Chinese Physics C Vol. 37, No. 4 (2013) 047001

Recalculation of the HIRFL-SSC injection and extraction system

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Abstract: In order to further improve beam transmission efficiency at the SSC, the beam center trajectory and injection and extraction system are recalculated based on the program group used in the final design of the GANIL accelerator, with some necessary changes and the addition of some auxiliary programs. The two different types of injection and extraction elements (the bending magnet and the inductive septum) are distinguished, and their interaction with the ambient field is considered. More focus is placed on considering the differences in the magnet field inhomogeneity of the ambient field in the located area of the inductive septum where the ends are situated in the ambient field (between the main magnet poles). Thus the gradient magnetic field problem of the inductive septum is solved perfectly. As well as preparing the necessary auxiliary programs and taking the structural integration of the SSC magnetic field maps, the measured magnet field correction is completed. Therefore, the trajectory and a variety of injection and extraction system parameters are obtained. According to the recalculation results, the SSC beam transmission efficiency will be enhanced significantly.

Key words: beam transmission efficiency, beam center trajectory, injection and extraction system, measured magnet field correction

PACS: 29.20.dg **DOI:** 10.1088/1674-1137/37/4/047001

1 The SSC current injection and extraction system

The main accelerator of the Heavy Ion Research Facility in Lanzhou (HIRFL) is the Separated Sector Cyclotron (SSC) (K=450). A sketch of the injection and extraction system is shown in Fig. 1.

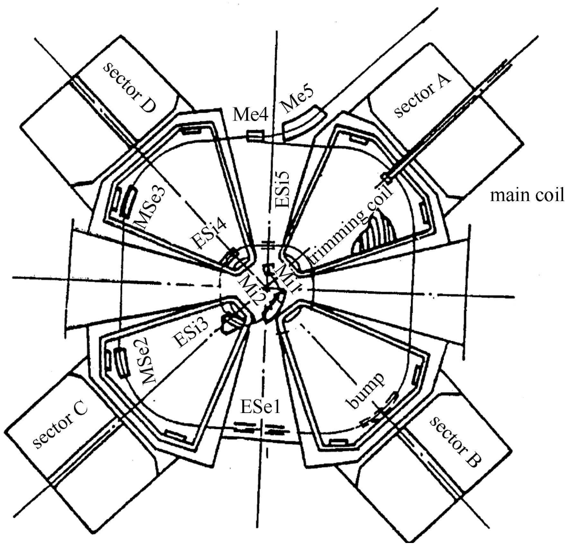

Fig. 1. The SSC injection and extraction system.

The SSC injection and extraction system was designed and constructed based on the calculation programs provided by scientists at GANIL, France, in the 1980s. The basic physical idea for the design was based on the soft-edge approximation method.

The calculation was performed using the initial program group of the Abacus, Syn, Iso, Cour and Acc to calculate the beam center trajectory and the relevant parameters of the injection and extraction system elements.

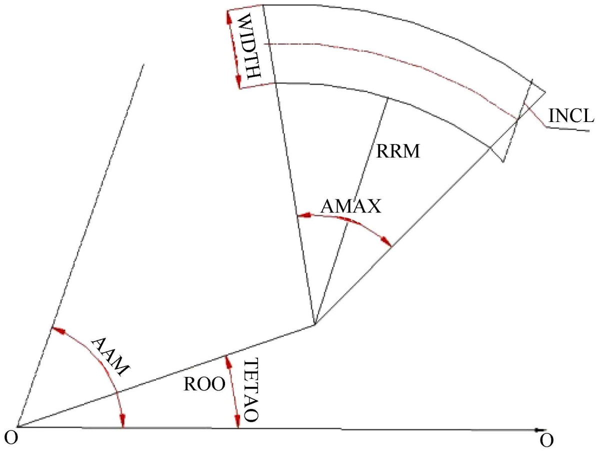

Fig. 2. Description of the defined symbol of the calculation parameters.

Received 10 October 2011

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Table 1. SSC injection system parameters.

	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	BBM/T	WIDTH/mm	INCL/(°)
Mi1	0.792	38.66	0.602	188.8	30	30	−.9347	30	10
Mi2	0.3689	231.15	0.465	330.8	30	102.5	1.225	30	0
MSi3	0.4739	219.7	0.467	232.5	30	76.0	.243	30	0
MSi4	0.4504	140.0	0.54	156.4	30	25	.0690	30	0

	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	POT/kV
ESi5	1.769	273.7^o	2.70	92.4^o	10	9	8.3

Table 2. SSC extraction system parameters.

	ROO/m	TETAO/(°)	RRM/mm	AAM/(°)	GAP/mm	AMAX/(°)	POTINT/kV	EN
ESe1	78.9525	270.45	76.0	90.47	15	1.0186	18.785	0

	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	BBM/T	WIDTH/mm	INCL/(°)
MSe2	1.418	224.68	1.9703	205.4	30	30	0.02635	30	0
MSe3	1.304	129.15	2.1779	157.97	30	30	−.103	30	0
Me4	4.8617	98.5	1.6947	278.64	30	14	−1.144	30	0
Me5	4.7724	90.86	1.4796	311.08	30	48	−1.280	30	8

A definition of the parameters used in the calculation is shown in Fig. 2. With $^{132}\mathrm{Xe}^{22+}$ as the typical ion, the calculated parameters for the injection and extraction system are listed in Table 1 and Table 2.

2 Injection and extraction system status

Since 1989, when the SSC was officially put into operation, the location of the elements in the injection system has been adjusted to try to improve beam transmission efficiency.

In March 1994, the MSi4 was moved. The mid-point of the entry and exit ends was moved 5 mm and 7.4 mm towards the center of the machine, respectively. However, debugging results showed that the movement had little effect on beam intensity.

Based on careful analysis of SSC operation and calculations of the orbit of the SSC injection system, the measured magnetic field data and K_b-K_r method were used to build the isochronous field. Hao Huan-feng et al. [1] found that the calculated value of the MSi3 and MSi4 locations was very different from the original design value. In August 2009 the position of the MSi3 exit end had been moved 10 mm to the large radius. Debugging results also showed that in certain conditions the injection efficiency did improve. However, due to the constraints of the conditions, the experiments did not proceed. Overall, the effect is not obvious.

These results also imply that neither the beam center trajectory designed in the original nor the beam center trajectory running now is the optimized one. This is the main reason for the very low beam transmission efficiency.

3 The main problems of the existing injection and extraction system

After a thorough study, we [2] believe that the main problem is that the deviation in the designed parameters for the beam center trajectory and the injection and extraction system from the exact one is too large. The reason for this is that firstly an early version of the GANIL calculation program was used in the design of the injection and extraction system, and the program group is based on a soft-edge approximate magnetic field (analytical magnetic field). The different inhomogeneity of the ambient field of the area where the injection and extraction system elements are located and the different interaction between the ambient field and the magnet field of different types of elements were treated simply. Secondly, the main magnetic field changes caused by the curved edge of the main magnets were not considered and the measured magnetic field correction was not carried out at all.

4 The basic physical ideas of injection and extraction system design

It is well known that the basic motion equations of charged particles in a magnetic field is as follows

$$\frac{\mathrm{d}(m\vec{v})}{\mathrm{d}t}=q\vec{E}+q\vec{v}\times\vec{B}.$$

In cylindrical coordinates, the ρ, θ, z direction expression can be obtained, and the unique equation solution can be received under certain boundary conditions.

In the case of a separation sector cyclotron, the optimized beam center trajectory and various parameters of the injection and extraction system elements can be solved completely by using the appropriate programs.

From a mathematical point of view, the beam center trajectory is a continuously differentiable curve; there is no inflection point and break point. Thus in a certain error range, optimizing the beam center trajectory is unique and complete. Among the various elements there is a strong correlation, therefore we must pay attention to the uniqueness and integrity of the trajectory in dealing with the relevant events of the trajectory and the injection and extraction system.

In the process of dealing with the beam transmission efficiency of the SSC, one must recalculate the whole beam center trajectory and the element parameters of the injection and extraction system.

5 The basic characteristics of programs recalculating the injection and extraction system

The program groups used in the recalculation are EJEC51, TRAJ21 and TRAJ33. These were adopted in the formal design and construction of GANIL in France, and are essentially different from the initial version of the programs in the two fundamental features.

1) In the case of soft-edge approximation, the programs pay attention to the fact that the two different types of injection and extraction elements (the bending magnet and the inductive septum) have to be distinguished and their interactions with the ambient field (the main magnet field) are considered, and then focus on the difference in the inhomogeneous magnet field in the located area of the inductive septum, whose ends are situated in the ambient field (between the main magnet poles). The calculation is then carried out. This is the case with a septum whose ends are in the field trailing edges of a pole. Thus the problem of the gradient magnetic field of the inductive septum can be solved perfectly. The trajectory of the injection system is close to the actual needs of the trajectory. In the existing design of the injection and extraction system, the MSi3 location parameters are: R=0.848–0.981 m, ΔR=0.143 m; θ=207°–245.5 °, $\Delta\theta$=38.5°. In this large position range, the main magnet field varies approximately from 2000 to 4000 Gs. The magnet field distribution on the centerline of MSi3 and MSi4 at the unperturbed and perturbed fields is shown in Figs. 3 and 4, respectively. It can be seen from the figures that the magnet field distributions have large changes due to the injection and extraction elements that were put into their positions.

Such a large magnetic field gradient must be given assiduous attention in the calculation. In the extraction system, there is a similar problem. In the calculating results, the location parameters of the inductive septum change significantly. This confirms that the physical consideration is correct.

In the calculation program TRAJ33, the parameter combination of IPROP and ATT is used to distinguish and control two different types of injection or extraction element parameters and their interactions with the ambient field. Meanwhile, CBMAX and other parameter combinations are used to distinguish and control the difference in the septums and their interactions with the ambient field. Therefore, the real trajectory of a typical ion in the complex magnetic field can be obtained successfully.

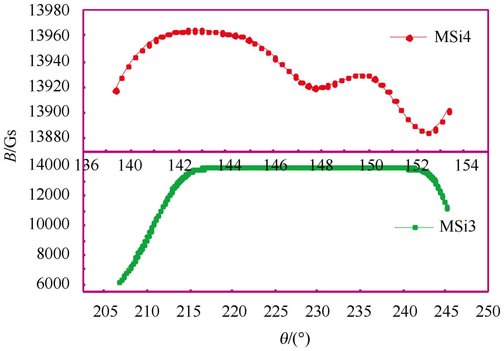

Fig. 3. Magnet field distribution on the center line of MSi3 and MSi4 at the unperturbed field.

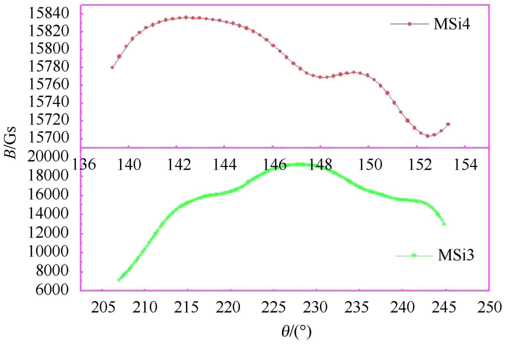

Fig. 4. Magnet field distribution on the center line of MSi3 and MSi4 at the perturbed field.

2) The program group provides the possibility of measured magnet field correction. In general, there is a difference between the magnet field of the soft-edge approximate and the actual magnetic field. The difference is more than 4% in the SSC injection region. Therefore, after the calculation of the center trajectory and the injection and extraction system by soft-edge approximation, the measured field correction must be put into practice. The program group can then carry out the correction precisely.

With these two important physical considerations, the recalculation results will give good transmission efficiency for the SSC.

6 Recalculation of the SSC beam trajectory and the injection and extraction system

6.1 Computation program

The recalculations were carried out using the programs provided by our counterparts at GANIL. The programs are EJEC51, TRAJ21 and TRAJ33. In order to match our conditions, appropriate auxiliary programs were used. EJEC51 gives a soft-edge approximate normalized basis field, TRAJ21 gives the isochronous field and static equilibrium orbits and all relevant parameters for the selected typical particles, and TRAJ33 is used to calculate the beam center trajectory and the variety of parameters of the injection and extraction system.

6.2 Calculation steps and results

6.2.1 Calculation of the center trajectory and the injection and extraction system by the soft-edge approximate method

Firstly, according to the specific circumstances of HIRFL-SSC, some of the parameters in the original program are changed, and one of the programs is modified slightly. According to calculation requirements, an auxiliary program is then written.

^{129}Xe^{32+} was selected as the typical particle. After obtaining the soft-edge approximate basis field, the isochronous field and some static equilibrium orbits are received from TRAJ21.

A large number of complex calculations focused on TRAJ33 are performed. In order to optimize the center trajectory and the variety of parameters of the injection and extraction system, the calculation is divided into five steps. (1) Forward calculation of the acceleration orbit up to 10 laps. (2) Reverse calculation of the deceleration orbit from the end of the 10 laps, which is then put into the various elements of the injection system successively. (3) Adjustment of the calculation parameters in order to make the injection trajectory consistent with the injection conditions. (4) Forward calculation leading to an accelerated orbit to the extraction match point, and careful adjustment which leads to energy (magnetic rigidity) for the required calculation value. (5) Calculation of the whole acceleration process, where the particle is accelerated from 4.08 m out of the accelerator, injected into the injection system and accelerated at the acceleration orbit, and then finally extracted to 4.8 m out of the accelerator. The center trajectory and the variety of parameters of the injection and extraction system at the soft-edge approximate method were obtained successfully. The partial results are shown in Table 3 and Table 4.

6.2.2 Measured magnet field correction

Measured magnetic field correction is where the calculation of the trajectory and the variety of injection and extraction parameters are carried out in the case of measured magnet maps.

Firstly, the necessary auxiliary programs and the structural integration of the SSC measured magnetic data must been prepared. The measured magnet basis field for a typical particle ^{129}Xe^{32+} is obtained. Then the isochronous field and some static equilibrium orbits are calculated in the case of a measured magnet field.

After the measured isochronous magnetic field of ^{129}Xe^{32+} is received, one can repeat the five similar calculation steps with the soft-edge approximate method to calculate the trajectory and injection and extraction system. The center trajectory and the variety of injection and extraction system parameters are calculated in the case of measured magnet maps. Some of the new parameters of the SSC injection and extraction system are shown in Tables 5 and 6, respectively.

6.3 Analysis of the recalculation results

The injection match points are at R=0.92632 (valley center-line) for both the existing case and the soft-edge approximate method in the new calculation. But comparing the recalculation results in Table 3 and Table 4 with the data of Table 1 and Table 2, we can see that the positions of the electrostatic deflector are consistent within errors. However, two different types of injection device and their differences are distinguished, and we take into account the differences in the inhomogeneity of the ambient field in the located area of the inductive septum, both of whose ends encroach on the ambient

Table 3. The parameters of the injection system at the soft-edge approximate method.

	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	BBM/T	WIDTH/mm	INCL/(°)
Mi1	0.8276	38.26	0.602	188.6	30	30.0	−1.1280	30.0	10
Mi2	0.3531	234.7	0.465	331.3	30	102.5	1.3690	30.0	0
MSi3	0.4828	219.2	0.467	233.2	30	76.0	1.5650	30.0	0
MSi4	0.4651	133.8	0.540	156.0	30	25.0	0.075	30.0	0
	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	POT/kV		
ESi5	1.76420	1.76420	2.70	93.8	10	9.0	−16.7		

Table 4. The parameters of the extraction system at the soft-edge approximate method.

	ROO/m	TETAO/(°)	RRM/mm	AAM/(°)	GAP/mm	AMAX/(°)	POTINT/kV	EN	
ESe1	78.9380	270.32	75.9925	90.46	15	1.0186	−23.60	0	
	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	BBM/T	WIDTH/mm	INCL/(°)
MSe2	1.4015	224.68	1.9703	205.4	30	30	−0.035	30	0
MSe3	1.3007	129.25	2.1779	156.1	30	30	1.14930	30	0
Me4	4.8572	98.5	1.6947	278.4	30	14	−1.453	30	0
Me5	4.7634	90.86	1.4796	311.02	30	48	−1.683	30	8

Table 5. The new parameters of the SSC injection system.

	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	BBM/T	WIDTH/mm	INCL/(°)
Mi1	0.814	38.26	0.602	188.4	30	30.0	−1.17	30	10
Mi2	0.3581	235.3	0.465	331.4	30	102.5	1.3730	30	0
MSi3	0.4967	219.9	0.467	234.3	30	76.0	1.5320	30	0
MSi4	0.4764	133.6	0.540	157.1	30	25.0	0.0550	30	0

	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	POT/kV
ESi5	1.76240	270.9	2.70	93.8	10	9	−14.6

Table 6. The new parameters of the SSC extraction system.

	ROO/m	TETAO/(°)	RRM/mm	AAM/(°)	GAP/mm	AMAX/(°)	POTINT/kV	EN
ESe1	78.9332	270.32	75.9925	90.45	15	1.0186	−25.0	0

	ROO/m	TETAO/(°)	RRM/m	AAM/(°)	GAP/mm	AMAX/(°)	BBM/T	WIDTH/mm	INCL/(°)
MSe2	1.4010	224.68	1.9703	207.3	30	30	−0.035	30	0
MSe3	1.3016	129.41	2.1779	152.3	30	30	1.1250	30	0
Me4	4.8790	98.5	1.6947	278.60	30	14	−1.453	30	0
Me5	4.7919	90.78	1.4796	311.05	30	48	−1.6656	30	8

field (the main magnet pole), and adopt a different way to make the MSi3, MSi4 location different from the old program results. Of course the Mi1, Mi2 positions are also changed, and the location of the extraction system elements leads to similar changes.

In previous research [1–3], the beam center trajectory of the SSC was studied from different aspects. This raised the issue of the location of the injection and extraction system elements, and focused on the inductive septum of MSi3 and MSe3. On the other hand, it showed that the efforts to solve the difference in the regional inhomogeneity of the ambient field of the inductive septum was quite correct.

From Table 5 and Table 6 one can see, after the measured magnet field correction in the case of the soft-edge approximate method, that all the injection and extraction element positions have been changed. This is the inevitable result of the change in the basis magnet field. From the effective magnetic angle discriminator θ_{m}=90°/K_{b}, it can be found that the effective magnetic angle of the measured magnetic field of θ_{m2}=51.579° is much smaller than the magnetic angle (θ_{m1}=53.936°) in the case of soft-edge approximation, but the regional magnetic field values are higher than the values of the soft-edge approximate method. One of the matching requirements between two cyclotrons is the magnetic rigidity (energy) match. In the calculations of the static equilibrium orbit in the case of the measured field, the injection match point is 0.92385 m. This value is different from that of the soft-edge case by about 2.5 mm. It must be pointed out that the effective electrostatic deflector space is only 9 mm, so this difference is equivalent to 30% of the gap. To provide such beam transmission efficiency loss is therefore very impressive. Of course this inevitably leads to corresponding extraction match point changes, so from this point the measured field correction is absolutely necessary.

7 Conclusion

Using the program groups EJEC51, TRAJ21 and TRAJ33, the SSC beam center trajectory and various parameters of the injection and extraction system elements were recalculated. Based on these parameters of the location of the injection and extraction elements and using careful alignment and commissioning with the new injection and extraction system, the beam transmission efficiency of HIRFL-SSC can be improved by a wide margin.

The author would like to sincerely thank Prof. E. Baron and Dr. H. Moscattlo of GANIL in France for their generous gift calculation programs, along with the manuals, and their enthusiastic help and encouragement.

The author would also like to thank Dr. HAO Huan-Feng and Dr. WANG Bing of IMP for their help with understanding the program and writing the auxiliary programs, Mr. YANG Shang-Yun, Mr. YANG Yi-Ping, Prof. SONG Ming-Tao and Prof. YANG Xiao-Dong for many helpful discussions and suggestions, and Prof. ZHANG Yu-Hu of IMP for helping with the French translation.

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