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Construction Progress of Two Superconducting Cyclotrons for Proton Therapy and Proton Irradiation at CIAE*

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Abstract

There are very strong demand for mid-energy of proton machine recent years due to the surging cancer patients and fast progress of the space science in China. For the applications of proton therapy and proton irradiation, the energy range of proton beam usually is from 200 MeV to 250 MeV, or even higher for astronavigation. Based on the R&D starting from 2009, two construction projects of 230 MeV and 250 MeV superconducting cyclotron, have been implemented recently at China Institute of Atomic Energy (CIAE). That was started in Jan 2015 for the 230 MeV machine, for the program of proton therapy and space science launched by China National Nuclear Corporation (CNNC), and in Jan 2016 for the 250 MeV machine, for the program of proton therapy launched by the Ministry of Science and Technology of China (MOST). In this paper, the designs for the two SC cyclotrons and their key components, including the superconducting main magnet, RF system, internal ion source and central region, extraction system, etc, and the construction progress of the machines will be presented.

INTRODUCTION

In China, there are strong demand for the same proton cyclotron in two independent fields, cancer treatment and aerospace science. Proton therapy based on the cyclotron is undoubtedly beneficial for more than 4 million new cancer patients every year. For the rapid development of China's space exploration, the radiation simulation based on proton cyclotron is also very useful, as all you may know. After 5 years R&D for the superconducting cyclotron development, the construction of a 230 MeV SC cyclotron was started in Jan 2015[1], and another one, 250 MeV SC cyclotron in Jan 2016[2].

GANERAL CONSIDERATION FOR CYCLOTRON DESIGN

According to the reasons mentioned in [1], we design the cyclotron main magnet based on superconducting technology instead of room temperature. For the convenience of engineering design and construction, we designed the two SC cyclotrons with the same pole radius, the inner/outer diameter of the return yoke, the structure of the upper/lower yokes, and the similar RF cavities. However, with the adjustment of the excitation current and RF frequency, the fine adjustment of the shape of the pole and centre plug is very difficult to meet all the requirements: the beam centering and phase planning in the central region, the smaller phase shift and the better vertical focus in the acceleration region, the high extraction efficiency in the outer region.

General Layout

The layout of the 230 MeV SC cyclotron CYCIAE-230 is illustrated in Figure 1. It consists of 16 sub-systems, e.g. the main magnet, SC coils and cryogenic system, RF cavities, ion source, etc. The CYCIAE-250 has the similar structure though the fine adjustment for the design of the machines is quite different.

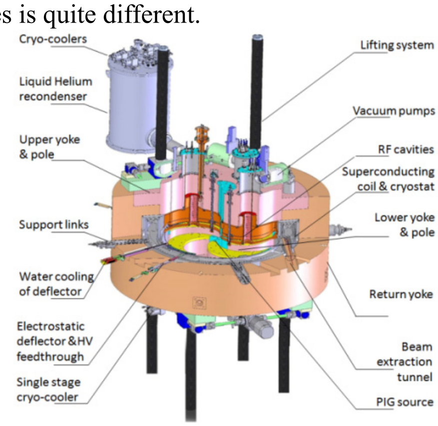

Figure 1: The layout of superconducting cyclotron CYCIAE-230.

Beam Dynamics

The tune diagrams of the CYCIAE-230, CYCIAE-250 and other medium energy SC cyclotron design, i.e., the MSU K250 design and the optimized version [3] are shown in Figure 2.

Obviously, the beam mainly crosses $\upsilon_r - \upsilon_z = 1$, $2\upsilon_z = 1$ and Walkinshaw resonance. Actually, the high extraction efficiency requires that only part of the particles with radial amplitude smaller than 1.5 mm can be accepted from the central region. So, the first two resonances, which are driven by field errors, have little effect on the beam quality. However, the Walkinshaw resonance, which is driven by the main field and is crossed at a few MeV before the extraction energy, will cause significant increase of beam profile in the case of ±2 mm off-centred beam [1].

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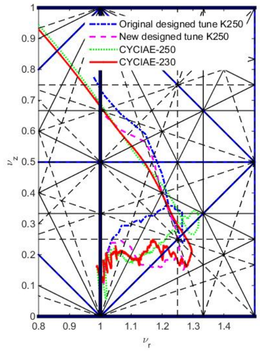

Figure 2: The comparison of tune diagram between the design results of CYCIAE-230, CYCIAE-250 and a K250 superconducting cyclotron [3].

Different from the straight cavity structure, the varying magnetic field generated by the spiral cavity is asymmetric hence has an impact on the particle trajectory, which was added in the main field to calculate the acceleration orbit. Beam dynamics, including static and acceleration state, are calculated with emphasis on the factors leading to envelop or emittance growth. Many resonances are crossed at large radius, which are investigated by adding imperfect driven term in main field and observing the influence on envelop. The tolerance for the first harmonic field is 2Gs in the range 15 cm to 25 cm, ensuring the off center less than 0.5mm to get a high extraction efficiency, while fortunately the trim rod for tuning isochronous field [4], is now adopted at central region to tune the harmonic field, could relax this constraint [5].To limit the axial oscillation amplitude less than 1 mm, the field Br should be less that 2 Gs at r < 20 cm and r > 70 cm, as indicated in Figure 3. The detailed descriptions of the resonances and tolerances are listed in [5] in detail, and will be referenced for the quality control of the main magnet.

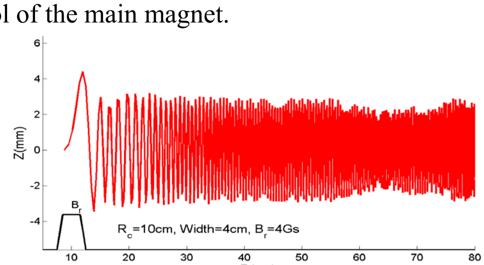

Figure 3: Influence of Br on the axial oscillation amplitude.

As indicated in Figure 2, more efforts have been made in beam dynamics design of CYCIAE-250, to increase vertical focusing before the extraction energy, in addition to get more smooth design result.

DESIGN AND PROGRESS OF THE SUPERCONDUCTING MAIN MAGNET

The superconducting main magnets of CYCIAE-230 and CYCIAE-250 consist of pure iron magnet and the superconducting coil system. The pure iron magnet contains upper yoke/poles, bottom yoke/poles, a return yoke, multiple shimming plates and shimming bars. As the superconducting cyclotrons are dedicated for proton therapy, the superconducting coil technologies which are popular in superconducting MRI magnet for medical image, i.e., NbTi superconducting coils made of high copper/Sc ratio monolith or wire-in-channel NbTi wires working at 4.2 K, and the liquid Helium zero-boiling cooling using GM coolers, are found to be extremely suitable for long term, high availability operation in hospital. The inner wall of the cryostat, made of low carbon steel, is not only the outer-layer vacuum chamber of the superconducting coil but also the vacuum chamber for the proton acceleration, and more importantly is part of the magnetic path, which turns out to be important for shaping the magnetic field in large pole radius [1].

3D full 360° magnet models are used to perform detailed pole shape and shimming plates optimization to reduce the phase slip and optimize spiral angles to improve beam-focusing properties. The average magnetic field of CYCIAE-230 and CYCIAE-250 are shown in Figure 4. Although the magnetic rigidity of CYCIAE-250 has increased, we have managed to maintain the same pole radius as CYCIAE-230. This will greatly simplify the design of other subsystems for CYCIAE-250.

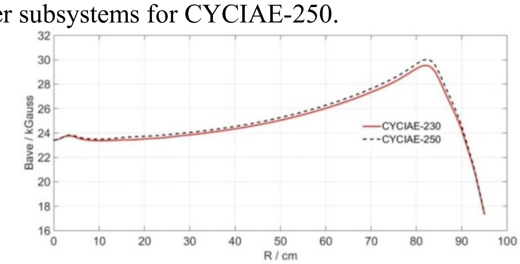

Figure 4: The average magnetic field of CYCIAE-230 and CYCIAE-250.

From the construction experience of CYCIAE-100 [7], a room temperature 100 MeV cyclotron with 416 ton main magnet, more dedicated pure iron forging pieces from domestic supplier with specified chemical composition, are used for the main magnet of CYCIAE-230, and the B-H curve measurements show comparable magnetic properties of the pure iron forging pieces of CYCIAE-230 with the imported rolled plate used for the pole of CYCIAE-100 [5]. After a slow but very carefully construction process, as highlighted in Figure 5, the main magnet of CYCIAE-230 has been delivered to CIAE.

Although this is the first time that CIAE conducts the superconducting cyclotron, after 18 months' very close cooperation with the superconducting coil system manufacturer on the R&D, it took less than 1 week to cooled down the superconducting coils system to the liquid Helium temperature ~4.2 K by using first liquid Nitrogen and then liquid Helium bath in December 2016 [6]. The superconducting coil has been successfully ramped to its design current without any quench. Then after the field mapping tests without iron magnet, the check upon delivery organized by CIAE with the witness of expert from CNNC, and a low field forced-quench test, the superconducting coil system has been successfully transported to CIAE on 29th June 2017.

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In April 2018, the superconducting coil system has been installed into the main magnet at a clean room at CIAE, as is shown in Figure 6.

Figure 5: Highlights of main magnet fabrication. (From left to right, top to bottom: fine machining of pole and yoke, turnover of pole pieces, fine alignment of pole, installation of central plug and lifting system).

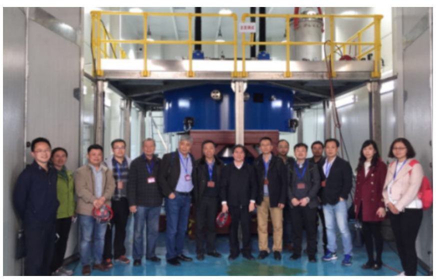

Figure 6: The superconducting main magnet installation.

Field mapping and shimming will be performed after the acceptance tests of the superconducting coil system.

The pure iron forging pieces for the main magnet of CYCIAE-250 are produced and ready for fin machining, as is shown in Figure 7. According to the chemical composition test results from the manufacturer, all the forging pieces fulfil our specification. The double check of the chemical composition and the measurement of BH curves are under way.

Figure 7: The pure iron forging pieces for the main magnet of CYCIAE-250.

DESIGN AND PROGRESS OF RF SYSTEM

General Description of RF System

The CYCIAE-230 cyclotron has its own unique characteristics in the RF system design. The RF system has four cavities. Each opposing pairs of cavities are mechanically connected through/underneath the central region. The two pairs of cavities jointed together by distributed capacitance in the central region. These coupled Dees are driven by two separated 75kW RF amplifiers through two independent couplers located in two valleys of the cyclotron. The voltage and the phase of the Dees are controlled by one set of low level RF(LLRF) controller. The usage of rigid bridge to connect the two satellite resonators could firstly eliminate a parasitic resonance mode, and secondly make the usage of two set of 75kW amplifiers to drive two set of cavities be possible. The latter gives the advantage of better phase balance between the main cavities and the satellite cavities.

The CYCIAE-250 cyclotron has inherited the design of the RF system of CYCIAE-230, but slightly changes the shape and size of cavities near the extraction radius.

Construction Progress of the RF system

The four RF cavities of CYCIAE-230 have been manufactured as is shown in Figure 8. The initial low power measurement gives a very promising result that unloaded Q value of 8000 is achieved.

Figure 8: RF cavities of CYCIAE-230.

The hardware of the LLRF control unit which is based on the previous experience with RF control of CYCIAE-100 cyclotron, as is shown in Figure 9, has been successfully tested with a 162MHz double-Dees resonator system at low power level [8].

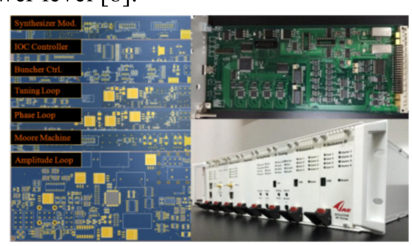

Figure 9: The LLRF control unit.

The two sets of 75 kW amplifiers are also manufactured. The 8 hours' endurance test has been performed before the delivery in the beginning of 2018. And now all the elements of RF system have been delivered to CIAE. Further tests on RF system are under way before the installation.

For CYCIAE-250, the two sets of amplifiers are under construction now and the RF cavities are also under fabrication by the same manufacturer.

OTHER SUBSYSTEM

The structure of the ultra central region and ion source is shown in Figure 10.

The ultra compact central region contains dual hard bridges which connect each opposing pairs of RF cavities, electrodes for beam focusing, and connect port to ion source. To reduce sparks in central region, the accelerating voltage of ~72 kV is chosen for stable operation.

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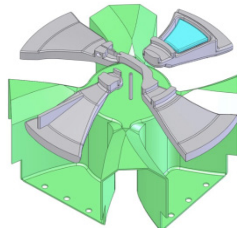

Figure 10: The structure of the central region and ion source.

The ion source is an ultra compact internal PIG source. The prototype ion source has already been manufactured and tested on a test stand as is shown in Fig. 11. More than 60 μA proton beam has been obtained.

Figure 11: The internal PIG source test stand.

The extraction system contains two electrostatic deflectors (ESD1 and ESD2) with ~7 mm gap/operation voltage less than 60 kV and magnetic channel (MC) consisting of multiple focusing and compensating iron bars with field gradient of ~3 kGauss / cm. Beam tracking at the extraction region shows that the most of the beam are lost on the deflectors, less than 2% of beam are lost at iron bars, and ~80% beam could be extracted [1].

The ESD1 which contains an extra water-cooling port is already manufactured and under test now as is shown in Figure 12.

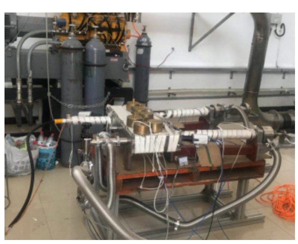

Figure 12: The ESD1 test stand.

The manufacture and test of other elements of extraction system of CYCIAE-230 will be finished before the RF conditioning.

As the extraction radius of CYCIAE-250 is slightly larger the arrangement of the extraction elements will also changed accordingly.

The construction of other subsystem, like the vacuum system, water cooling system, etc., will also be finished in 2018.The integration of all subsystems should be finished in early 2019 for beam commissioning test.

Special attention has been paid to the design of control system, as design specifications for control system of proton therapy machine are quite different from a research machine like CYCIAE-100, especially in system redundancy, dose stability control and control of fast turn-on/off of beam.

CONCLUSION

Motivated by the very strong demand for mid-energy of proton machine recent years due to the surging cancer patients and fast progress of the space science in China, and based on the R&D starting from 2009, two construction projects of 230 MeV and 250 MeV superconducting cyclotrons, have been launched recently at CIAE. The designs for the two SC cyclotrons have been finished. The constructions of the main components of CYCIAE-230, including the SC main magnet, RF system, internal ion source are already finished and initial test results are quite promising. Other key components like the central region, extraction system, etc, of CYCIAE-230 will be finished in 2018. The construction of CYCIAE-250 has also started since 2017.

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