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SIMULATION AND ANALYSIS OF HIMM-IC BEAM DYNAMICS WITH OPAL*

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Abstract

Since 2020, HIMM (Heavy ion medical machine) facilities in both Wuwei and Lanzhou cities have been installed and put into clinical application or commissioning experiments. As an injector cyclotron (IC), HIMM-IC can provide 6.8 MeV/10eμA $^{12}C^{5+}$ beam for the synchrotron. Nevertheless, in terms of better beam quality and operation efficiency, HIMM-IC design still has a lot of room for improvement. We used OPAL (Object oriented Parallel Accelerator Library) simulation program to complete the 3D multi-particle dynamics simulation of HIMM-IC including the space charge effect. And the results show that it is in good agreement with the actual experimental measurements.

INTRODUCTION

China's carbon ion therapy facility, also named HIMM, is a cancer treatment facility designed by the Institute of Modern Physics of the Chinese Academy of Sciences. It has two ECR ion sources and uses an axial injection to deliver $^{12}C^{5+}$ into HIMM-IC (see Fig. 1), which can accelerate the beam to about 7 MeV/u. The main accelerator HIMMSYN (HIMM Synchrotron) accelerates the beam further to 120-400 MeV/u. Its maximum particle number at the terminal is about 1.2×10^9 ppp. Through the HEBT line, the beam will be delivered to 5 fixed treatment terminals in 4 treatment rooms. As the injector cyclotron of the HIMM, HIMM-IC is a compact isochronous cyclotron. The overall diameter is only 2.92 m. The magnetic field is composed of a whole magnet without any trimming coils. It can provide 7 MeV/u, 10 eμA $^{12}C^{5+}$. The other basic parameters are shown in the Table 1 [1, 2].

Table 1: HIMM-IC Basic Parameter

Parameter	Value
Central magnetic fields	1.212 T
Injection radius	2.7 cm
Injection Energy	111.6 keV
RF frequency	31.02 MHz
Harmonic number	4
Extraction radius	75 cm

According to the operation of HIMM-IC (taking the Wuwei heavy ion therapy facility as an example) [3], the ECR ion source provides 82.5 eμA $^{12}C^{5+}$, and the extraction beam intensity of HIMM-IC is up to 11.06 eμA, with an overall transmission efficiency of about 13.75%. Considering the strict safety operation standard of the medical facility, we stop to overhaul (including check and clean inflector and RF cavities) every two years and clean the inflector once a year. In long-term stable operation, HIMM-IC can extract about 5.5 eμA $^{12}C^{5+}$ with the injection beam intensity of about 50 eμA provided by the ECR ion source and the total transmission efficiency is more than 10%. Although the operating status meets the need of clinical treatment, there is still a lot of room to upgrade it for better performance.

Figure 1: HIMM-IC.

During the design phase, we used the cyclotron dynamics simulation software – SNOP to model and simulate the HIMM–IC and obtained a better coincidence between the two by comparing with experimental measurements. Therefore, we use a new cyclotron dynamic simulation software, OPAL [3, 4], to re-model and simulate the HIMM-IC with 3D beam dynamics including space charge effects.

To overcome the operation problems of the low beam intensity and quality and to prepare for the further upgrade, the following approaches are considered in this work:

- Generation of the three-dimensional electric and two-dimensional magnetic field map.
- Analysis of the performance of the cyclotron units: CR (Central Region), Acceleration and Extraction. The other units (like LEBT) are not discussed in this work because they are not suitable for simulation using OPAL.
- Estimation of the overall cyclotron transmission (extraction to injection beam intensity ratio) and output beam parameters (emittance, energy spread, time pulse, and dispersion).

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The aim of the simulation was to increase the cyclotron transmission and output beam quality by improving the matching at the injection, optimizing the acceleration regime parameters, and increasing focusing at the extraction.

The 2D (two dimensional) magnetic fields used in the beam dynamics simulation were from the measurements of the manufactured magnets. The measurement of the magnetic field, including manufacturing errors, has a better reliability than the modelled field used in the design phase, and can reflect more realistically the magnetic field that governs the beam in the cyclotron. Since there were no data on the physically measured RF cavities after manufacturing, the three-dimensional electric fields we used were extracted from the CST software.

For the analysis of the beam dynamics, a detailed computer model of the HIMM-IC was built including the central region, acceleration and extraction, based on the real structure of the HIMM-IC, including some variations in manufacturing and installation.

ISOCHRONOUS ANALYSIS OF MAGNETIC FIELDS

Static Equilibrium Orbit Calculation

The analysis of the isochronous magnetic field is the first step in the design and simulation of the cyclotron. SEO (Static Equilibrium Orbit) is obtained from the tunes calculation module of OPAL-cycl, as shown in Fig. 2.

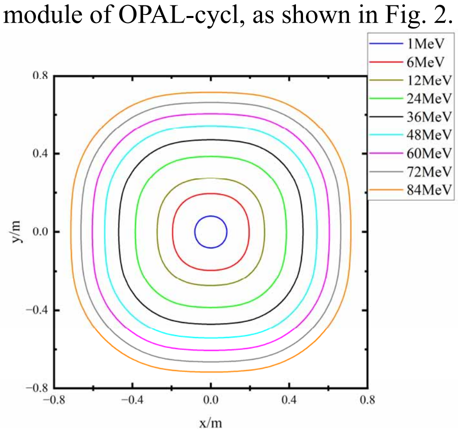

Figure 2: Static Equilibrium Orbit.

In addition, the RF phase shift error (see Fig. 3) for various energies according to the output results, which represents the size of the phase shift due to the error between the measured magnetic field and the theoretical isochronous field. We define the frequency shift error as:

$$\Omega(E) = \frac{\omega_0}{\omega} - 1. \quad (1)$$

$$\omega_0 = \frac{2\pi f_{RF}}{h}. \quad (2)$$

where ω_0 is the particle cyclotron frequency at the theoretical isochronous field, determined by f_{RF} and the harmonic number h. From this, the relationship between phase shift and energy can be obtained as:

$$\sin(\varphi(E)) = \sin(\varphi_i) + \frac{\pi h}{2Vq}\int \Omega(E)dE. \quad (3)$$

where V is the voltage of RF cavity.

From the calculation of the RF phase shift at various energies, we obtain the results as shown in Fig. 3, which shows that the overall frequency shift has a small error. When the integral calculation is performed according to the above equation, we can obtain a total phase shift of 13° throughout the acceleration process.

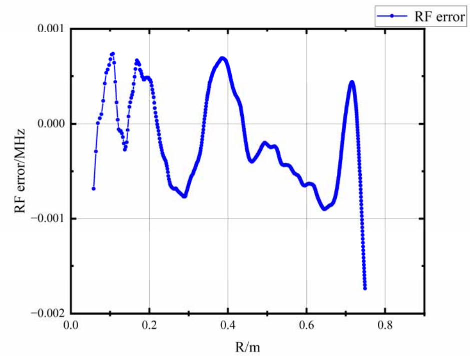

Figure 3: RF phase shift error.

Betatron Tunes

The analysis of the isochronous magnetic field is the first step in the design and simulation of the cyclotron. We have calculated the radial and axial focusing frequencies of the HIMM-IC in the measured magnetic field according to the tunes calculation module of OPAL-cycl, and the energy step is taken as 0.1 MeV. According to the calculation and analysis of the tunes in the whole range from the injection to the extraction energy(see Fig. 4), we can see that the HIMM-IC does not have the problems of dangerous resonances in both radial and axial directions, and the axial focusing frequency is kept above 0.4 in the most of the energy range, which basically satisfies the focusing of the beam transversely to avoid the deterioration of the beam transverse quality due to various resonances.

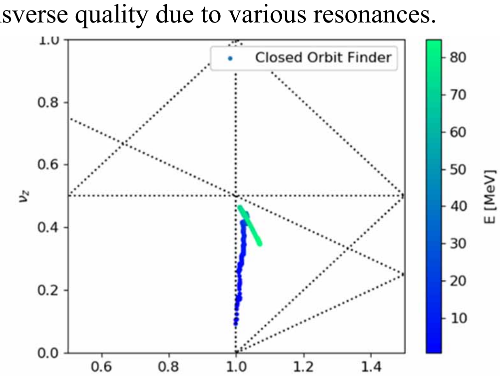

Figure 4: Tune diagram.

Therefore, from the above rechecked calculations of the isochronous magnetic field of HIMM-IC, we can see that the measured magnetic field ensures good results in both SEO calculations and tunes calculations, satisfying the focusing and isochronous requirements for the stable operation of the cyclotron with basically no obvious problems.

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SIMULATION OF ACCELERATION

In the particle tracking simulation stage, we set the initial injection point of the particle at the exit position of the inflector cylinder. According to the 3D modelling and particle tracking simulation of the inflector in other software, and the installation mode of the inflector, we obtained the information of the initial particle injection point as follows: R=37.5 mm, φ=140 deg, E_k=112.2 keV, P_r=0.101 rad [2]. We modelled and analysed the beam status evolution during the whole acceleration region from the injection to the extraction energy, using the single and multi-particle modes of OPAL. The modelling and beam simulation of the elements of the extraction system are not completed and will not be reported in this paper.

Single Particle Simulation

In the single-particle mode, we obtained a stable AEO (Accelerated equilibrium orbit) using a 3D electric field, a 2D magnetic field and a known initial injection point, by scanning the initial phase of the electric field within 2π as shown in Fig. 5.

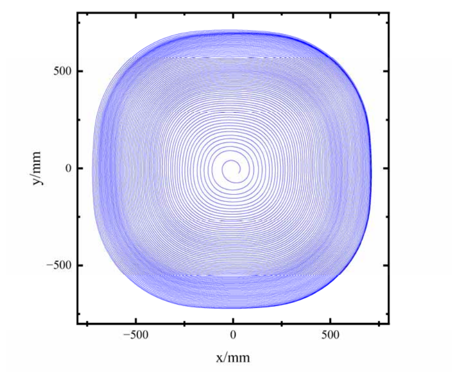

Figure 5: Accelerated equilibrium orbit.

According to the analysis of the results, HIMM-IC could accelerate $^{12}C^{5+}$ from 0.1122 MeV to 84.917 MeV in 77 turns and obtain a variation of the turn separation at an azimuth of 45 deg. The last turn separation could reach 5mm, and the energy gain per turn is about 1.2 MeV (see Fig. 6).

Multi-Particle Simulation

The initial information of the beam corresponding to the exit of the reflector was generated according to the primary settings in the single-particle model in Table 2.

Table 2: Initial Beam Parameters

Parameters	Value
Beam Intensity	20 μA
Horizontal Geometry emittance(4σ)	50 mm·mrad
Vertical Geometry emittance(4σ)	50 mm·mrad
Energy spread	±0.5%
Phase spread	±10°
Number of macro particles	10^4

In the transverse direction, we pay attention to the beam size, emittance and other parameters that show the beam quality. From the simulation results (see Fig. 7), we can see that the beam size oscillates throughout the acceleration but the overall is under control, and the RMS beam size at the extraction energy point is 3.91 mm in horizontal and 1.58 mm in vertical. Considering the comparison with the turn separation, there is an overlap between the inner and outer turns of the beam at large radius, which causes the problem of increasing the emittance of the beam. In the horizontal direction, the RMS geometry emittance of the beam reaches its maximum in the low-energy region (~15 MeV) and then gradually decreases, and a similar situation occurs in the vertical direction. The emittance at the extraction point is 22.27 pi·mm·mrad in horizontal and 2.77 pi·mm·mrad in vertical, which is in good agreement with the simulation results of SNOP in the design phase [5]. In the longitudinal direction, we pay attention to the variation of energy dispersion and momentum dispersion of the beam. From the simulation results, the energy dispersion is about 0.3 MeV, and the momentum dispersion is about 0.34% (see Fig. 8), which meet the requirements of HIMMSYN for beam injection. In addition, the beam acceleration efficiency from the injection point to the extraction is about 99.07% (see Fig. 9), which is in a good agreement with the operational measurement results [6].

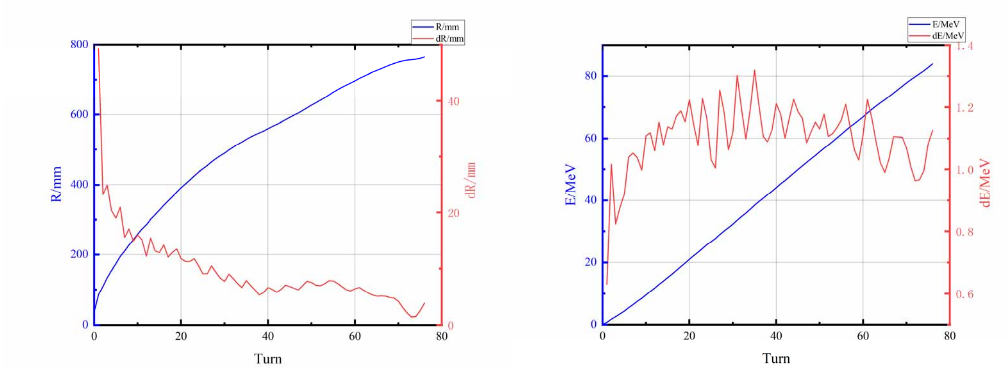

Figure 6: Turn separation(left) and Energy gain(right). The last turn separation could reach 5mm, and the energy gain per turn is about 1.2 MeV.

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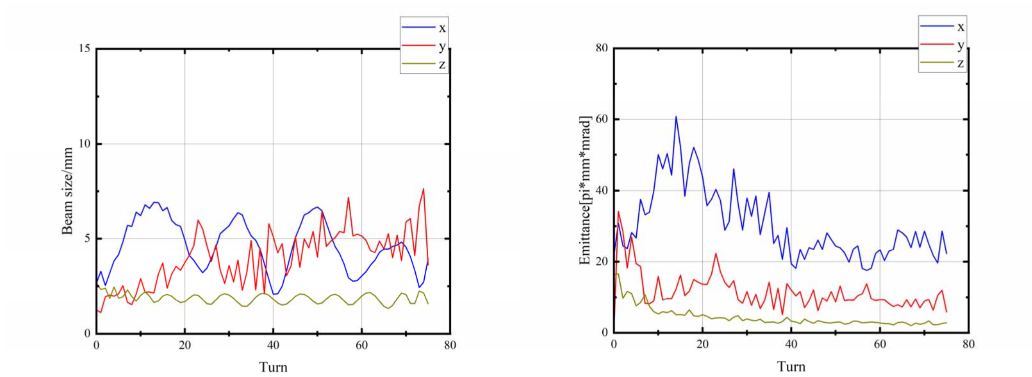

Figure 7: RMS Beam size(left) and RMS Geometry Emittance(right). The RMS beam size of last turn in x, y and z is 3.91555, 3.60329 and 1.58493mm; The RMS geometry emittance of last turn in x, y and z is 22.27046, 5.83704 and 2.77792 pi•mm•mrad.

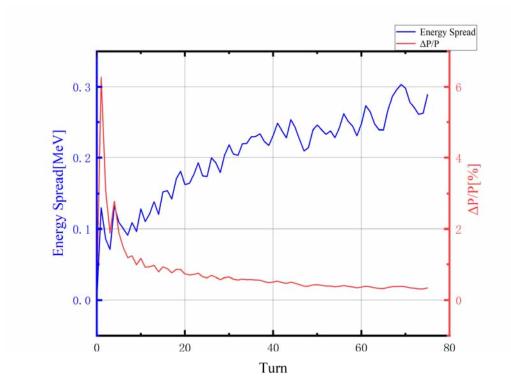

Figure 8: Energy spread and momentum dispersion.

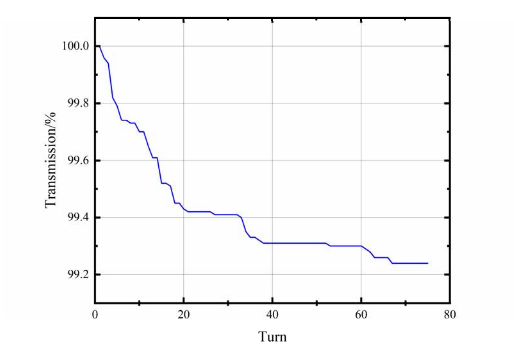

Figure 9: Transmission.

In general, the OPAL simulation results agree well with the SNOP design results in the transverse directions and the operation measurements in the longitudinal direction. The increased transverse emittances and small turn separation of the beam in the cyclotron during acceleration is a critical issue that affects the extracted beam intensity (or efficiency) and quality in the extraction system.

CONCLUSION AND OUTLOOK

According to the simulation results of OPAL, the real magnetic field of HIMM-IC is good in isochronism and focusing. In the acceleration region, the transverse emittances of OPAL and SNOP are in good agreement, and the transmission efficiency is in good agreement with the experimental measurements. Moreover, we have confirmed the issues of transverse emittances and small turn separation in large radial. Although the simulation of the extraction system has not been completed yet, it can be seen from the results of the beam analysis in the acceleration region that this is a major reason for the low extraction intensity and poor beam quality, which needs obvious improvement and optimization to refine the cyclotron extraction so as to extract more intense beam with good quality for the synchrotron injection.

As a continuous work of this study, the simulation of the extraction system needs to be fully implemented to help us find the main reasons for the low efficiency and intensity of the extracted ion beam from the cyclotron. In addition, we also want to use OPAL to complete a "end to end" beam dynamics simulation of the cyclotron, and therefore the cyclotron injection parts should be included in the simulation in the future.

REFERENCES

[1] B. Wang *et al.*, "Design and construction progress of a 7 MeV/u cyclotron", in *Proc. 19th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'10)*, Lanzhou, Sep.2010, China, TUA2CCO03, pp. 317-320.

[2] H. F. Hao, "Design and development of a 7 MeV/u heavy ion cyclotron", Lanzhou, China: Ph.D. thesis, 2014.

[3] OPAL, `https://gitlab.psi.ch/OPAL/src/-/wikis/home/`

[4] A. Adelmann *et al.*, "OPAL a versatile tool for charged particle accelerator simulations", *arXiv e-prints*, May. 2019. `doi:10.48550/arXiv.1905.06654`

[5] B. Wang *et al.*, "Computer design of a compact cyclotron", *Physics of Particles and Nuclei Letters*, vol. 9, no. 3, pp. 288–298, 2012. `doi:10.1134/S1547477112030053`

[6] Lanzhou Ion Therapy Co., Ltd, "Operation of HIMM-IC in Wuwei", unpublished.

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