calculate the energy and other parameters, the extraction energy W is 92.60 MeV/u instead of the theoretical value of 100 MeV/u, $\Delta W/W \approx 7.4\%$, while $\Delta B\rho_{\rm into}/B\rho_{\rm into} \approx 3.3\%$. It also indicates that the ion magnetic rigidity (energy) from the injector SFC and the magnetic rigidity of the SSC injection point is mismatched. In other words, the injection match point of the SSC found from the calculation using the soft-edge approximation method is not appropriate.

4.2 SSC extraction energy measurement

Accurate ion energy is needed for nuclear physics experiments. Therefore, the ion energy must be calibrated. The energy of C^{6+} −46.7 MeV/u is adopted in a variety of experiments for the theoretical value of 50 MeV/u ion. The difference is of ΔW=3.3 MeV, that means $\Delta W/W$=7.0%. We take into account that the main power current in actual operation is higher than the calculated value by about 0.8% and that it in fact caused an extraction energy increase of 1.6%. Therefore the total error of extraction energy is basically the same as the theoretical calculation value of 8.7%.

5 Conclusions

From the above discussion it is clear that the energy match between the SFC and the SSC, the SSC RF voltage and the first harmonic field of the SSC are not the main reasons causing the SSC beam transmission efficiency to be so low. The initial simplified GANIL programs had been used for the calculation of central trajectory and injection and extraction system. The magnetic field distribution calculated with the soft-edges approximations method used in the design of the SSC is very different from that calculated using the real measured magnet field. The measured magnet field correction was not carried out. The above two reasons have led to the large SSC beam center trajectory deviation and the injection and extraction system element parameters. Therefore these factors affect the SSC beam transmission efficiency seriously.

The results calculated for the deviation of center trajectory and the beam acceptance of the SSC, as well as the experimental results, also confirm the existence of these problems.

Both theoretical and practical data indicate that it is necessary to recalculate the beam center trajectory and injection and extraction system parameters by using the actual programs that were used in the design and construction of GANIL, and the measured magnetic field correction should also be taken into account. This is only practical approach to increase the SSC beam transmission efficiency.

The authors would like sincerely to thank Mr. YANG Yi-Ping of IMP for many valuable discussions and providing many of the operation data. And thank Dr. HAO Huan-Feng for many helpful discussions. Also would like to thank many experts inside and outside, and the home and abroad for the care and support.

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