



Magnetic field test of superconducting coils for the compact proton therapy cyclotron

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Received: 11 May 2018 / Accepted: 31 July 2018 / Published online: 10 August 2018
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Abstract

The superconducting cyclotron for proton therapy that is under design by ASIPP (Hefei, China) and JINR (Dubna, Russia) will be able to accelerate protons to the energy 200 MeV with the maximum beam current of 1 μA . The performance of superconducting magnets is the key to the superconducting cyclotron, and it will directly affect the quality of the proton beam and the therapeutic effect. To measure the magnetic induction intensity of the superconducting coil with the cryogenic Hall probes on the testing platform. As the current has been increased from 0 to 160 A, the measurement error of probes decreases obviously whose tendencies are consistent. By comparing the measuring results with the theoretical results, we can confirm the quality of superconducting coil and the installation location. Meanwhile, the basic operation of cryogenic Hall probes and data acquisition system is grasped, and the experimental experience for the magnetic intensity test of superconducting cyclotron has been accumulated.

Keywords Cyclotron · Superconducting coils · Magnetic intensity measurement

Introduction

Proton beam therapy is a method for treating tumor with externally generated energetic proton beams [1]. The most essential requirement for a compact proton therapy cyclotron is high reliability and availability of the complete system. Compact proton therapy cyclotrons are increasingly used for cancer treatment, nuclear medicine, ion implantation, and nuclear materials testing [2, 3]. Superconducting coils have been used for cyclotrons due to advantages high magnetic intensity and low operation costs compared with conventional magnets. As a key component of cyclotron, the superconducting magnet is responsible for the beam path guidance and beam stability gather; meanwhile, it provides the isochronous magnetic intensity for particles [4, 5].

The primary goal of magnetic intensity test is to provide the necessary data for cyclotron stable operation, or for accurate analysis of data from some detectors. It also can check whether the superconducting coils winding are correctly assembled. It is necessary, therefore, to precisely measure the field in the as-built superconducting coils. The measurements can also be used to monitor trends and random errors in production operation of a large magnet [6].

This paper mainly describes the magnetic intensity test and analysis of the superconducting magnet in compact proton therapy cyclotron. The detailed design of the superconducting magnet has been described in the another under-reviewed paper <Superconducting Magnet Design for Compact Superconducting Cyclotron>, which displays the superconducting magnet design, assembly analysis, and the magnet tests so on.

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Superconducting magnet

The superconducting magnet system mainly consists of the iron yoke, superconducting coils and cryostat. The magnet pole is composed of four spiral sectors, which is fourfold

axisymmetric. The superconducting coil winding includes upper and lower symmetrical structure coils. The superconducting magnet cryostat contains low-temperature superconducting magnet, the thermal shield, the cryostat, the heat exchanger, and the current leads. The high vacuum state is formed between its inner wall and the upper and lower of the magnet pole. The proton beam will be accelerated and do the turning movement to achieve the required energy by the radio frequency (RF) cavity under the vacuum field, which is extracted by the electrostatic deflection plate. As the superconducting magnet operating in nuclear environment, the superconducting coils are researched and designed with a sufficient temperature margin and high precision. At last, the cross-sectional view of the test platform for coil pair is shown in Fig. 1.

The main components of the test platform are: superconducting coils, thermal shield, cryostat, and current lead. The one pair of compact superconducting coils are symmetrically arranged which is surrounded by the iron. The NbTi has been adopted as the superconducting conductor. The coils carry the current in the same direction which can provide a magnetic intensity. When the excitation current reaches 750,000 A*turn, the average magnetic induction intensity will achieve 4.5 T. The main parameters of superconducting coils are shown in Table 1.

Using conductor NbTi and operating at 4.2 K liquid helium temperature, its specific parameters are shown in Table 2. The superconducting magnet has been fabricated by the wet winding method by using epoxy. The NbTi multi-filamentary composite superconducting wire, consisting of 40 filaments of 82 μm embedded in copper matrix, was used. The superconducting wire was wound on the skeleton with stainless steel 304. And the strict quality control was enforced during coil winding. The stainless-steel wire with 1 mm diameter was employed to support the electromagnetic force in the superconducting coils. The

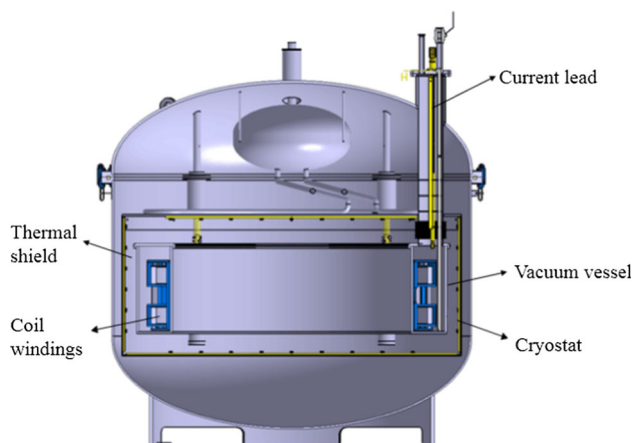


Fig. 1 Cross-sectional view of the test platform

Table 1 Main parameters of the superconducting coils

Items	Value
Magnet type	Compact, SC coils
Main coil	2
Conductor	NbTi
Average magnetic intensity (T)	4.5
Stored energy (MJ)	4.3
Inner diameter (mm)	1200
Outer diameter (mm)	1285.4
Operating current (A)	160
Inductance (H)	158
Coil height (mm)	106.5
Total layers per coil	74
Conductor turns per layer	85

Table 2 Parameters of conductor NbTi

Items	Value
Insulation thickness (mm)	0.05
Filament diameter d (μm)	82
Critical current I_c (A)	$> 500@4.2 \text{ k}, 5.0\text{T}$
Transverse sizes of the coil (mm)	1.20*0.75
Temperature margin T_{marg} (K)	> 1.5
Current density (A/m^2)	7.58×10^8
Cu/NbTi ratio	4

standard NbTi conductor is adopted and the number of coil turn is 4700.

Taking into account the operation environment of superconducting magnet, its energy storage can compare with the medicinal superconducting magnetic resonance imaging (MRI) device [7]. The two-stage Gifford–McMahon (GM) cryo-cooler technology is being considered for steady state liquefaction of evaporated helium gas from magnet cryostat. A two-stage GM cryo-cooler was installed at the top right corner of system, which can condense helium gas. In addition, a single-stage GM cryo-cooler was used to cool the cryostat thermal shield [8, 9]. The system can also be self-sustaining operation under the power failure or cryo-cooler malfunction for a period of time. Therefore, the GM cryo-cooler has been employed by the superconducting magnet coil system, whose refrigeration efficiency is very high. Consequently, the overall system is almost no liquid helium loss.

The quench detection system can detect the magnet quenches timely and cut off its power supply to protect the superconducting magnet effectively. The stored energy of the superconducting magnet is about 4.3 MJ. The

appropriate quench protection system is required to protect the superconducting magnet against damage during a quench. The quench protection circuit has been designed to limit the quench hot spot temperature and the quench voltage. The two split coils are subdivided into four sections to limit the quench voltage. Each section is in parallel with a back-to-back diode and a dump resistor. To accelerate the quench propagation, the quench heater was adopted. As a further study, we will describe the quench protection design and the relevant quench analysis in detail in the following paper.

Furthermore, the superconducting joint quality is one of the most important standard of coil quality. Accordingly, the joint stability directly affects the stable operation of the superconducting magnet in low temperature. There are three coil joints and the design resistance for coil joint is less than 10 nΩ.

Test platform for the superconducting magnet

Theoretical calculation and simulation

The superconducting coils are the critical components in cyclotron, which are responsible for the beam path guidance and gathering stability. Because of the manual winding method for superconducting magnet, therefore, some human factors come from positional or shape deviations that will cause inaccuracy of magnetic intensity. As a result, it is extremely essential to calculate and measure the magnetic intensity generated by superconducting magnet, which can validate the rationality design and processing of superconducting magnet.

Owing to the circular superconducting magnet, the magnetic intensity computation formulas of circular current loop are following. According to these formulas, the axial magnetic induction intensity B_z and radial magnetic induction intensity B_r can be calculated at any location in the superconducting magnet.

$$B_r = \frac{\mu I}{2\pi r} \frac{z - c}{\sqrt{[(R + r)^2 + (z - c)^2]}} \left[-K + \frac{R^2 + r^2 + (z - c)^2}{(R - r)^2 + (z - c)^2} E \right] \tag{1}$$

$$B_z = \frac{\mu I}{4\pi} \frac{1}{\sqrt{[(R + r)^2 + (z - c)^2]}} \left[K + \frac{R^2 - r^2 - (z - c)^2}{(R - r)^2 + (z - c)^2} E \right] \tag{2}$$

$$k = 2\sqrt{\frac{Rr}{(R + r)^2 + (z - c)^2}} \tag{3}$$

where the center O is $(0, 0, c)$, the point a is (r, z) , the radius is R , the current goes in counterclockwise.

The K and E are the first and second complete elliptic integrals, respectively.

$$K = K(k) = \int_0^1 \frac{dx}{\sqrt{(1 - x^2)(1 - k^2x^2)}} (|k| < 1) \tag{4}$$

$$E = E(k) = \int_0^1 \sqrt{\frac{1 - k^2x^2}{1 - x^2}} dx (|k| < 1) \tag{5}$$

According to the above theoretical formulas and the actual superconducting magnet size, the magnetic intensity distribution around the superconducting magnet was calculated, and it is shown in Fig. 2. The inside and the upper magnetic induction intensity is bigger, but that of outside is smaller. The distribution shows that the closer it gets to the coil, the bigger the magnetic intensity strength gets.

According to the cyclotron design requirements, a 3D model of superconducting coil has been built. Then the magnetic intensity distribution of superconducting magnet and its cross-sectional plane was achieved by the ANSYS code. Since the superconducting coils are circular and their installation position is symmetrical, the red rectangle represents the superconducting magnet skeleton cross section, and those different curves represent different magnetic intensity values in Fig. 2. More specifically, it can provide an important reference for selection of test points in the future.

Experimental testing of superconducting coil

Many measurement tools can be utilized to measure the magnetic intensity like the Hall probe, the Nuclear magnetic resonance (NMR) probe or the search coil. The C235 IBA-SHI proton therapy cyclotron has adopted the Hall probe to measure the magnetic intensity because its resolution is better than 1Gs [10]. The IBA’s C70 cyclotron has adopted a Hall probe connecting to some home-made electronics, and azimuthal accuracy obtained by mechanical index [11]. The magnetic intensity at median plane of SCC Magnet with peak field of 5.8T is measured over its

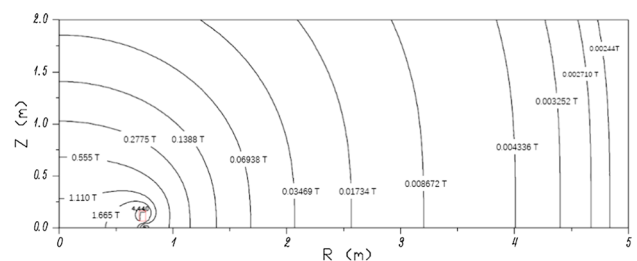


Fig. 2 Magnetic intensity distribution generated by superconducting magnet

operating range. The combination of search coil and digital integrator are used to measure the difference in the field between the center and any other point of the magnet. An optical encoder system of 360 LPI was used to measure the search coil position [12, 13]. The newly developed superconducting synchrocyclotron S2C2 is the first non-isochronous and superconducting cyclotron build at IBA. The mapping system consists of a search coil, a Hall probe and an NMR probe, which are all mounted on a wheel. The NMR probe can be positioned in the center of the S2C2, where the field homogeneity is good enough to measure the 5.72 T field with a high precision [14].

All in all, although the NMR probe can provide sufficient resolution to detect any deviations from the linear field description, considering testing environment from Table 3, the cryogenic Hall probe Lakeshore 3020 is a more appropriate measurement tool. For convenience, we define the cryogenic Hall probe Lakeshore HGCT-3020 and HGCA-3020 as MI-01 and MI-02, respectively.

Based on the results in Figs. 2 and 3, in order to decrease the measuring error, we can choose the positions of maximum field as testing points, and then compare the testing results with the theoretical results. As a result, the Hall probes have been installed at point *a* and point *b* of blue skeleton shown in Fig. 4, and their positions are point *a* coordinate (691.2, 180 mm) and point *b* coordinate (701, 200 mm), respectively. The data transmission cables have been extracted from the superconducting magnet through aerial socket, which were accessed to the general control machine.

Table 3 Testing requirements of magnetic intensity

Characteristic parameters	Value
Magnetic range (T)	< 4.6
Magnetic sensitivity (mv/kG)	0.55–1.05
Transmission line type	AWG copper wire of 12 m
Temperature environment	4.2 K with liquid helium
Material of probe holder	
Measuring environment	G10
Vacuum	

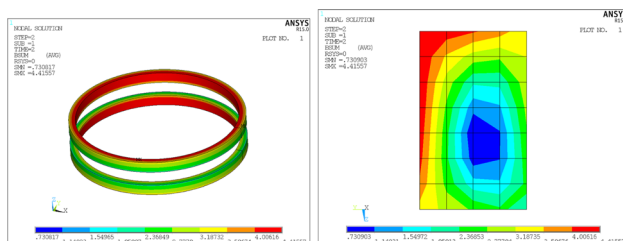


Fig. 3 Magnetic intensity distribution of superconducting magnet and its cross-sectional plane

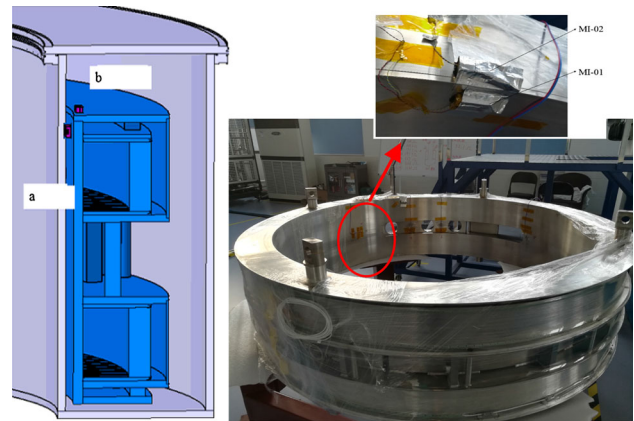


Fig. 4 Installation of cryogenic Hall probe

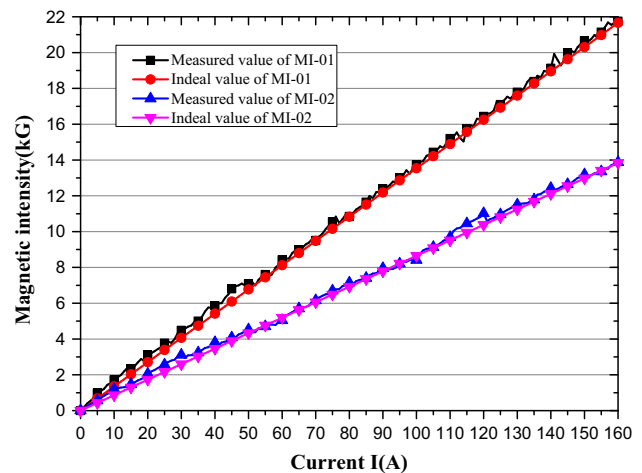


Fig. 5 Fitting curves of MI-01 and MI-02

The two cryogenic Hall probes MI-01 and MI-02 are axial and transverse probe, respectively, that can measure the magnetic induction intensity directly. The characteristic of probe is that its magnetic sensitivity will increase along with the decreasing temperature. And its nominal control current and maximum load current are 100 mA and 300 mA, respectively. The transverse probe measures the radial magnetic induction intensity of superconducting magnet at the testing point A; meanwhile, the axial probe measures the axial magnetic induction intensity of superconducting magnet at the testing point b.

Before the operation of superconducting magnet, it should be ensured that the installations of probes are correct. To achieve more accurate results, the sensitive surface of probe should be perpendicular to the magnetic induction intensity. Therefore, the fixtures were made to fix and protect probes with material G10, which were fixed on skeleton by cryogenic adhesives.

Secondly, the probe cable extracted through the aerial socket, the red and yellow wires were connected to the

constant power supply of 100 mA, while the black and blue wires were connected to the data acquisition system that can output and store voltage signals U_a and U_b . Then the magnetic induction intensity values B_a and B_b were transformed from the voltage signals.

As a result, it could provide the basic performance parameters for the superconducting magnet. Moreover, it will be used as the critical reference basis to verify whether the superconducting coils can work normally or not.

Results and discussion

By adjusting the exciting current of superconducting magnet, the data acquisition system gathers the voltage signals U_a and U_b from cryogenic Hall probes MI-01 and MI-02, respectively. Thus, the magnetic induction intensity values B_a and B_b of testing points have been measured. Consequently, the measured values are following which can be compared with the theoretical values.

As shown Fig. 5, the distribution trends of magnetic measurement data and simulation data are consistent. For the cryogenic Hall probe MI-01, the error is bigger in the current range of 0–53 A. As the current increases to 160 A, the measurement error decreases. For the cryogenic Hall probe MI-02, the error is bigger in the current range of 0–38 A. As the current increases to 160 A, the measurement error decreases. The absolute error and relative error are shown in Fig. 6, and the measuring error curves tendency of MI-01 and MI-02 are consistent. When the current is 160 A, the magnetic induction intensity with B_a is 1.387 T and that of B_b is 2.1747 T. By the theoretical calculation formulas (1)–(3), the theoretical magnetic induction intensity with B_a is 1.3836 T, and that of the B_b is 2.1656 T. Therefore, the measuring errors are 0.02426% and 0.00740%, respectively. The measurement accuracy of the

B changes with the current. For the current range of 0–53 A, the measuring error ascends in low field. For the current range of 53–160 A, the measuring error decreases in high field. The maximum relative error of probes is less than 120 Gs.

In experiments, the factors causing error have been analyzed. Many factors will contribute to the measurement error, such as probe positioning, probe temperature, probe precision. There are two important factors: one is that the installation location of Hall probe is relatively close to the current lead, which has a serious impact on Hall probe working; the other factor is that the other much higher voltage level of wires may be serious interference on the measured voltage signals. In addition, as the water in the aerial socket, it will cause certain influence on the test results. Therefore, it shows that the probe wires should be picked up alone.

The installation position and wiring of the cryogenic probe are very important, in particular, doing a good job for cable shielding protection, so that, the experience of the experiments will be referenced for hall probe and have important guiding significance on the cyclotron magnetic intensity measurement in the future.

Conclusion

From the measurement results, the curves of magnetic induction intensity are consistent with the theoretical values. It confirms the magnetic intensity distribution of superconducting magnet is reasonable. The design and winding quality of the superconducting magnet are qualified. At the same time, it also shows that the structure design of cryostat, heat transfer and current lead are reasonable and reliable. The work has accumulated a lot of valuable experience for further research and practical application of superconducting magnet system and magnetic intensity measurement of superconducting proton cyclotron in the future.

Acknowledgements The authors would like to express thanks to members of team for their enthusiastic helps and useful discussions.

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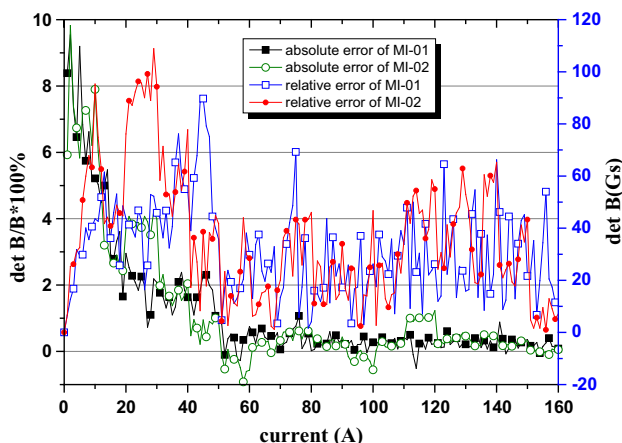


Fig. 6 Measuring error curves of MI-01 and MI-02

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