The Design of a Curved Cryostat for the 90° DCT Superconducting Magnet

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Abstract. In order to enable the 90° curved Discrete Canted-Cosine-Theta (DCT) superconducting magnet for heavy ion Gantry to operate at low temperature normally, a 90° curved cryostat that can rotate on rotating gantry is developed. For the convenience of welding, the vacuum chamber and thermal shield of the cryostat are both welded by three cylinders. The cryostat uses four high-temperature superconducting current leads, two of which are connected to the superconducting cables for power supply to the magnet, and the other two are connected to the copper wires for quench protection of the magnet. To ensure the stability of the superconducting magnet during rotation, the superconducting magnet is fixed on the vacuum chamber with 12 carbon fiber rods. A heat leakage calculation is conducted on the cryostat, which shows that the first stage heat leakage is 74.6W@50K, and the second stage heat leakage is 1.16W@4.2K. Therefore, two GM cryocoolers are used for cooling the superconducting magnet. The strength of the rods, vacuum chamber and the base are simulated and checked at different angels (0°, 30°, 60°, 90°, 120°, 150°, 180°). According to the analysis results, the stress at the above structures is less than the corresponding allowable stress, which meets the strength requirements of the system. The cooling process of the cryostat shows it takes 13 days to cool down the whole system with a mass of 900 kg from room temperature until heat balance.

1. Introduction

With the development of accelerator physics and technology, accelerators are playing more and more important roles in many fields. In terms of medical applications, accelerators have been used in cancer treatment. In cancer treatment, rotating gantry has many advantages. For proton cancer therapy, several rotating gantries have been constructed around the world [1-2]. Compared to proton cancer therapy, heavy-ion cancer therapy has a sharper Bragg peak and a higher relative biological effectiveness, which can accurately and efficiently kill tumour and reduce the occurrence of radiation complication. However, for heavy-ion cancer therapy, the size and weight of the gantry is larger and more difficult to build because the required magnetic rigidity is three times that of protons. At present, there is only one heavy-ion gantry in the world [3], which uses heavy-ion for cancer treatment. In order to reduce the size of the gantry, a compact rotating gantry was designed and manufactured in Japan, in which the superconducting coils were cooled by conduction [4-5]. In order to realize superconducting heavy-ion therapy in China, we are developing superconducting gantry and have designed and manufactured a prototype. This paper introduces the structure of the cryostat used in the prototype and the cooling results.

2. Structure Design

The structure profile of the 90-degree DCT thermostat is shown in Fig.1. The main structures include: vacuum chamber, thermal shield, current lead, refrigeration system, superconducting magnet, thermal shield center tube and beam center tube.

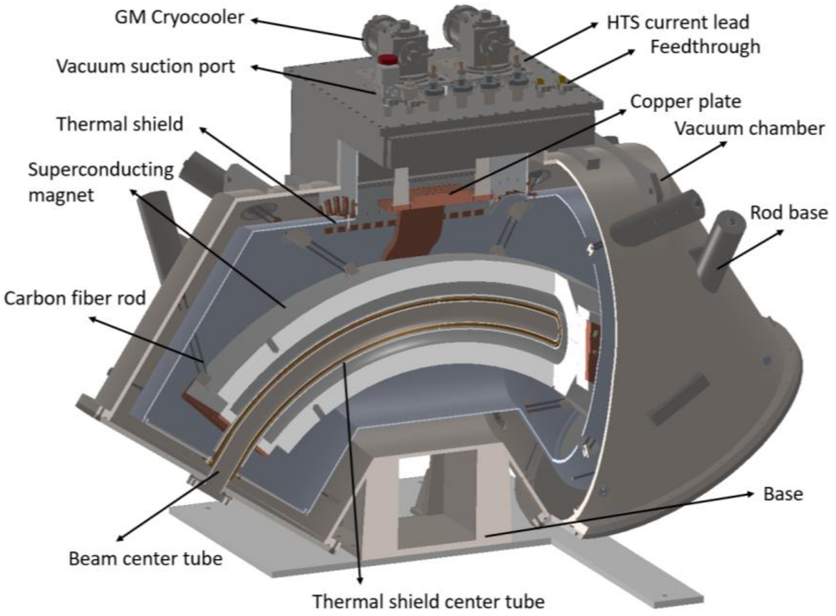

Figure 1. The structure of the cryostat

The superconducting magnet is a 90° curved Discrete Canted-Cosine-Theta (DCT) superconducting magnet, mainly composed of NbTi wire, industrial pure iron, epoxy resin, and aluminum alloy. The NbTi wire is a superconducting material, which determines the targeted operation temperature of the superconducting magnet should be below 5K. A total of four high temperature superconducting (HTS) current leads with a design current of 310A are used, of which two are used to power the magnet and the other two are used for quench protection.

The refrigeration system mainly includes two GM cryocoolers, RDE-418D4, produced by Sumitomo Heavy Industries, Ltd. and the connected cooling copper plate. The first cold head and the second cold head of the cryocoolers cool the thermal shield and the magnet respectively.

The vacuum chamber and the thermal shield are both welded by three straight cylinders because the superconducting magnet is arc-shaped, and the materials of them are 316L and aluminum alloy respectively. The thermal shield's cylinder is fixed radially by 4 stainless steel rods at both ends, and the maintenance tower is fixed axially by a pair of G10 rods.

The beam center tube and the thermal shield center tube are both welded by a middle arc section and two straight edges at both ends, and the materials of them are 316L and mirror polished brass respectively. In addition, in order to prevent these two pipes from contacting each other, a G10 support ring is installed between the beam center tube and the thermal shield center tube. Similarly, one is also installed between the thermal shield center tube and the superconducting magnet. The support ring adopts the design of point contact at one end, which reduces the contact heat leakage.

The cryostat is installed on the rotating gantry and rotates around the central axis of the gantry cavity. The overall structure is shown in Figure 2. The rotating condition of the gantry puts forward high requirements for the fixation of the superconducting magnet in the cryostat. The superconducting magnet is fixed by 12 carbon fiber rods. One end of the rod is connected to the magnet, and the other end is fixed on the vacuum chamber by means of bellows sealing. The method of bellows sealing realizes the adjustment of the magnet position by the rods. By adjusting the end nut to add preload to the 12 rods during assembly, the rods will be stressed in all three dimensions to ensure that the magnet remains stationary during rotation.

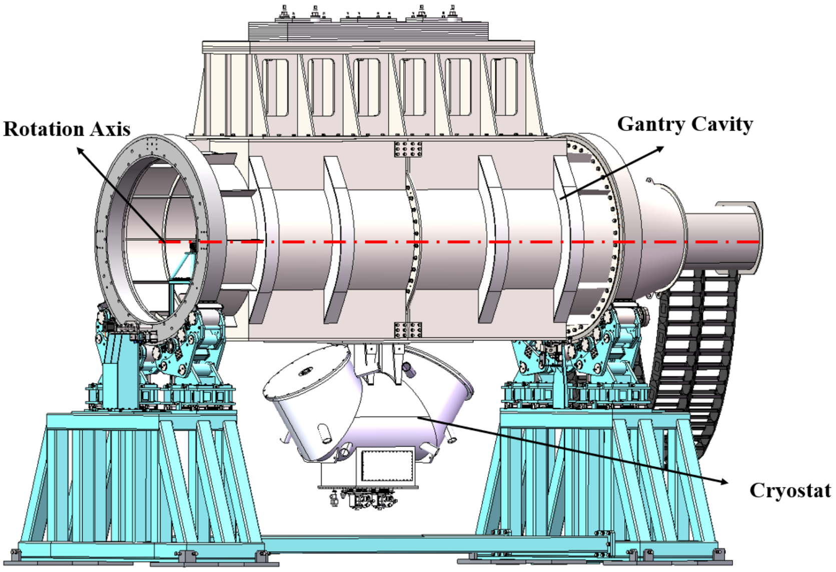

Figure 2. The structure of the rotating gantry

3. Heat leakage calculation and strength check

3.1 Heat leakage calculation

The vacuum degree is less than 10^{-4}Pa in the cryostat, so the heat leakage of the residual gas can be ignored. The heat leakage forms mainly include heat conduction and heat radiation.

The heat leakage through conduction is given by

$$Q_c = \frac{A}{L}\int_{T_L}^{T_H} k(T)dT$$

where A is surface area, L is length, T_L is low temperature, T_H is high temperature and $k(T)$ is temperature-dependent thermal conductivity.

The heat leakage through radiation is given by

$$Q_r = \frac{\sigma(T_H^4 - T_L^4)}{\frac{1-\varepsilon_H}{\varepsilon_H A_H} + \frac{1}{A_L}(\frac{1}{\varepsilon_L} + \frac{2N}{\varepsilon_N} - N)}$$

where A is surface area, σ is the Stefan–Boltzmann constant and ε is the emissivity of the surface. N is the number of multi-layer insulation. The subscripts H and L represent high-temperature and low-temperature surfaces, respectively.

According to calculation, the heat leakage of the first and second stages of the cryostat is shown in table 1.

The cooling capacity of a single 418 cryocooler is 1.8W@4.2K and 42W@50K. Therefore, two cryocoolers are selected to cool the cryostat.

Table 1. The heat leakage of the cryostat

Form	Item	Heat leakage(W)	
		First stage	Second stage
Heat Conduction	Rods	13.2	0.03
	HTS current lead	54.6	0.26
	Others	2.8	0.01
Heat Radiation	~	4	0.86
Total	~	74.6	1.16

3.2 Strength check

In the process of rotating around the axis of the gantry, the force on the cryostat is very different. As shown in table 2, the strength of the cryostat is simulated and checked at different angels (0°, 30°, 60°, 90°, 120°, 150°, 180°) by using ANSYS.

Table 2. The force on the cryostat

Structure	Item	Angle(°)						
		0	30	60	90	120	150	180
Carbon fiber rods	Max force（N）	6060.9	6315.9	4149	4886.1	5158.5	5619.7	5155.1
	Max stress (MPa)	384.2	384.1	384.6	544	385	384	385
Vacuum chamber	Max deformation(mm)	0.177	0.398	0.633	0.789	0.644	0.421	0.21
	Max stress (MPa)	124.9	124.3	190	94.5	191.9	146	121.7
Base	Max deformation(mm)	0.012	0.018	0.019	0.033	0.02	0.02	0.013
	Max stress (MPa)	40.6	47.2	46.9	88.8	47.1	55	43.7

For the carbon fiber rods, the maximum force occurs when the rotation angle is 30°, but the maximum stress occurs when the rotation angle is 90°. For the vacuum chamber, the maximum deformation occurs when the rotation angle is 90°, but the max stress is the smallest at this rotation angel. For the base, the maximum deformation and stress are both occur when the rotation angle is 90°.

The allowable stresses are 747 MPa, 465MPa and 235MPa for the carbon fiber rods, vacuum chamber and base respectively. And the stress at the above structures is less than the corresponding allowable stress, which meets the strength requirements of the system.

4. Cryostat Cooling Performance

The cryostat uses two GM cryocoolers for conduction cooling. The figure 2 shows the temperature change of the internal structure of the cryostat during the whole cooling process.

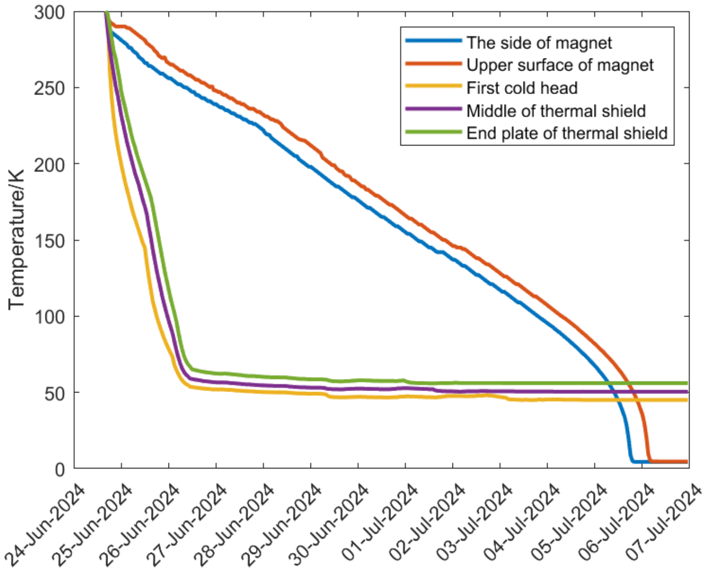

Figure 3. Temperature in the cryostat during cooling

The superconducting magnet with a mass of 900 kg takes 13 days to cool from room temperature until heat balance. The temperature of the first-stage cold head takes 3 days to drop to 54.7K rapidly and then decreases to 45.1K slowly, while the temperature of the superconducting magnet decreases slowly at the beginning and then decreases rapidly until heat balance from the 11th day. In addition, there is a temperature difference between the thermal shield and the first-stage cold head, but the cooling trend is consistent.

5. Conclusion

A 90° curved cryostat that contains the 90° curved Discrete Canted-Cosine-Theta (DCT) superconducting magnet and can rotate on a rotating gantry is developed and manufactured. Through the heat leakage calculation, the cryostat uses two 418 GM cryocoolers for cooling. To ensure the stability of the superconducting magnet during rotation, the superconducting magnet is fixed on the cryostat with 12 carbon fiber rods. And through the simulation calculation on ANSYS, the strength of the cryostat meets the requirements. Through the cooling test, it takes 13 days to cool down the whole system from room temperature until heat balance.

Acknowledgement

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