Cryogenic System Design and Performance Test of Calibration Magnet

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Abstract. According to the requirements of high-energy particle accelerators, a cryostat system was designed and manufactured to provide a low-temperature environment for high uniformity superconducting magnet used for calibration. The performance test of the calibration magnet system including linearity, locking area, stability, and uniformity was completed. This system uses a single 1.5 W @ 4.2 K refrigerator by combining direct conduction cooling with indirect conduction cooling of the gravity heat pipe. The superconducting magnet was cooled to 4 K and entered the superconducting state, and the minimum temperature reached 2.8 K within 40 hours. The maximum excitation current is 300 A and the maximum magnetic field reaches about 6.2 T. At present, the equipment has been running stably for more than 90 days.

1. Introduction

In high-energy particle accelerators, the superconducting magnet is an important part. The properties of the magnet and the magnetic field map will directly affect the dynamic performance of the particles [1]. The range of magnetic field measurement is required to be 1.0 T ~ 5.0 T [2], and the deviation value of the isochronous field needs to be less than one-tenth of the magnitude. Therefore, the accurate measurement and calibration of the magnetic field in the accelerators is critical. In practical applications, the Hall sensors can be applied to magnetic field measurement of complex structures and narrow regions in the accelerator systems. They can meet a wide range of magnetic field measurements [3][4]. However, the Hall coefficient is nonlinear under the high magnetic field (more than 1.2 T) [5], which is inconvenient for the high precision measurements in the high magnetic field.

In recent years, different calibration magnets at the accuracy level of one-millionth have been developed. However, the magnetic field is no more than 3.0 T in most calibration magnets, and the superconducting coils were immersed in liquid helium of the cryostat during operation [6][7]. In addition, there are also some studies on room temperature magnets to fulfill the field calibration requirements, such as the Brook National Laboratory [8]. However, the immersion cryostat increases the complexity of the device, and it is not convenient to calibrate the magnetic field at any time and move at different locations. Moreover, the room temperature calibration magnet cannot meet the requirements of a large current and high magnetic field. Therefore, according to the requirement of magnetic field measurement and sensor calibration of the isochronous cyclotron in the Hefei superconducting proton therapy project, a superconducting magnet system for the calibration of Hall sensors needs to be designed and manufactured.

In the previous study [9], the conceptual design was established. The magnetic field uniformity, external stray field, and mechanical stress in the binding, cooling, and excitation of the superconducting magnet were analyzed, and a superconducting magnet with high uniformity was manufactured.
In the current study, since the superconducting magnet system is a user-oriented product, to meet the needs of long-term stable operation and periodic magnetic field calibration, a cryostat including the gravity heat pipe and micro-gap heat exchangers is optimized and fabricated to provide a low-temperature background for the high-uniformity superconducting magnet. This system uses a single 1.5 W @ 4.2 K refrigerator and realizes zero evaporation with few liquid heliums in the circulation. Subsequently, the cooling test of the cryostat was carried out. The minimum temperature of the superconducting magnet reaches 2.8 K within 36 hours. The cryostat reduces the system's complexity and weight by using heat pipe indirect conductive cooling and dramatically reduces the consumption of liquid helium. The total weight is controlled within 110 kg. The eccentric layout reduces the system volume, and the total capacity is only 370 L, which is convenient for maintenance and assembly and has the characteristics of mobility and flexibility. Finally, the magnetic field linearity, locking range, and uniformity of the superconducting magnet system were tested. The coil is excited to 300 A without quench and the maximum magnetic field reaches about 6.2 T. The tested uniformity of the magnetic field reaches about 75 ppm @ φ20 mm × 20 mm.

2. Design and optimization of the cryostat
The design and manufacture of cryostats need to involve cryogenic technology, thermodynamic technology, vacuum, insulation, mechanical and material sciences. The cryostat not only needs to meet the low-temperature background, high vacuum degree, and sufficient structural strength but also needs to consider the influence of the high homogeneity magnetic field and temperature uniformity, as well as the compact size and mobility flexibility.

2.1. Cooling system of the cryostat
In the cryostat, several oxygen-free copper tapes with high thermal conductivity are connected to the magnet directly from the heat exchanger. Moreover, the helium gas at room temperature is injected into the cooling chamber from the inlet of the refrigerator flange. As shown in Fig. 1 and Fig. 2.

The helium gas is cooled through the two-stage heat exchangers of the refrigerator and turned into liquid helium in the tank. The liquid helium flows into the finer pipe and cools the magnet through indirect conduction cooling of several gravity heat pipes, which adopts an 8-way parallel connection with six risers and two inner ring pipes embedded in the copper flanges. The helium flows down the inlet and up the outlet to form a cycle. The liquid helium absorbs the heat from the magnet and turns into helium vapor, then the gas is flowed back to the storage tank and cooled again through the heat exchanger. In addition, a relief pipe with a large diameter is added to the outlet pipes above the magnet. The liquid nitrogen cooling cycle is added to the system and connected directly to the magnet to reduce the cooling time.

In calculating the circulating pressure in the heat pipes, the influence of capillarity should be taken into account, and the mass flow rate of liquid helium should be pre-checked according to the heat load. The reasonable size of the pipe should be designed to ensure that there is sufficient pressure difference to realize the circulating flow in the pipes.

In the cooling process, the heat transfer mainly depends on the micro gap heat transfer of the two-stage male and female heat exchangers. When the temperature drops below 30 K, the gravity heat pipe plays the leading role, and the copper braided tape plays an auxiliary role.

The gravity heat pipe and micro-gap heat exchanger reduce the vibration influence on the high-uniformity magnetic field in direct connection and improve the magnet's temperature uniformity by using the high heat transfer pipes. In the test, the superconducting magnet is below 3 K and improves the stability in engineering applications. The micro-gap heat exchanger makes the helium close to the static state in the gap. The fin area is doubled through the male and female exchanger, and the thermal conductivity of helium at low temperature is one order of magnitude higher than that at room temperature, which replaces the traditional convective exchangers in the G-M refrigerators. The cooling time of the system is reduced from 45 hours to 36 hours in the following test.
2.2. Layout type and design result

Current leads are set on the same side of the magnet to facilitate the arrangement and welding of superconducting wires in the cryostat. The low temperature superconducting (LTS) leads were cooled through the cooling plates on the magnet, and the 1060 aluminum alloy is used as the thermal shield. This arrangement makes the thermostat structure clear and easy to install and maintain. At the same time, the larger spacing is beneficial for the laying of multilayer insulation, heat treatment of narrow locations, and assembly operations. The eccentric arrangement was used between the magnet and the refrigerator to ensure compact internal space. The equipment such as the refrigerator, valves, and pipes was connected from the refrigerator's right side, and the operator measures the magnetic field near the room temperature hole on the left. The structural section of the cryostat is shown in Fig. 2.

In this paper, the heat leakage of the cryostat was calculated and verified by experiments, the heat loads of the first and second stages were optimized, and the stress distribution was checked and analyzed. The final design results of cryostat are shown in Table I.

Table I

| Items                        | Value      |
|------------------------------|------------|
| Diameter of Dewar            | 660 mm     |
| Height of Dewar              | 1027 mm    |
| Maximum height               | 1300 mm    |
| Temperature                  | 4.2 K/55 K |
| Heat load of the first stage | 34.65 W    |
| Heat load of the second stage| 0.368 W    |

2.3. Processing and assembly of the cryostat

The cryostat mainly consists of several parts, including the Dewar and thermal shield, the cooling pipes, the current leads, the heat exchangers of the refrigerator, the accessory parts, and measuring units.

In the process of manufacturing, different welding types were selected according to different materials and design requirements. For example, the indium bismuth tin solder with a melting point of about 90 °C was used for welding the gravity heat pipes buried in copper tiles. In addition, the flux with
a low melting point was added to increase the bonding strength of solder. Before installation, the heat pipes were immersed in liquid nitrogen to verify the strength at low temperatures.

The system is composed of many sub-assemblies in the assembly process, and each sub-assembly is composed of several parts. So every component needs to be classified in advance and trial-assembled to verify the reliability of the assembly sequence. Several parts need to be optimized and simplified as much as possible to save the materials. The internal structure during assembly is shown in Fig. 3, and the two-stage heat exchanger of the refrigerator is shown in Fig. 4.

The critical current of the Bi 2223/ Ag-Au superconducting tapes does not change obviously below 300 ℃ but decreases slightly after 500 ℃ [10]. Therefore, the welding temperature needs to be controlled below 300 ℃. The local peak temperature shall not exceed 480 ℃, and the welding time should be controlled within half an hour as far as possible.

The heat transfer efficiency of AlN insulating gaskets produced by different factories and batches varies significantly due to internal defects in grains [11]. When the domestic gaskets are used in the current leads, the temperature difference can reach above 5 K at the position of the thermal shield. According to Fourier's law of heat conduction, the thermal conductivity $\lambda$ is inversely proportional to $\delta T/\delta X$ when $Q$ is a constant. Since the thermal conductivity of AlN is 25 W/(m·K)[11], and the PET film is 0.157 W/(m·K)[12], the very thin PET film with good contact can also achieve the same heat transfer. Therefore, the PET films were installed in the current leads, and the temperature difference of the current leads was successfully controlled at 2 ~ 3 K.

The welding of the transmission pipeline includes the cooling loops, precooling circuit, refrigerator chamber channel, relief channels. The design pressure of the cryogenic pipeline is set to 3 barA, and the leakage rate is set to $10^{-10}$ Pa·m³/s. The leakage of the pipelines was checked after the welding was completed. During the welding, prefabricated stainless steel sleeve joints were used to adjust the assembly errors, and shorter bellows were used for the elbow compensation. In the Bayonet structure of nitrogen pipeline, the female head was directly welded on the flange, and the male head was in the type
of plug and pull. Cold shrinkage caused by liquid helium injection should be considered in welding to prevent thermal short circuits. At last, the multilayer insulation package is carried out.

3. Performance test of calibration magnet

The test platform of the superconducting magnet system has been built in the superconducting Test Center of Hefei Institute of Physical Science, Chinese Academy of Sciences. The stability of the cryostat and the temperature uniformity of the high homogeneity superconducting coils were verified. The linearity, locking area, and the uniformity of the magnetic field are tested.

In order to realize the uniformity and stability of the magnetic field, the superconducting magnet also requires a stable power supply with high precision. Thus, the current fluctuation can be calculated to be less than 4.8 mA at 300 A according to the 1 Gs fluctuation requirement of the magnetic field. In the accelerators, the magnetic field fluctuation should not exceed 0.3 mT in the same coordinate, and the deviation of the hourly current fluctuation should not exceed 14.5 mA in meeting the use requirements. The stability of the available power supply should be less than 48.3 ppm/h.

3.1. Cooling test

The cryogenic system has been tested three times. As shown in Fig.5, the magnet was cooled to 4 K in about 36 hours. Then liquid helium is formed in the tank and liquefied continuously for 2 hours, and the gas consumption can be calculated to be about 0.13 Mpa when the high-pressure vessel is 15 Mpa @ 40 L. During the cooling test, the minimum temperature of the superconducting magnet reached below 2.85 K, the outlet temperature of the heat pipes stabilized at 2.79 K, and the temperatures were stable in more than six hours. According to the pressure of 0.17 bar-A on the acquisition system, the second stage temperature of the refrigerator can be calculated at about 2.7 K. The cryogenic system has been continuously operated for 72 hours under negative pressure in this test stably.

In the magnet excitation test, the magnet was tested five times in total. The continuous excitation and demagnetization tests and the temperature rise of HTS lead with the time are shown in Fig. 6. The excitation rate was 0.1 A/s for about 1 hour. The temperature rise does not exceed 0.1 K when around 40K. The demagnetization time is about 1 hour and stable within 10 minutes, and the temperature fluctuation is less than 0.02 K. The design of current leads was verified to meet the requirements. It can be seen from Fig. 6 that the temperature rises were rippled in the process of rising, which is different from the hypothetical situation. The main reason is that the accuracy of coordinates is relatively high and is only about 0.01 K, so that the fluctuation in the acquisition equipment may cause the ripple.

![Figure 5. Cooling curve of the superconducting magnet system.](image-url)
3.2. Magnetic Field test

Three different power sources were used for testing to evaluate the stability and reliability of superconducting magnets. The excitation process takes about 1 hour to reach 300 A and stops briefly at 100 A, 200 A, 250 A, and 300 A, respectively, to make the magnet reach a stable state, as shown in Fig. 7. The cryostat also runs stably during the whole process. The voltage at both ends of the power supply gradually increases from 0 V to about 15.5 V, the power supply and the temperature of the magnet were kept at 2.8 K to 3 K, and no quench occurred in the magnet when the current reached 300 A.

The linearity of the magnetic field and excitation current is shown in Fig 8. It can be seen that the linearity is good, and the magnetic field of 204 Gs~205 Gs can be generated per ampere. The magnetic field locking region of the NMR probe is shown in Fig 9. The height of the lock-in range is increased with the magnetic field from 1 T to 5 T. The maximum height of the region can reach about 113 mm when the magnetic field reaches 5 T. This locked area is 18 times larger than the design area and far beyond the initial design value of 160 ppm/cm @ φ20 mm× 20 mm.

Figure 7. Temperature of current leads during excitation.

Figure 8. Linearity test of the magnetic field.

Figure 9. Lock-in range test of high uniformity superconducting magnet system.
Table II
Specifications of the NMR probe

| Probe type  | Probe ranges (T) | Frequency range (MHz) | Active sample (mm) | Required field homogeneity (ppm/cm) |
|-------------|------------------|-----------------------|--------------------|-----------------------------------|
| 1062-6-10M  | 1.5–3.4          | 7.5–22.5              | 4(dia.) 4.5(L)     | 240~280                           |
| 1062-7-10M  | 3.0–6.8          | 15.0–45.0             | 4(dia.) 4.5(L)     | 160~300                           |

In the stability test and uniformity test, the NMR probes of Metrolab were mainly used for testing, and the specifications of the NMR probes are shown in Table II. In Fig. 10, the stability of the magnetic field at each coordinate can be obtained by recording the same point more than 10 times. It can be seen that the magnetic field deviation of each position is not more than 0.01 mT, and the magnetic field is stable during the operation of the system. However, the magnetic field stability is not only related to the performance of the magnet itself but also the fluctuation of the excitation power supply, so a high uniformity magnet must be equipped with a superconducting power supply with high stability during its operation.

According to the magnetic field measurement results in different regions, the maximum and minimum magnetic field in the range can be calculated, and then the uniformity of the magnetic field

![Figure 10. Stability of the magnetic field at different heights from the center.](image)

Table III
Calculation results of magnetic field homogeneity

| Current(A) | Magnetic field difference (mT) | Magnetic field homogeneity (ppm) |
|------------|--------------------------------|----------------------------------|
|            | $\varphi 20 \text{ mm}\times20 \text{ mm}$ | $\varphi 10 \text{ mm}\times10 \text{ mm}$ | $\varphi 20 \text{ mm}\times20 \text{ mm}$ | $\varphi 10 \text{ mm}\times10 \text{ mm}$ |
| **NMR probe 1062-6-10 M (1.5 – 3.4 T)** | | | | |
| 100        | 0.151                          | 0.038                           | 74.15                           | 18.54                          |
| 150        | 0.225                          | 0.056                           | 73.88                           | 18.47                          |
| 170        | 0.253                          | 0.063                           | 73.34                           | 18.33                          |
| 200        | 0.298                          | 0.075                           | 73.47                           | 18.37                          |
| 220        | 0.321                          | 0.08                            | 71.84                           | 17.96                          |
| **NMR probe 1062-7-10 M (3.0 – 6.8 T)** | | | | |
| 170        | 0.265                          | 0.066                           | 76.77                           | 19.19                          |
| 200        | 0.287                          | 0.072                           | 70.68                           | 17.67                          |
| 220        | 0.322                          | 0.08                            | 72.05                           | 18.01                          |
| 268        | 0.391                          | 0.098                           | 71.93                           | 17.98                          |
can be obtained. According to the above test of the magnetic field, it can be found that the magnetic field value changes linearly in different areas and the deviation and uniformity of the standard area φ20 mm × 20 mm magnetic field can be calculated by interpolation method in Table II below.

4. Conclusion
A cryostat system was designed for the calibration magnet. The cryostat combines direct conduction cooling and gravity heat pipes, which realize zero evaporation with a small amount of liquid helium circulation. In order to meet the need for irregular calibration measurement, the system adopts the structure of male and female heat exchangers that can be inserted and pulled out. The superconducting magnet was cooled to 2.8 K, and the temperature of the Thermal shield was cooled to 40 K, which meets the requirements of the operating environment. Finally, the cooling and excitation tests were completed, the operating parameters of the superconducting magnet system were obtained. The maximum magnetic field reaches 6.16 T without quench, and the magnetic field of 204 Gs–205 Gs can be generated per ampere current. The linearity, stability, and uniformity of the magnetic field are good. At present, the equipment has been running stably for more than 90 days.

5. References
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