STATUS REPORT ON THE CYCLOTRON INJECTOR FOR HIMM*

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Abstract

HIMM (Heavy Ion Medical Machine) is an accelerator complex designed by Institute of Modern Physics, CAS, which accelerates carbon ions to the energy 400 MeV/A for tumour therapy. The main accelerator of HIMM is a synchronous accelerator. As a special design, we use a cyclotron as the injector of the synchrotron. The cyclotron is a compact cyclotron to accelerate $^{12}C^{5+}$ ions to the energy 6.8 MeV/A, and the extracted beam intensity of the cyclotron is 10 eμA. For stability and simplicity operation, we use two identical permanent magnet ECR ion sources in the axial injection line, that the ion sources can interchange with each other rapidly with the same performance, and only one main exciting coil with no trim coils in the cyclotron magnet. Up to now, three cyclotrons have been accomplished, one of them was operated in Gansu Wuwei Tumour Hospital to treat more than six hundred cancer patients in the last two and a half years, the other one had been fully commissioned in Lanzhou Heavy Ion Hospital about two years ago. After a short introduction to the heavy ion cancer treatment facility development in China, this paper will present operation status of the cyclotrons for HIMM. Typical performance and on-line operation reliability will be discussed.

INTRODUCTION

HIMM (see Fig. 1) is an accelerator complex designed by Institute of Modern Physics, CAS, which can accelerate carbon ions to the energy 400 MeV/A for tumour therapy. The beam is generated from the ECR ion source and passes through the LEBT, the injector HIMM-IC (Injector cyclotron), the MEBT, the main accelerator HIMM-SYN (Synchrotron) and the HEBT to the treatment terminals.

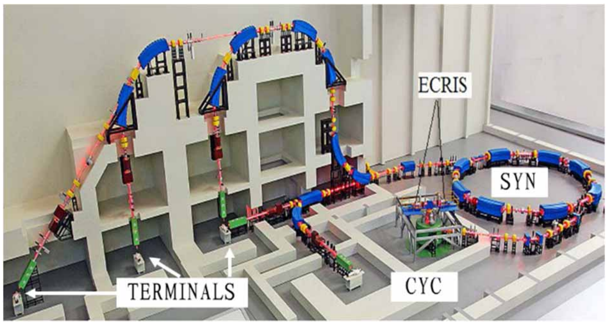

Figure 1: Layout of HIMM. ECRIS: ECR ion sources. CYC: Injector cyclotron. SYN: Synchrotron. TERMINALS: Treatment terminals.

As a unique design, HIMM is the only medical cancer treatment facility in the world that uses a cyclotron as an injector. HIMM-IC (see Fig. 2) is a compact isochronous cyclotron [1, 2], which has a whole magnet without any trimming coils. It can accelerate $^{12}C^{5+}$ ions to the energy of 6.8 MeV/A at extraction, beam intensity no less than 10 eμA.

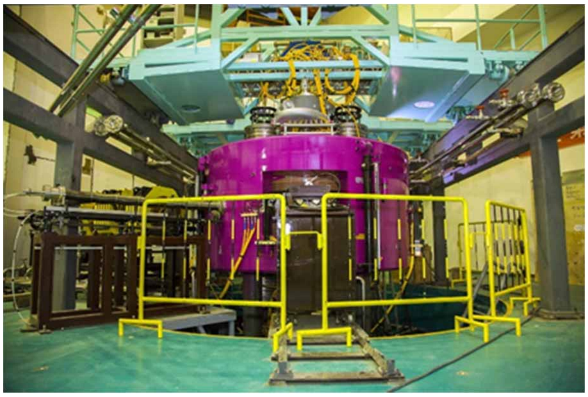

Figure 2: HIMM-IC installed on site.

Up to now, there are three HIMM facilities built and installed in China [3]. The HIMM in Gansu Wuwei Tumour Hospital (see Fig. 3) has treated more than six hundred cancer patients in the last two and a half years. The other two HIMMs in Lanzhou and Putian have also completed installation and are now being prepared and commissioned before clinical treatment.

Taking Wuwei's HIMM facility as an example, for routine operation of the HIMM-IC, an extraction of 5.5 μA (CW) ion beam has been made, which enables the acceleration of 2000 μA (pulsed) C^{5+} beam intensity (see Fig.3) with the main accelerator HIMMSYN, and the beam intensity delivered to the treatment terminals is typically 4×10^8 ppp. These indexes have well met the requirements of medical cancer treatment facilities.

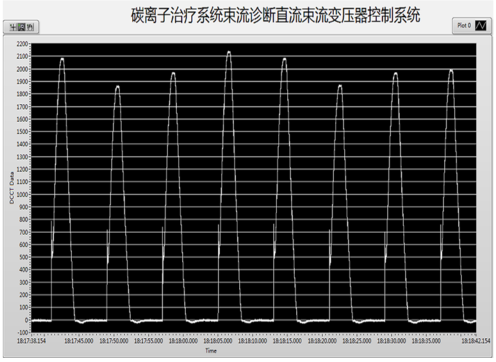

Figure 3: Beam intensity in the synchrotron.

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CHARACTERISTICS OF HIMM-IC

The HIMM-IC is a compact cyclotron without any trimming coils. Considering the conditions of application of medical facilities, we focused on the stability and simplicity of the cyclotron in design and manufacture phase. The main parameters of the cyclotron are shown in Table 1.

Table 1: HIMM-IC Main Parameters

Parameter	Value
Particle	$^{12}C^{5+}$
Energy	6.8 MeV/A
Intensity	10 eμA
Emittance	20-25 π•mm•mrad
Magnet Size	Φ2920mm×1520mm
Energy spread	±1%
Extraction radius	750 mm

Injection System

We use the external ion source combined with axial injection line [4] in order to obtain a high beam stability and beam intensity. The axial injection system of HIMM-IC is mainly composed of two permanent magnet ECR ion sources and axial injection line. The structure of axial injection system is shown in Fig. 4.

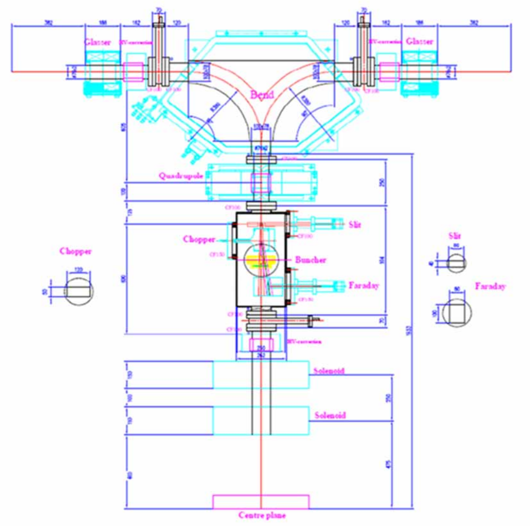


Figure 4: Layout of axial injection system.

The permanent magnet ECR ion source has the advantages of high stability and lower cost. We designed and installed two ECR ion sources for HIMM-IC, which can make continuous beam supply in case of breakdown of the operating ion source. The ion sources can provide maximum 150 eμA $^{12}C^{5+}$ beam at the extraction energy of 4.4 keV/A was used for long-term routine operation.

The axial injection system is composed of double direction dipole magnets, measurement chamber, solenoids and multi-harmonic buncher. It is very compact, and the whole length is only 3.5 meters. It can transport the beam from the exit of ECR ion source to the inflector at the cyclotron central region. The multi-harmonic buncher can improve the utilization of the DC beam deliverd by the ECR ion source, which enables the transmission efficiency to reach 59%.

Magnet

Considering the conditions and requirements of medical facility, the magnet [5] of HIMM-IC (see Fig. 5) is simple which is composed of a whole magnet without any trimming coils. So, we trim the sector edge and optimize the hill gap to achieve the requirement of the isochronism. The main parameters is shown in Table 2.

Table 2: Magnet Main Parameters

Parameter	Value
Central magnet field	1.212 T
Maximum magnet field	1.705 T
Magnet sectors	4
Sector angle	56°
Pole radius	84 cm
Hill gap	70-80 mm
Valley gap	360mm

The designed magnet can provide isochronous magnetic field with ±10 Gs error (see Fig.5) to the theoretical magnetic field. The results of the tune diagram satisfy the focusing in the acceleration region and avoid dangerous resonance before extraction (see Fig. 6).

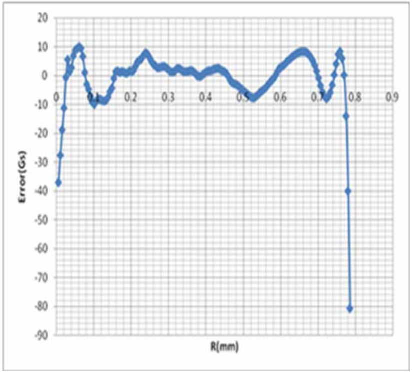


Figure 5: Magnet field error.

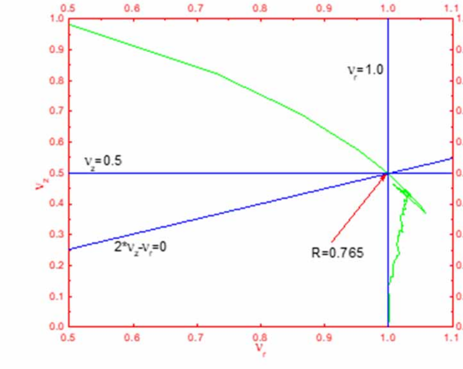


Figure 6: Tune diagram.

RF System

HIMM-IC has two independent RF cavities (see Fig. 7) and two 50 kW amplifiers to generate the acceleration electric field. The RF cavities were installed into the valleys of the magnet, two capacitance couplers near the outer radius of Dees imported rf power into cavities, two 50 kW rf amplifiers connected the couplers with coaxial transmission lines respectively. Near the short plane of cavities, we installed frequency tune device and rf sampling device to tune the cavities tinnily. To satisfy the stability of the accelerator operation, we demanded the higher stability of the cavity's amplitude, phase, and frequency. The detailed parameters of RF system are shown in Table 3.

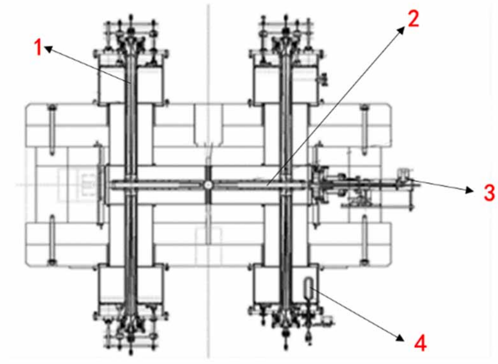


Figure 7: RF system.1-Inner steam, 2-Dee, 3-Coupling import, 4-Tuner.

Table 3: RF System Main Parameters

Parameter	Value
RF frequency	31.02 MHz
Dee voltage	70 kV
Dee angle	30°
Outer radius	750 mm
Inner radius	35 mm
Phase stability	±1°
Amplitude stability	$\pm 5\times 10^{-4}$/day
Frequency stability	$\pm 1\times 10^{-6}$/day
Q value	7800
Amplifier number	2
Amplifier power	50 kW

Extraction System

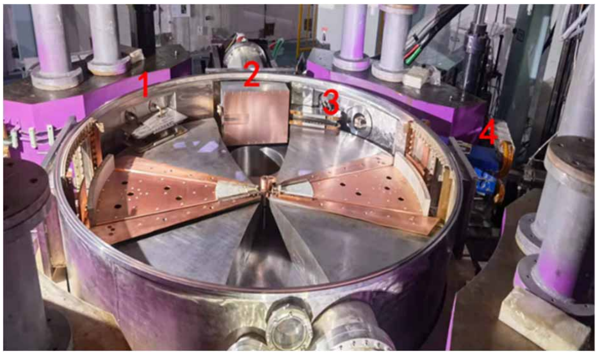


Figure 8: Layout of extraction system:1-BUMP, 2-ESD, 3-GCC, 4-MC.

The extraction system (see Fig. 8) was composed of a bump coil (BUMP), a electrostatic deflector (ESD), and a gradient corrector with compensation coil (GCC) and a magnetic deflector channel (MC) [6]. We could increase the turn separation to 10 mm using the bump field before the entrance of ESD. To improve the horizontal focus of MC and reduce its effect to sector's magnetic field in the outer radius, we optimized the MC's design to add a GCC ahead of it and make its yoke to be magnetic saturation. The detailed parameters are shown in Table 4.

Table 4: RF system main parameters

Parameter	Value
ESD E field	80-85 kV/cm
ESD gap	10 mm
BUMP B field	300 Gs
GCC G field	10 T/m
MC B field	1.1 T
Turn separation	10 mm

Beam Simulation

After the basic design, we simulate the beam transport from the ECR ion source to the match point of the MEBT (middle energy beam line). We used the cyclotron beam dynamics software-SNOP to complete the above simulation and obtained the end-to-end orbit (see Fig. 9) [2].

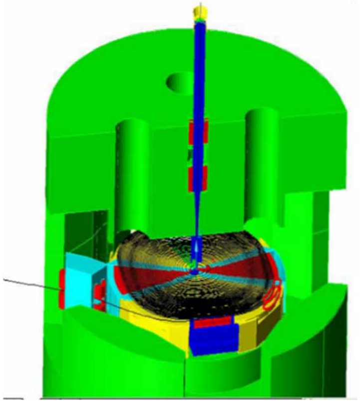
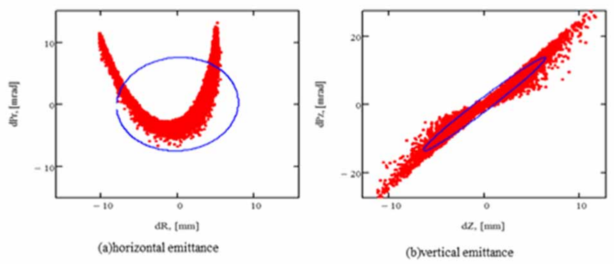


Figure 9: The end-to-end orbit.

We tracked the beam trajectory throughout the simulation and obtained the beam horizontal emittance of 60 π•mm•mrad and an axial emittance of 13 π•mm•mrad at the matching point of the MEBT, with a momentum dispersion of ≤±0.5% (see Figs. 10 and 11), which meet the requirements of the synchrotron. In addition, by tracking the number of macro-particles at different positions during the simulation, we obtained the beam transmission efficiencies as shown in Table 5.

Table 5: Beam Transmission Efficiency (Simulation)

Parameter	Value
Emittance of ECR	75 π•mm•mrad
ECR beam intensity	100 eμA
Efficiency of beam line	90%
Efficiency of injection	43%
Efficiency of extraction	47%
Total transmission efficiency	18%



(a)horizontal emittance

(b)vertical emittance

Figure 10: The phase space at the match point of the MEBT. Left: (x, x') plane. Right: (z, z') plane.

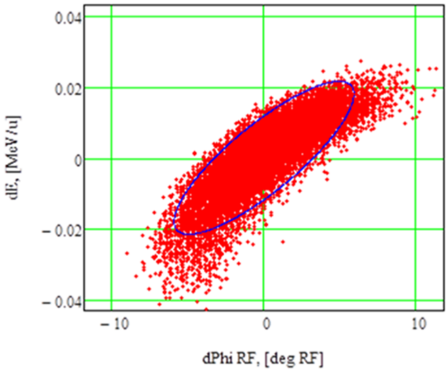


Figure 11: The longitudinal phase space at the match point of the MEBT.

MANUFACTURES AND OPERATIONS

Manufactures

HIMM-IC was designed from 2006 until its successful commissioning in 2014. The milestones are given below [3].

- The design phase: 2006-2014.
- The first cyclotron (see Fig.12) installed in IMP: 2014.08.
- The first commissioning of the cyclotron: 2014.08.15.
- The first extracted beam: 2014.08.16, 1 enA beam extracted.
- Extracted beam intensity reached 12 eμA: 2014.09.26.

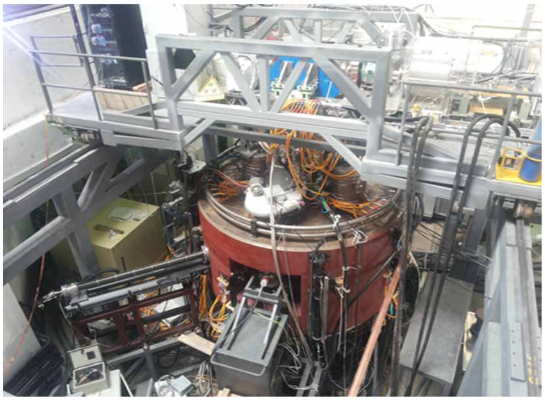


Figure 12: The first HIMM-IC in IMP.

Operations

The HIMM-IC was relocated in Gansu Wuwei Tumor Hospital in 2015 and used for treating the patients since April 1st, 2020. Up to now, more than 600 patients have completed their treatment in the hospital. It shows a good operation status.

The operating efficiency of HIMM-IC in the last two years is shown in Table 6, which is well above 99%. And the maximum beam current can reach 11 eμA (see Fig. 13) when the ECR ion source provided 80 eμA. So, the overall transmission efficiency of HIMM-IC is about 13 percent.

Table 6: Operating Efficiency of HIMM-IC

Scheme	Operation time(h)	Failure time(h)	Operation rate
20200326-20210123	7296	31.62	99.57%
20210322-20220129	7536	66.05	99.12%
20220216-20220822	6936	54.15	99.22%

谷总靶	0.000220465	20uA	山总靶	0.000288049	200uA	10FC01	-0.00240443	200uA
谷上	0.000131108	20uA	山上	0.000131937	20uA	30FC01	11.0578	20uA
谷中	0.000619016	20uA	山中	0.000445007	20uA	30FC02	0.000348901	20uA
谷下	0.000171539	20uA	山下	-0.000128259	20uA	41FC01	6.445E-5	20uA

Figure 13: The extraction intensity in Cyclotron.

Considering the operating environment and condition of medical facility, we need to strictly control the beam radiation, stability of operation and other problems. We will stop the machine every two years for overhaul, and check and clean the inflector once a year. Consequently, long-term routine operation at the beam intensities (see Fig. 14) of HIMM-IC 5.5 eμA, and HIMM-SYN 2000 eμA is guaranteed that is essential for reliable clinical treatment operation. And the transmission efficiency is about 11% (see Table 7).

Table 7: Beam Transmission Efficiency (Measurement)

Parameter	Value
Exit of ECR	50 eμA
Central region	19.2 eμA
Extraction region	18.94 eμA
Match point of MEBT	5.5 eμA
Efficiency of injection	38.4%
Efficiency of extraction	29%
Total transmission efficiency	11%

The second HIMM-IC was installed in Lanzhou Heavy Ion Hospital, Lanzhou city, Gansu province, China, in 2017. And the third cyclotron was installed in Mazu Heavy Ion Hospital, Putian City, Fujian province, China, in 2020.

HIMM-IC in Lanzhou has been used for clinical treat-ment trial operation in 2022, and HIMM-IC in Putian has been recently successfully commissioned with beam extraction.

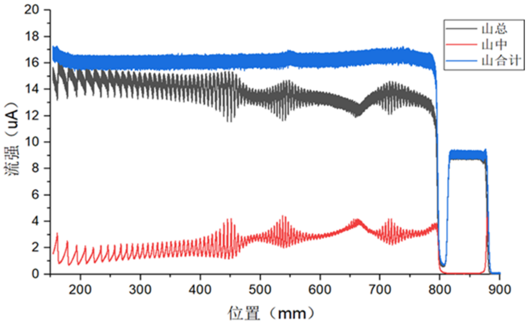


Figure 14: The beam intensity measured by radial probe. Red: Beam intensity measured by differential target. Black: Beam intensity measured by total target. Blue: Real beam intensity.

CONCLUSION AND OUTLOOK

According to the operation status of HIMM-IC, we think the cyclotron can be stably and reliably used as injector of synchrotron for heavy ion therapy. And the design of the cyclotron injector for HIMM is feasible.

As a continuous work of this study, we are not satisfied with the total transmission efficiency of the cyclotron injector and the extracted beam quality, and expect to improve it in the future to further boost the performance of the overall HIMM facility.

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