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BEAM COMMISSIONING IN THE FIRST CHINESE DEMO CANCER THERAPY SYNCHROTRON*

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Abstract

Heavy Ion Medical Machine in Wuwei (HIMM-ww) is the first Chinese heavy ion accelerator facility developed for cancer therapy. After commissioning, the particle number after acceleration reached 1.5e9 ppp (particles per pulse), while injection exceeded 3e9 ppp. The slow extraction efficiency reached nearly 90% for all energies from 120 to 400 MeV/u. The spill duty factor exceeded 90% at a sample rate of 10 kHz. This paper reports the results of the synchrotron commissioning.

INTRODUCTION OF THE SYNCHROTRON

Heavy ion medical machine (HIMM) was constructed on the basis of the experience gained from the Heavy Ion Research Facility in Lanzhou-Cooler Storage Ring (HIRFL-CSR) project [1]. HIMM facility consists of an electron cyclotron resonance (ECR) ion source, a cyclotron injector, a compact synchrotron ring, and 5 nozzles [2]. The C5+ beam generated by the ECR ion source is pre-accelerated by the cyclotron to 6.2 MeV/u and then injected into the synchrotron using the charge exchange injection method [3]. The injected beam is accelerated from 6.2 MeV/u to an extraction energy ranging from 120 to 400 MeV/u.

The layout of the synchrotron, which has a two-fold symmetry structure composed by 8 dipoles and 12 quadrupoles, is shown in Fig. 1. Two long straight sections are used for injection and extraction respectively and four medium-long straight sections are occupied by RF cavity, DCCT (DC Current Transformers), ES (Electrostatic Septum), transverse RF, respectively. The parameters of the ring are listed in Table 1.

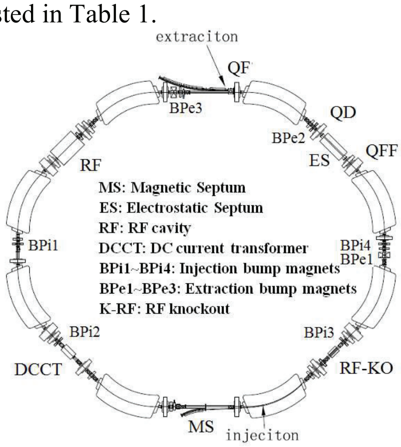

Figure 1: Schematic layout of the HIMM synchrotron ring.

BEAM COMMISSIONING RESULTS OF THE SYNCHROTRON

Figure 2 shows the current ramping shape of the synchrotron's main quadrupole power supply (the power supply of the dipoles has the same shape as the quadrupoles) and the extraction bump at the extraction flattop [3]. The synchrotron cycle is 7 seconds. The extraction beam energy is 260 MeV/u. The horizontal and vertical axes represent the time and amplitude of the power supply, respectively. The extraction duration is 2 seconds. The ramping time of the extraction bump is less than 10 ms, and the flattop duration is the same as that of the dipole magnet.

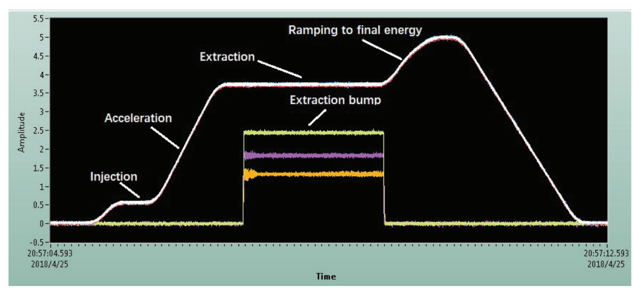

Figure 2: Ramping shape of the quadrupole and extraction bump.

Beam Injection and Acceleration

Different with other cancer therapy facility in the world, the cyclotron is adopted as the injector. The beam intensity of the cyclotron is less than 10 uA. To store enough particles in the ring, the CEI (charge exchange injection) method, which regardless of Liouville's theorem allows beams to be injected at the point of phase space already occupied by previously injected beam [3], is adopted. Therefore, an intense beam can be accumulated in the ring without largely increasing the beam emittance. In addition, the injected beam can be painted in the horizontal phase space by changing the local closed orbit during injection to reduce the hitting probability at the stripping foil, thus increasing the injection efficiency.

Figure 3 is the DCCT signal which shows the beam intensity during the whole cycle. The extraction beam energy is 260 MeV/u in Fig. 3. The beam intensity after injection is 1800uA which corresponding to the particles number of 3e9. The beam capture efficiency is 50%, and the accelerate efficiency is approximately 95%.

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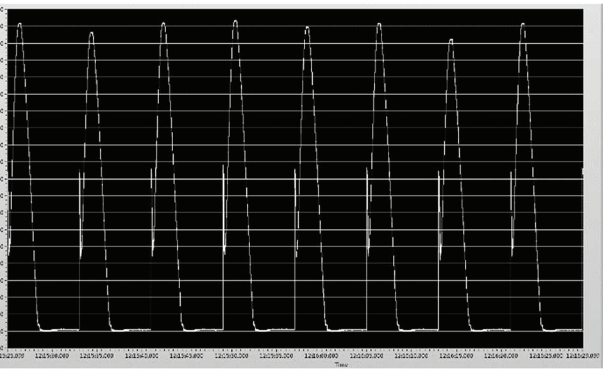

Figure 3: beam intensity of on the DCCT.

Slow Extraction

Five beam energies, 120, 190, 260, 330, and 400 MeV/u, with an energy separation of 70 MeV/u were chosen as the commissioning energies for passive scanning. A total of 123 energies separated by nearly 2.3 MeV/u corresponding to the Bragg peak in water with a range step of 2 mm from 120 to 400 MeV/u were used for active scanning.

The beam duty factor is an important parameter to indicate the spill quality. The duty factor defined as follows [4]:

$$D = \frac{\left[\int_{T1}^{T2} I(t)dt\right]^2}{\left[\int_{T1}^{T2} dt \cdot \int_{T1}^{T2} I^2(t)dt\right]},$$

where I(t) is the spill intensity and T1 and T2 define the time range where the duty factor is computed.

To improve the spill duty factor, amplitude modulation [5] and longitudinal RF modulation [6, 7] were adopted. The longitudinal RF voltage keeps in a constant value on the extraction duration to improve the spill duty factor.

To flatten the whole spill, the TRF voltage should be changed exponentially with time [5]. The polynomial function was adopted in our case to save the calculation time in every synchrotron cycle. The beam duty factor is approximately 90%.

The fast quadrupole (FQ) feedback system is adopted to flatten the spill. The FQ feedback system is mainly used for beam flattening in the macroscopic aspect of the spill. The main quadrupole ripple is less than 3×10^{-5}; therefore, the feedback system for spill microscopic flattening is unnecessary. Inversely, the FQ system may import extra spill ripple because it has the response time during the feedback procedure. Additionally, the beam position in the terminal will change as the FQ causes the separatrix change. Therefore, the beam feedback system was adopted only for the passive scanning. Figure 4 shows the spill with feedback. The beam energy is 400MeV/u. The duty factor exceeded 95%.

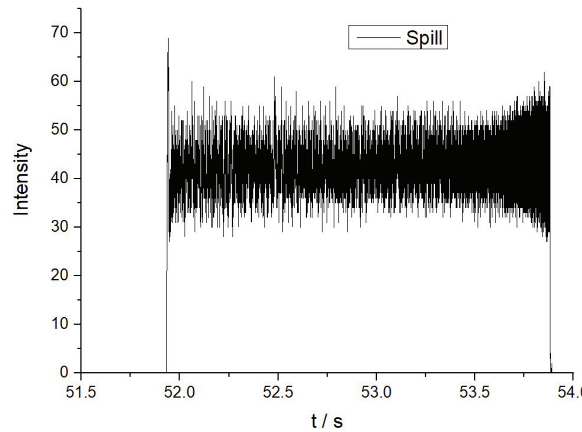

Figure 4: Spill structure with feedback.

Typical spill structures for 4 other passive scanning energies, 120, 190, 260, and 330 MeV/u, are shown in Fig. 5.

The sample rate of the spill is 10 kHz. The extraction flattop is 2 seconds, but in fact the extraction time is usually less than 2 seconds. This is because the particle numbers in every synchrotron cycle fluctuate. The reference intensity must be slightly larger than the actual beam intensity to ensure the beam is extracted completely during the extraction flattop.

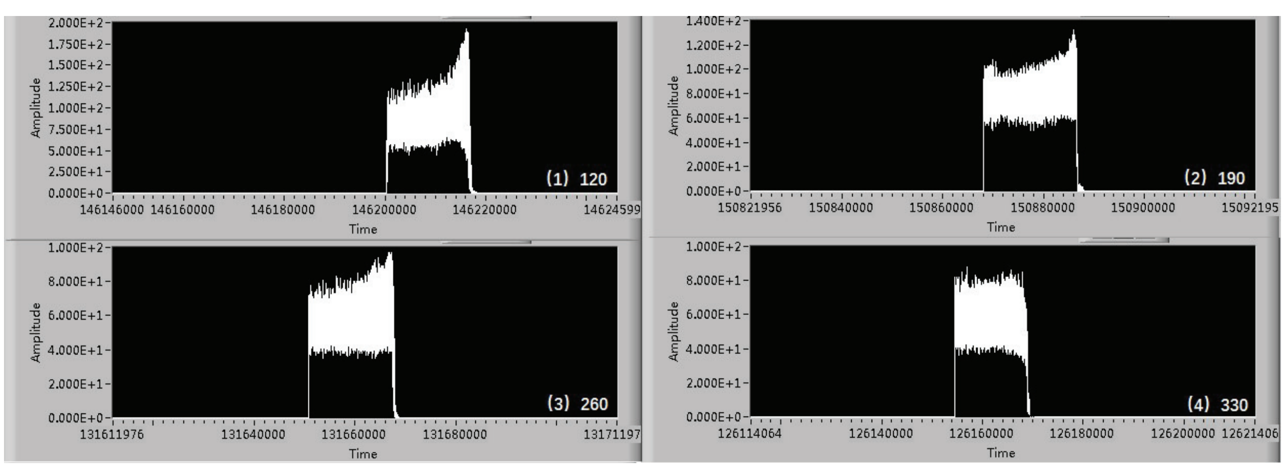

Figure 5: Screenshot of the time structure shown in the ionisation chamber.

Figure 6 shows the 400MeV/u beam signal viewed in the anode-stripped ion chamber in the terminal. The anode-stripped ion chamber has an effective area of 200mm×200mm. There are 200 strips in each of the horizontal and vertical directions. The definition of the beam position is less than 0.2 mm after gaussian fitting. The two

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upper figures show the beam profile in x (horizontal) and y (vertical) direction, respectively. The horizontal axis is the position of the beam, while vertical axis is the time duration. The colours represent the relatively beam intensity, black is 0 while white means great than or equal to 5.0. The lower two figures show the beam profile and the gaussian fitting.

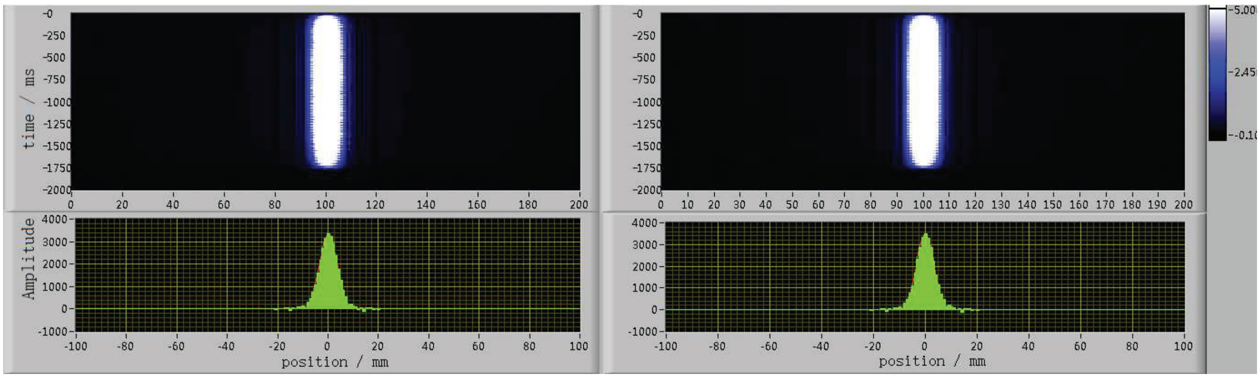

Figure 6: Beam signal viewed in the anode-stripped ion chamber.

Figure 7 shows the extraction efficiency vs energies. The ionisation chamber was installed only in the treatment room. The slow extraction efficiency measured includes the HEBT transfer efficiency. The theoretical extraction efficiency can reach 99% since the step width of the beam is nearly 10 mm at the entrance of the ES, the thickness of the wire is 0.1 mm, and the HEBT efficiency is 100% in theory. Actually, to decrease the spark of the ES, the maximum ES voltage is 115 kV, which is lower than the designed value of 135 kV. The gap of the ES also decreased from the designed value of 15 mm to 12.5 mm to maintain the electrical field strength. The alignment error of the ES wire, the closed orbit, the large horizontal chromaticity, and the large momentum spread vs the narrow gap of the ES will cause beam loss, which decreases the extraction efficiency.

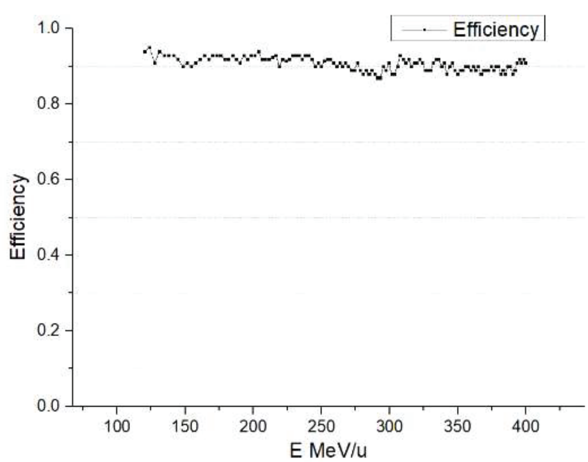

Figure 7: Beam energies vs. extraction efficiency.

SUMMARY

After commissioning, the particle number after acceleration reached 1.5e9 ppp (particles per pulse), while injection exceeded 3e9 ppp. The slow extraction efficiency reached nearly 90% for all energies from 120 to 400 MeV/u. The spill duty factor exceeded 90% and 95% at a sample rate of 10 kHz without feedback and with feedback, respectively.

For a square irradiation field, the uniformity was better than 106% after the magnet scanning in treatment rooms. The uniformity defined as D_{max}/D_{min}, where D_{max} and D_{min} are the maximum and minimum lateral dose distribution in the middle line of the horizontal and vertical directions.

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