PRELIMINARY DESIGN OF HALF HIGH-TEMPERATURE SUPERCONDUCTING BENDING MAGNET CRYOSTAT

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Abstract

This paper focuses on a preliminary design study of the cryostat for the insertion device magnet—specifically, a high-temperature superconducting bending magnet—in the HALF (Hefei Advanced Light Facility) national major science and technology infrastructure project. Based on three-dimensional modeling and finite element analysis, the structural and thermal performance of the cryostat was simulated and evaluated. Key optimizations were made to the mechanical configuration, thermal conduction characteristics, and spatial layout of the support structures at the temperature ports. A low thermal conductivity tension rod support structure was designed for the cold shield and superconducting magnet assembly, along with a rationally planned layout for the current leads and thermal management pathways. Through systematic heat leak analysis of the dual-temperature zones, a balance was achieved between structural deformation control and heat leak suppression. A preliminary design scheme that meets both structural stiffness requirements and low thermal load criteria is proposed, providing a reference for the subsequent development of an engineering prototype of the cryostat.

INTRODUCTION

The storage ring lattice of the Hefei Advanced Light Source adopts the Modified Hybrid 6BA structure scheme. The entire storage ring consists of 20 periods, including 20 long straight sections and 20 medium straight sections. The magnetic elements within each period are arranged with central symmetry. Figure 1 shows the magnet layout within one period, where each half-period contains three longitudinal gradient bending magnets (red), eight quadrupole magnets (blue), two reverse bending magnets (purple), and four sextupole magnets (green) [1, 2].

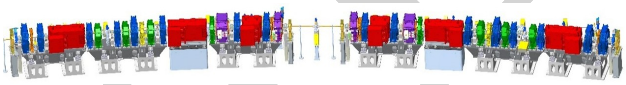

Figure 1: Arrangement diagram of HALF magnets.

According to the engineering plan, the High-Temperature Superconducting bending magnet (HTS Superbend) is proposed to replace the B4 bending magnet in the 5th and 15th periods of the HALF storage ring. The magnet layout after replacement is shown in Fig. 2. To ensure the stable operation of the HTS Superbend, the design of its cryostat is particularly critical.

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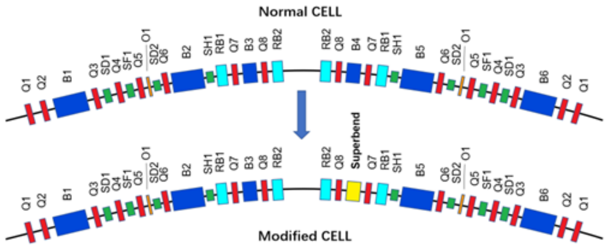

Figure 2: Magnet layout of a normal and modified cell, blue for LGB, yellow for Superbend.

CRYOSTAT DESIGN

Figure 3 shows the overall structure of the HALF HTS Superbend cryostat. The internal core component is the high-temperature superconducting coil, which is surrounded by a copper thermal conduction plate. The upper end of the plate is connected to the second-stage cold head of the GM cryocooler, maintaining the low temperature through conduction cooling. A thermal radiation shield is placed outside the coil to reduce radiative heat leakage. The outer surface of the shield is wrapped with multilayer insulation (MLI) composed of insulating paper and polyester-aluminum-coated film. The outermost layer is a square-tube-shaped vacuum vessel, with a vacuum valve on its side wall, allowing the interior to be evacuated to a high vacuum state, thereby effectively suppressing convective heat transfer of gases.

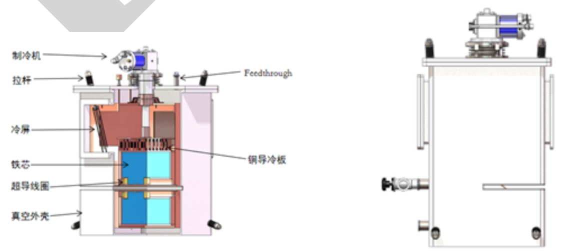

Figure 3: Overall structure of the HTS Superbend Cryostat.

The first-stage cold head of the GM cryocooler is efficiently coupled to the top of the thermal radiation shield. Cooling is achieved via a flexible “copper braid” structure, which effectively suppresses the transmission of mechanical vibration while maintaining thermal conductivity. This cold head stage is primarily used to cool the radiation shield and the HTS current leads. Furthermore, service components and room-temperature feedthroughs are integrated on top of the vacuum vessel.

To prevent burnout of the HTS current leads due to improper operation, maintenance viewports are provided on the side of the vacuum vessel and on the corresponding position of the thermal radiation shield. This design creates a dedicated maintenance access path: when an abnormality occurs in the current leads, the side viewport of the vessel can be sequentially removed, the local MLI peeled back, and the shield viewport opened, allowing replacement or repair of the current leads.

The tie rods adopt a structure consisting of a room-temperature ball joint combined with a carbon fiber tension strap, in conjunction with spherical plain bearings. Eight tie rods provide three-dimensional support, allowing for self-adaptive adjustment and compensation for thermal contraction stresses. However, there is currently a design flaw that prevents the cryostat from maintaining its vacuum environment. Subsequently, bellows assemblies will be added to ensure vacuum performance.

STRUCTURAL AND THERMAL ANALYSIS

As the outermost structure of the cryostat, the vacuum vessel is directly exposed to the atmospheric environment. Its interior must be maintained under high vacuum conditions to minimize convective heat transfer, thereby ensuring a low-temperature working environment for the magnet. Consequently, the vacuum vessel must withstand the pressure difference between the internal and external environments, which may induce significant structural deformation. To evaluate its structural integrity, stress and deformation analyses of the vacuum vessel are essential. The vacuum vessel of the HTS Superbend cryostat is fabricated from AISI 316 stainless steel, with material parameters as follows: elastic modulus of 1.93×10^{11} Pa and Poisson's ratio of 0.31. Figure 4 shows a simulation schematic of the deformation results under an applied pressure of 0.1 MPa.

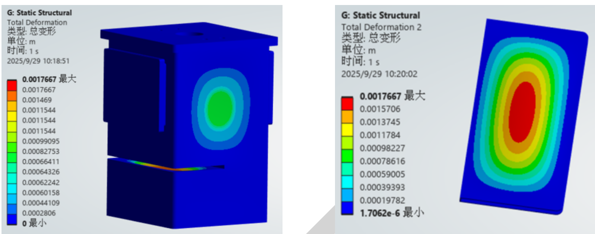

Figure 4: Overall deformation of the vacuum casing.

According to the simulation results shown in the figure, after applying an internal pressure of 0.1 MPa, the vacuum vessel exhibits good pressure-bearing performance overall, with relatively small deformations. It is worth noting that the maximum deformation (1.76 mm) occurs in the region of the feedthrough port, which has a thinner wall thickness, and from there it shows a trend of outward attenuation. In addition, due to the large flat plate structure of its side walls, the compression stiffness is relatively weak, resulting in a relatively large deformation of approximately 0.82 mm in this region.

Figure 5 shows the stress distribution of the vacuum vessel under an internal pressure of 0.1 MPa. The analysis results indicate that the stress level in the side wall regions is relatively low, generally remaining below 60 MPa. Stress concentration occurs at the corners and central regions of the side walls, with values around 60 MPa. It is worth noting that the maximum stress appears at the center of the structurally weak feedthrough port, reaching 224 MPa.

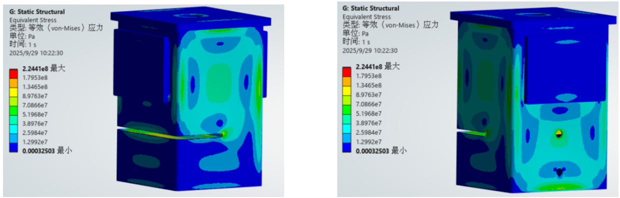

Figure 5: Stress Distribution in the Vacuum casing.

Subsequently, by adding up to 16 G10 support posts at the feedthrough ports and optimizing their layout, the maximum deformation was reduced to 0.74 mm, meeting the requirement of <1 mm. The stress concentration issue was resolved, and the structure satisfied the design criteria. As illustrated in Fig. 6.

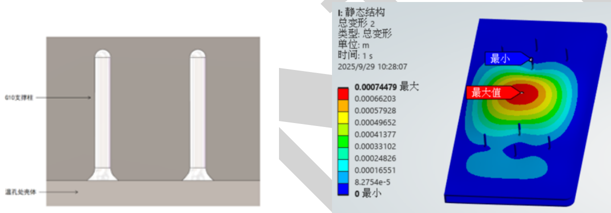

Figure 6: Structure of the support column.

Finally, a thermal analysis was performed for the second-stage temperature region. The main heat leakage paths in the second-stage region include solid conduction through the support structures, radiative heat leakage from the thermal radiation shield, conduction heat leakage from the HTS current leads, residual heat leakage from the cryocooler cold head conductive rods, and conduction heat leakage from the tie rod structures. The results are shown in Fig. 7. The total heat leakage in the second-stage region is only 0.73 W, which is well below the cooling capacity of 1.5 W provided by the cryocooler. The ample cooling margin ensures that the operating temperature of 4.2 K can be stably maintained.

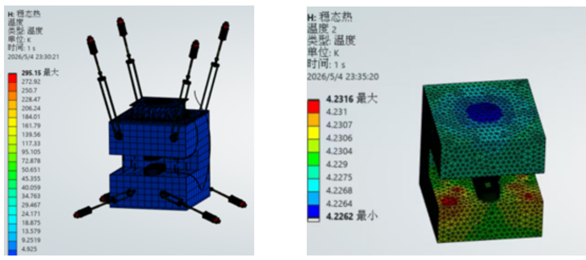

Figure 7: Secondary temperature zone heat loss.

CONCLUSION

This paper presents the preliminary design of the HALF HTS Superbend cryostat and analyzes the associated structural simulations and thermal analysis. By introducing a support post structure at the feedthrough ports, the deformation of the vacuum vessel is effectively reduced. The maximum deformation is decreased from an initial value of 1.8 mm to 0.77 mm. The simulated heat leakage of the second-stage temperature region is 0.73 W. This work provides a reference for the subsequent development of the actual cryostat.

ACKNOWLEDGEMENTS

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