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THE COMMISSIONING OF A 230 MeV SUPERCONDUCTING CYCLOTRON CYCIAE-230*

Chuan Wang†, Zhiguo Yin, Tianjue Zhang, Wei Fu, Hongji Zhou, Xueer Mu, Bin Ji, Xianlu Jia, Jiansheng Xing, Pengfei Zhu, Jie Liu, Zhengwei Liu, Hongru Cai, Jingyuan Liu, Lipeng Wen, Xia Zheng, Luyu Ji, Xiaofeng Zhu, Fei Wang, Junyi Wei, Shilun Pei, Guofang Song, Suping Zhang, Yunsheng Jia, Dezhi Zhang, Tianyi Jiang, Aolai He, Qiqi Song, Ping Liu, Mingzhi Hu, and the Cyclotron Team at CIAE, China Institute of Atomic Energy, Beijing, P. R. China

Abstract

There are very strong demands for proton accelerators in medium energy range in recent years due to the fast growth of proton therapy and the space science in China. For the applications of proton therapy and proton irradiation, the energy range of proton beam is usually from 200 MeV to 250 MeV, or even higher for astronavigation. An R&D project for constructing a 230 MeV superconducting cyclotron (CYCIAE-230) has been initiated at China Institute of Atomic Energy (CIAE) since Jan 2015. In July of 2016, after the funding was approved by China National Nuclear Corporation (CNNC), the construction project was fully launched. In Dec 2019, the superconducting main magnet and the RF system were transferred to the newly built commissioning site. Then, the RF commissioning, ion source and central region test were performed even during the pandemic in early 2020. In September 2020, after finishing the commissioning tests of all subsystems, the beam was reached the extraction channel but with very low efficiency. Since then, with more efforts on beam diagnostics, the fine tuning of the beam phase and the adjusting of the superconducting coil have been proven to be useful to get higher beam extraction efficiency ~55%. In this paper, the commissioning of the key components, including the main magnet, SC coils, internal ion source and central region, extraction system, etc, as well as the commissioning progress of the machine CYCIAE-230 will be presented.

INTRODUCTION

To meet the requirements of proton beam in the energy range of 200 MeV to 250 MeV for the uses of proton therapy and space science research in China, a superconducting cyclotron CYCIAE-230 was designed in CIAE. The overall parameters are listed in Table 1. And the layout of the very compact CYCIAE-230 superconducting cyclotron is shown in Fig. 1 [1].

Table 1: The Overall Parameters of CYCIAE-230

Beam	
Beam current from ion source	>10 μA
Ion source type	Cold PIG
Extracted beam energy	≥230 MeV
Extracted beam current	a few hundreds of nA
Magnet	
Pole structure	Spiral
Pole radius	85 cm
Weight	~ 80 ton
Hill gap	5.0 cm
Central field	2.3 T
Coils	
Coil type	NbTi wire
Current density	≤50 A/mm^2
Ampere-Turn Number	~600000 A.T×2
RF Cavity	
Number of cavities	4
RF frequency	~71.1 MHz
Harmonic Mode	2
Cavity Voltage	80 kV～110 kV
RF Amp. output Power	200 kW (max)
Extraction	
Method	Resonance crossing & processional motion
Elements for extraction	2 electrostatic deflectors and 6 magnetic channels
Deflector voltage	< 100 kV/cm
Deflector gap	5–7 mm

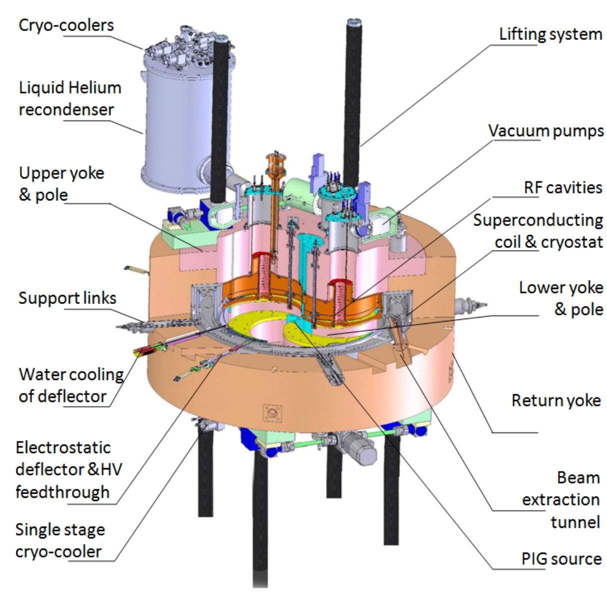

Figure 1: The layout of CYCIAE-230.

* Work supported by National Natural Science Foundation of China under Grants 11475269, 11375274; † cwang@ciae.ac.cn.

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COMMISSIONING OF SUBSYSTEMS

As the commissioning cite could not be in use before the end of 2019, the field mapping and shimming of the superconducting main magnet was performed in a different cite. The main magnet along with other subsystems of the cyclotron were then transferred to the commissioning cite.

Superconducting Main Magnet

As the requirements on the compactness, low cost and long-term operation stability for proton therapy, the warm iron with superconducting coil was adopted for the main magnet design of CYCIAE-230.

Enlightened by the superconducting coil technologies popular in the superconducting MRIs, the liquid helium zero-boiling cooling combined with GM coolers and the high copper/Sc ratio monolith or wire-in-channel NbTi wires, were used for CYCIAE-230 project. The R&D of the superconducting coil is successful for the team at CIAE as it is the first time for the team to deal with the superconducting magnet technology. Since the first cooling down and current excitation of the superconducting main magnet of CYCIAE-230 in 2018, it was only one time that helium leakage was encountered during last 5 years' operation, and it was due to both the failure of the power supply and the malfunction of the topology of the energy release module. The superconducting main magnet itself is very stable.

A search-coil based mapping system, consisting of a nuclear magnetic resonance (NMR) probe to precisely measure the field at the cyclotron centre and a moving search coil to obtain the field differences, was developed to satisfy the isochronous field accuracy requirements of 5×10^{-5}, as is shown in Fig. 2 [2].

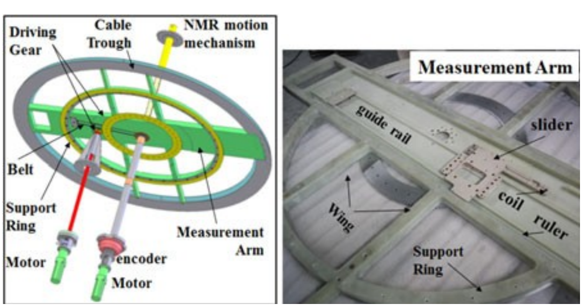

Figure 2: Layout of search-coil based mapping system.

After 5 times' shimming, the good isochronism has been achieved, and the integrated phase slip is within ±25°, as is shown in Fig. 3.

The first harmonic field is reduced to within 5Gs by slightly adjusting the radial support links of the superconducting coil, as is shown in Fig. 4.

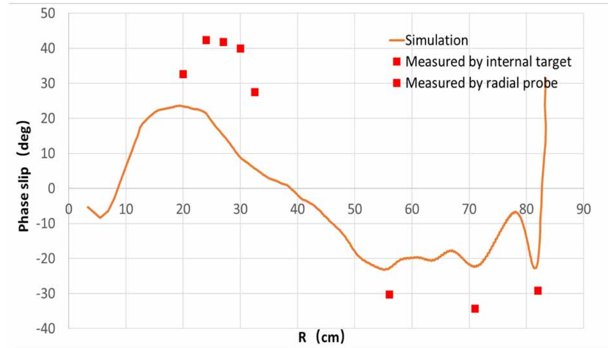

Figure 3: Integrated phase slip (solid line: SEO simulation with field mapping data; square dot: beam measurement using Smith-Garren method [3, 4]).

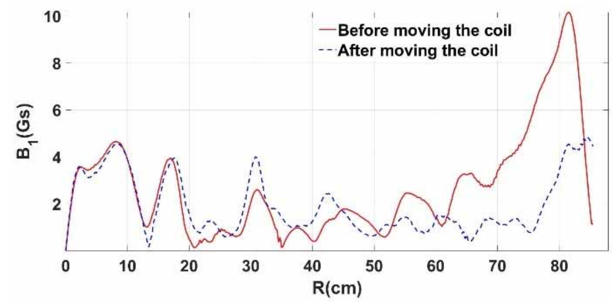

Figure 4: Shimming of the first harmonic field.

RF System

The RF system of CYCIAE-230 is quite unique. It contains four cavities working in push-pull mode to provide higher energy gain per turn, just like RF system design of other cyclotrons. However, each opposing pairs of cavities are mechanically connected in/underneath the central region and the coupled four Dees are driven by two separated power supplies through two independent RF couplers located in two valleys of the cyclotron [5]. The voltage and the phase of the Dees are controlled by one set of LLRF controller, as is shown in Fig. 5.

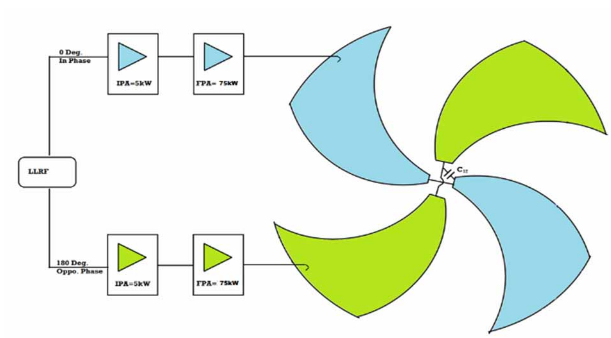

Figure 5: Layout of the RF system of CYCIAE-230.

The installation of RF cavities, coaxial line and RF amplifiers was finished in early 2020, as is shown in Fig. 6.

And both the frequency and Q value are within designed tolerance.

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Figure 6: Installation of RF cavities (upper left), coaxial lines (upper right) and RF amplifiers (lower).

Ion Source and Central Region

The ion source is a cold cathode PIG source. The beam trajectories in central region under different RF phase and the layout of the elements of central region are shown in Fig. 7. The central region consists of 4 electrodes, a fixed phase slit and a collimator.

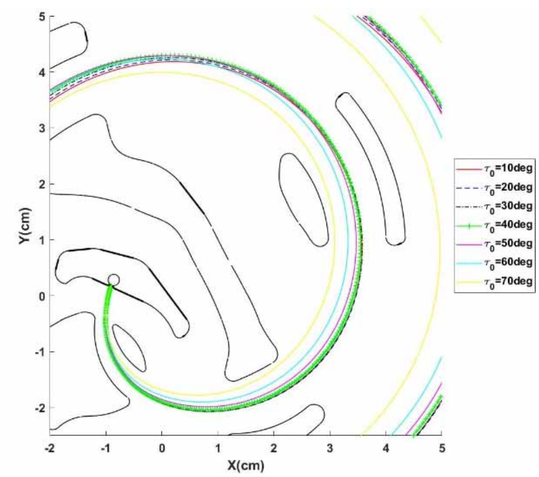

Figure 7: Beam trajectory at different RF phase in the central region.

By using an internal probe, the beam intensity in central region without any phase cut-off or collimation was measured and it is over 300 μA, which is more than adequate. The vertical centering of beam in the central region was verified by using copper films, phase slit or collimator, as is shown in Fig. 8.

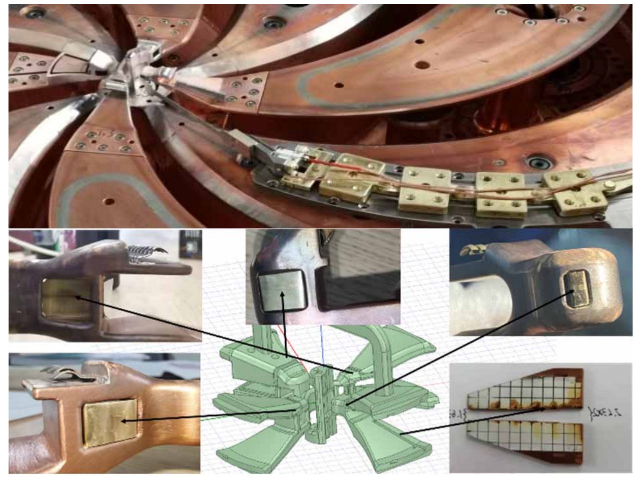

Figure 8: Beam measurement using internal probe (upper); vertical centering verification in the central region (lower).

Extraction System

The extraction system contains two electrostatic deflectors (ESD1 and ESD2) and multiple magnetic channels (MCs). The ESDs are each with 5~7 mm gap and operation voltages less than 70 kV. The MCs consist of multiple focusing and compensating iron bars with field gradient of ~3 kGauss/cm. A set of trim rods in extraction region is used to provide additional first harmonic field to generate processional motion and further enlarge the turn separation. Beam tracking at the extraction region shows that ~80% beam could be extracted and the most of the beam are lost on the deflectors. However, due to the compactness of the structure, the beam trajectory in extraction region is close to either ESDs, MCs or RF structure, as is shown in Fig. 9.

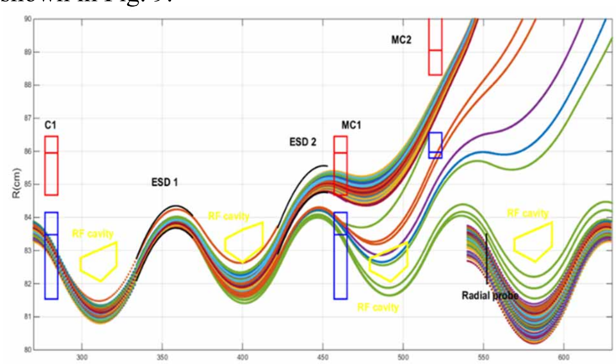

Figure 9: Calculated beam trajectories in extraction region.

Although the required the voltage for ESDs is not critical for high voltage (HV) engineering, many sparks in the ESDs were still encountered until a modification on HV feedthrough and a surface anodic oxidation on electrodes were applied. And now the operational HV of the ESDs could be achieved within 30 minutes without many sparks.

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BEAM COMMISSIONING

Compared to the experiences of beam commissioning of other cyclotrons at CIAE, the commissioning of CYCIAE-230 is more difficult. Due to the compact structure, the high and coupled magnetic-electromagnetic-electrostatic field, the beam diagnostics becomes difficult. And the use of the superconducting coil may introduce extra beam positioning error.

The commissioning process of CYCIAE-230 is also a process of inventing new beam diagnostics, which will be illustrated as follows.

Radial Centering

The beam is designed to be centered in central region, however, due to misalignment of the ion source, unexpected first harmonic field etc., beam off-centering is observed. A set of central region trim rods is used to generate a certain pattern of first harmonic field to suppress the beam off-centering, as is shown in Fig. 10.

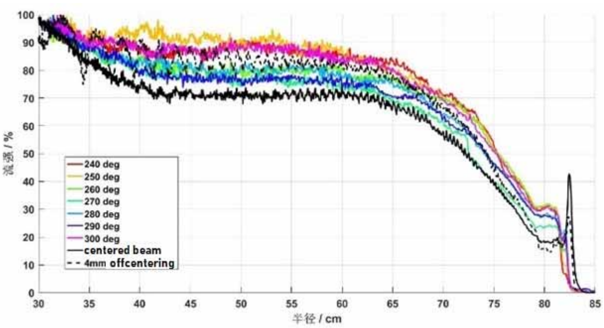

Figure 10: The comparison of simulated centered beam and measured beam in radial probe with different phase of first harmonic field in central region.

By using central region trim rods and with the signal from radial probe, beam centering could be achieved. Also, with the beam intensity signals from radial probe, the isochronous measurements were performed by using Smith Garron method [3, 4], as is shown in square dots in Fig. 3. The integrated phase slip is slightly larger than simulation using field mapping data.

Vertical Centering and SC Coil Alignments

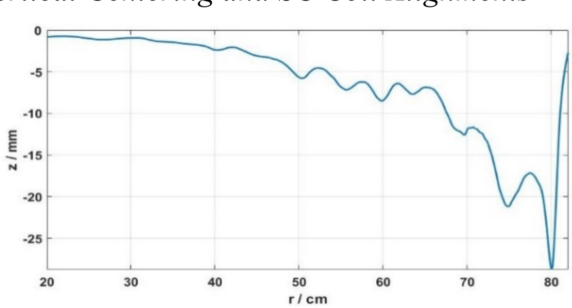

Figure 11: The change of vertical position of reference particle at different radius, when superconducting coil shifts 1 mm in vertical direction.

One of the major differences between superconducting and normal conducting cyclotrons is that the ratio of magnetic field generated by coil over the total magnetic field is much larger in superconducting cyclotron thus the coil position is very sensitive to the position of beam. According to our simulation, 1 mm coil shift in vertical direction equals to ~30 mm beam shift (as seen Fig. 11).

By using radial probe with 3 fingers, and adjusting the position of superconducting coil accordingly, the beam achieves vertical centering, as is shown in Fig. 12.

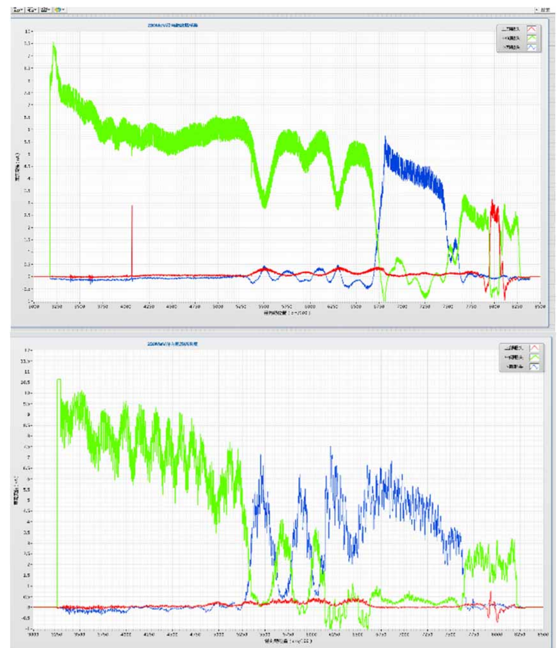

Figure 12: Radial probe signal before and after adjusting the position of superconducting coil. (green: middle finger; red: upper finger; blue: lower finger)

Beam Extraction Tests

The beam must pass the ESDs, MCs and the tailboard of the RF cavities before extraction with the tolerance of ~2 mm, where high magnetic field, electromagnetic field and electrostatic field are coupled. Special efforts have been made to develop reliable diagnostics to give more information on beam position, intensity etc., as is shown in Fig. 13.

Figure 13: Probe with radial fingers used for the commissioning of ESDs (left) and self-shielded probe for the commissioning of MCs(right).

After ~700 turns, the extracted beam has been measured at the end of the extraction port with a LIBERA current meter, as is shown in Fig. 14.

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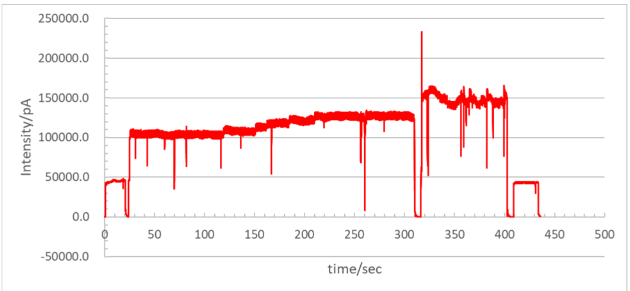

Figure 14: The beam on the copper target is over 150 nA with the energy of 241.6 MeV ~ 242.7 MeV (the energy is estimated by extraction simulation).

CONCLUSION

The commissioning progress of the machine CYCIAE-230 is presented and over 150 nA beam is obtained. However, the extraction efficiency is 55% at lower beam intensity (~10 nA) and will drop to ~40% at higher intensity. More efforts will be made to increase the extraction efficiency to further increase the beam intensity.

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