

Design of the superconducting magnet for 9.4 Tesla whole-body magnetic resonance imaging

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Abstract. A superconducting magnet for 9.4 Tesla whole-body magnetic resonance imaging is designed and fabricated in Institute of Electrical Engineering, Chinese Academy of Sciences. In this paper, the electromagnetic design methods of the main coils and compensating coils are presented. Sensitivity analysis is performed for all superconducting coils. The design of the superconducting shimming coils is also presented and the design of electromagnetic decoupling of the Z2 coils from the main coils is introduced. Stress and strain analysis with both averaged and detailed models is performed with finite element method. A quench simulation code with anisotropic continuum model and control volume method is developed by us and is verified by experimental study. By means of the quench simulation code, the quench protection system for the 9.4 T magnet is designed for the main coils, the compensating coils and the shimming coils. The magnet cryostat design with zero helium boiling-off technology is also introduced.

1. Introduction

Magnetic resonance imaging (MRI) technology is of great use for medical diagnosis, interventional therapy, and cognitive sciences. In order to obtain higher signal-to-noise ratio (SNR), superconducting magnet is developed to produce higher magnetic field over 0.5 T. So far, superconducting MRI magnets with magnetic field of 1.5 T and 3.0 T have been commercialized. With further increment of the magnetic field, the magnetic resonance SNR is enhanced, which makes it possible to obtain clear non-proton nuclide magnetic resonance signal, such as ²³Na, ³¹P and other elements for metabolism study. A 9.4 Tesla MRI system can provide higher resolution for observing fine structure, studying function of the boundaries of the nuclei, and revealing the metabolic processes of biological system.

A superconducting magnet for 9.4 Tesla MRI system is designed and fabricated in Institute of Electrical Engineering, Chinese Academy of Sciences (IEE, CAS) [1]. The magnet has a warm bore with diameter of 800 mm and length of 3000 mm. It generates highly homogenous magnetic field in the central diameter spherical volume (DSV) of 400 mm. Zero helium boiling-off technology is employed to avoid frequent refilling of liquid helium and keep low cost operation. In this paper, the electromagnetic design, superconducting shimming system, stress analysis, quench protection design and cryogenic system for the magnet are described.

2. Electromagnetic design

The electromagnetic design of the highly homogeneous 9.4 T superconducting magnet can be divided into two steps. The first step is to design the main coils for a high central magnetic field, and the



second step is to design the compensating coils for a highly homogeneous magnetic field [2]. Each step involves a complex iterative process in which balance is made between contradictory factors like wire cost, space limitation, field homogeneity, mechanical stress, and engineering feasibility.

2.1. Main coils and compensating coils design

For minimizing the volume of a superconducting coil to generate a specific magnetic field, the current density J_o should be theoretically as large as the critical current density J_c , which is determined by local magnetic field B at the operating temperature. Generally the local field from the inner to the outer of the coil is gradually reduced, and the critical current density is gradually increased. So the operating current density should be also increased for maximum wire utilization. Because all coils are operating in series under the same current, different sizes of superconducting wires are selected. The main coils of the 9.4 T magnet is designed with the minimum of superconducting wire consumption as the objective function V . The graded current density in the coils is based on the critical current curves (B - J_c) provided by the wire manufacturer. As shown in figure 1, the mathematical problem of the main coils design is described as:

$$\begin{aligned} \min \quad & \sum_{i=1}^{N_c} V(i) \\ \text{s. t.} \quad & \begin{cases} R_2(i) + R_{\text{gap}} \leq R_1(i+1), \\ \frac{J_{\text{opt}}}{J_c} < \eta \\ \left| \frac{B_{\text{dsV}} - B_0}{B_0} \right| < \varepsilon \\ \mathbf{x} = [R_1(i), R_2(i), Z(i), i = 1, 2, \dots, N_c], \mathbf{x} \in \Omega \end{cases} \end{aligned} \quad (1)$$

where N_c is the number of main coils, $R_1(i)$, $R_2(i)$ and $Z(i)$ are the inner radius, outer radius and half length of a main coil i , and R_{gap} is the gap between two adjacent coils for winding bobbin, winding outer reinforcement and liquid helium channel. η is the allowed maximum current margin. B_{dsV} is the target magnetic field of several samples in the DSV, and ε is the initial field homogeneity constraint for the main coils design, which is generally between $10^{-2} \sim 10^{-3}$. $\mathbf{x}$ is the optimization variables that are constrained by space limitation Ω . Equation (1) describes a nonlinear problem with linear and nonlinear constraints. The problem is solved by successive quadratic programming (SQP) algorithm.

Since the main coils can not reach the high homogeneity requirement, compensating coils are designed at the outside of the main coils to annul the field non-uniformity component. The specifications of the main coils and compensating coils are listed in table 1. The coils structure, shown in figure 2, is based on easy fabrication, stress limitation and conductor length for actual winding [3]. Five coaxial main coils, named A, B, C, D and E, are wound on 5 bobbins with almost the same lengths. Four compensating coils named F1, F2, G1 and G2, are placed outside the main coils in a split way. The inner most coil A has the inner diameter of 910 mm. The space between coil A and the warm bore is left for winding bobbin, radiation shield, and Dewar occupation.

In consideration of the stability of the superconductor, the current margin is set as 94% and the maximum magnetic field is 9.5 T located in coil A. All coils are wound with NbTi Wire-In-Channel (WIC) superconducting wire for high cryostability to avoid risks of quench. The copper to superconductor ratios (Cu/SC) are from 6 to 18 based on different critical current density and stress requirements. The superconducting coils are fabricated by wet-winding technology and impregnated with epoxy resin [3]. A layer of fiber-glass cloth with thickness of 0.04 mm is interleaved between each two layers to increase the electrical insulation and mechanical strength.

The designed homogeneity is better than 5 ppm (peak to peak, the same as the followings) on 400 mm DSV, shown in figure 3. The 5 Gauss line is at about 17 m in radial direction and 22 m in axial direction, shown in figure 4. All the optimal geometric parameters of the superconducting coils are calculated in assumption of full operating current of the magnet at the liquid helium temperature.

According to coils deformation by thermal and electromagnetic forces, the optimized parameters are transferred to parameters at room temperature for coils winding.

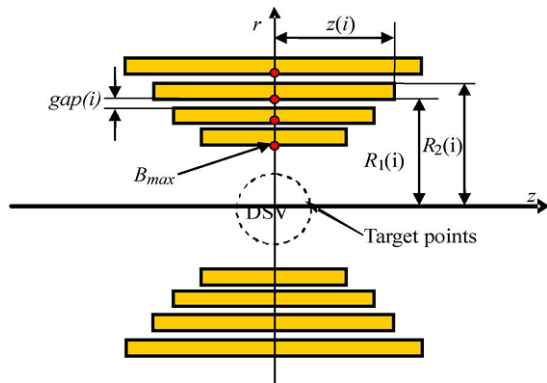


Figure 1. Optimal calculation model of coils.

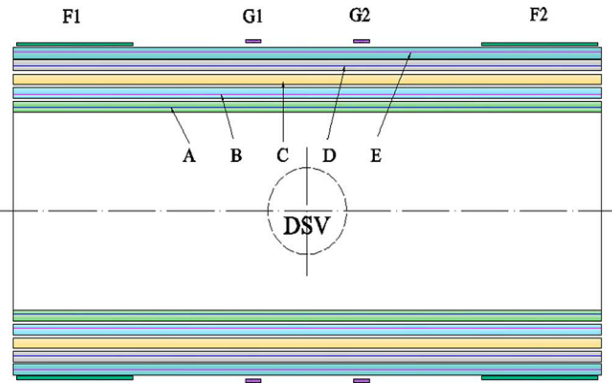


Figure 2. Coils structure.

Table 1. Specifications of the main coils and compensating coils.

Operating current	212.5 A
Central field	9.4 T
Maximum field	9.5 T
Field homogeneity	4.5 ppm @ 400 mm DSV
Number of main coils	5
Number of compensating coils	4
Clear bore size/Warm bore size	Φ910 mm / Φ800 mm
Outer diameter of outmost compensating coils	1630 mm
Coils Length	3000 mm
Inductance	5930 H
Stored energy	134 MJ
Mass	22.5 tons
5 Gauss line	r=17 m, z=22 m
Wire type	NbTi Wire-In-Channel

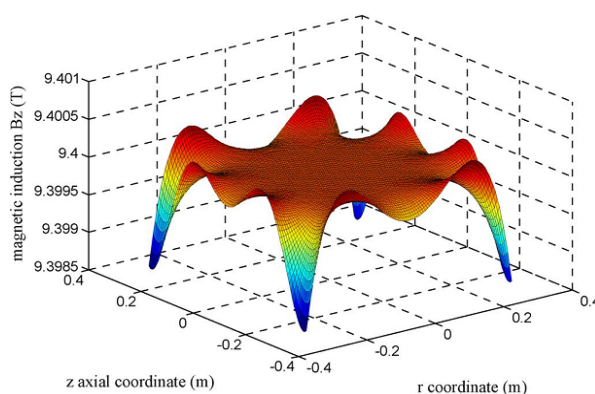


Figure 3. Field distribution in the DSV.

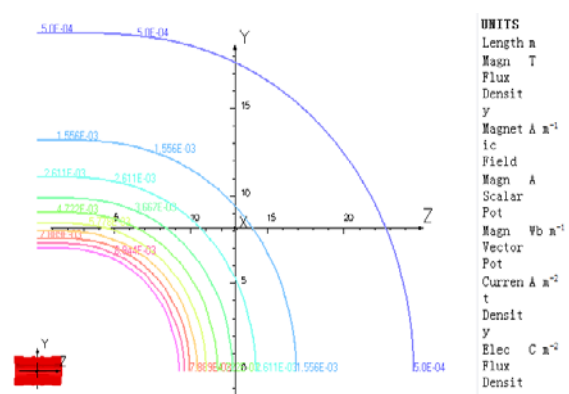


Figure 4. Stray field distribution.

2.2. Sensitivity study

The coil dimension errors will be caused during magnet fabrication, such as former machining, coil winding and coil assembling. The dimension errors will deteriorate the magnetic field homogeneity. Sensitivity analysis is carried out to assess the fabrication technology and improve it if necessary. In an analysis case it is assumed that for 10000 times homogeneity calculation, radii and the lengths of all coils vary randomly within 1.0 mm, and numbers of turns of all coils vary randomly below 5%. It is

found that the magnetic field homogeneity is more sensitive to the compensating coils than to the main coils. For large turns-error of 5%, the accumulated probability (counts to 10000 times) of the homogeneity below 20 ppm is only 50%, and the worst homogeneity is more than 120 ppm, while for a smaller turns-error of 1%, the probability of the homogeneity below 20 ppm is about 87%, and the worst inhomogeneity is only 44 ppm. The fabrication has been improved by interleaving epoxy slices between a winding and a former flange for turn numbers control. The winding results show that the actual turn numbers of all compensating coils are about 1% more than the designed ones, which we think is acceptable for further field correction by superconducting shimming.

3. Superconducting shimming coils design and electromagnetic decoupling of Z2 coils

A set of superconducting shimming coils have been designed for this 9.4 T MRI magnet, including Z1, Z2, Z3, X/Y, ZX/ZY, XY/X2-Y2, Z2X/Z2Y, and ZXY/Z(X2-Y2).

3.1. Design theory

The design of the superconducting shimming coils is based on the analytical method first to generate a set of ideal current loops and arcs, and then realized by nonlinear optimization method for real-sized zonal and tesseral shimming coils [4]. In the spherical coordinate system of (r, θ, ϕ) , magnetic flux density in a volume with no field source can be expressed by spherical harmonics function. The magnetic field generated by an ideal current loops/arcs at a point $P(r, \theta, \phi)$ can be expanded as a sum of orthogonal Legendre functions. Because of the symmetry property of the Legendre function, combination of symmetric current loops/arcs with the same or opposite current directions can eliminate unwanted terms, and leave the required term and negligible high-order terms.

Not ideal current loops but superconducting coils with multiple turns carry the large current to generate the required magnetic field in the DSV. Thus, the sizes and the positions of the coils are optimized to satisfy the requirements of field errors, shimming capacity, and the space constraints. The optimization mathematical problem for design of any shimming coils is described in equation (2).

$$\begin{aligned} & \min V(\mathbf{x}) \\ & \text{s. t. } \begin{cases} \text{Err}(\mathbf{x}) = \left| \frac{\max(B_{\text{opt}} - B_{\text{ideal}})}{\max(B_{\text{ideal}})} \right| < \varepsilon \\ \text{Eff}(\mathbf{x}) = \frac{\max(B_{\text{ideal}}) * 10^6}{B_0} > \eta, I_0 = 1\text{A} \\ \mathbf{x} \in \Omega. \end{cases} \end{aligned} \quad (2)$$

where V represents the volume of the shimming coils, Err represents the maximum field error in percentage, Eff represents the shimming capacity with unit current I_0 , and the domain Ω of the solution $\mathbf{x}$ is defined by space limitation. B_{opt} is the magnetic field generated by the optimized coils, B_{ideal} is the ideal field over the DSV, and B_0 is the basic field of 9.4 Tesla. The results for the 9.4 T MRI magnet are shown in figure 5. The total weight of all superconducting shimming coils is below 1 ton, and the total thickness is below 36 mm.

3.2. Electromagnetic decoupling design of Z2 coils

Among all shimming coils for the 9.4 T MRI magnet, due to the coils structures [4], only the Z2 shimming coils have electromagnetic coupling effect on the main coils (and compensating coils). As a result, problem may arise that large current is induced in the Z2 coils during the quench of the main coils. This may lead to high temperature rise and high voltage in the Z2 coils, which could damage the Z2 coils permanently [5]. So it is required that the Z2 coils should be designed to be much less electromagnetic coupling to the main coils. Different from other shimming coils design, the objective function for the Z2 coils design is the mutual inductance M between the Z2 coils and the main coils, instead of V in equation (3). By means of LP algorithm and nonlinear optimization algorithm, a 7-coils structure for Z2 coils is obtained, shown in figure 5. Trade-off between the field error, coils capacity

and the mutual inductance is made for the design. The optimal M is about 0.35 H, with self inductance of the Z2 coils of 27 H, the field error below $\pm 1\%$, and the Z2 shimming capacity of 16.1 ppm/A.

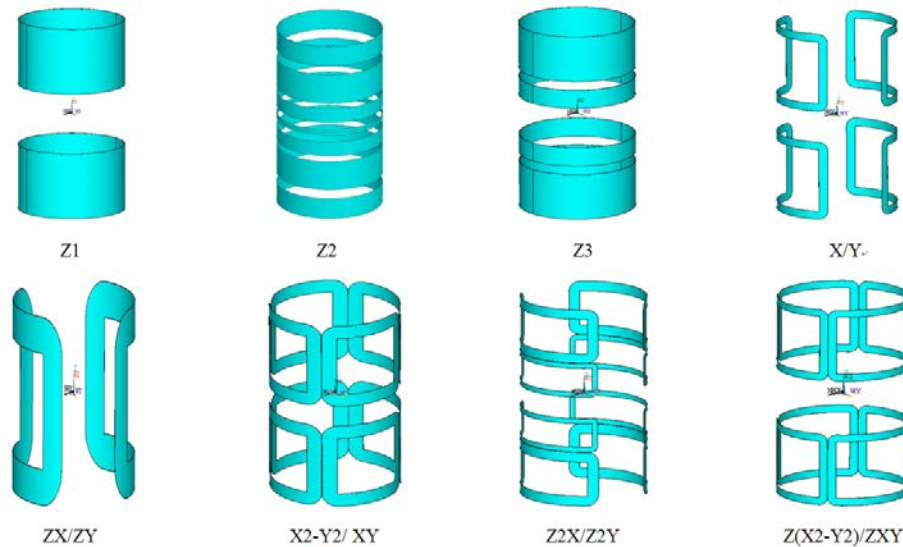


Figure 5. Superconducting shimming coils for the 9.4 Tesla MRI magnet.

4. Stress and strain analysis

Mechanical stress in the superconducting coils affects the superconductor properties and relates to most of coils quench, especially for this magnet with high field of 9.4 T, and clear bore diameter of 0.91 m. The superconducting wires may suffer plastic deformation, which leads to serious degradation of the critical features of the coils. It is necessary to understand the mechanical stress due to thermal contraction in the cool down process and the electromagnetic force during operation. The coil winding composite is a mixture of superconductor, copper, insulation, and filler with different mechanical properties. The stress and strain are analyzed based on equivalent finite element model in which mechanical properties of the elements are averaged on the different material components [3].

Thermal contraction analysis is performed on coils, together with AL5083 coil formers. The radial thermal contraction of the former and the winding composite are estimated as 0.415% and 0.403%. It indicates that the coil winding has a tendency to peel off the former if the coil is cooled down to the liquid helium temperature. In the axial direction, the coil former tends to contract more than the coil winding. It indicates that the coil winding will sustain axial squeezing force from the coil former.

Stress and strain due to electromagnetic force are also assessed at full operating current. Reinforcements on the outside of the 5 coil windings are set as a stainless steel shell with a thickness of 4 mm. The distribution of coil stress is shown in figure 6. In figure 6, the maximum hoop stress of 159 MPa lies in the reinforcement shell of coil B and coil B will withstand the highest hoop stress less than 110 MPa. The design limit of the hoop stress in main coils can be up to 180 MPa which is the yield strength of copper matrix stabilizer of the WIC wire. Since the maximum hoop stress locates in coil B, a more accurate calculation for stress distribution in coil B is carried out. A detailed model with hierarchical group structure refinement mesh takes mutual force between any two adjacent turns of WIC wire in consideration [1]. The result is shown in figure 7. The maximum hoop stress in the WIC conductor is about 131 MPa, some higher than the averaged mode, but still below the design limit. Therefore, the above simulation results indicate that the superconducting coils are safe under full current operation. Since electromagnetic design is for full operating current at liquid helium temperature, the deformation due to thermal contraction and Lorentz force will not deteriorate the field homogeneity much.

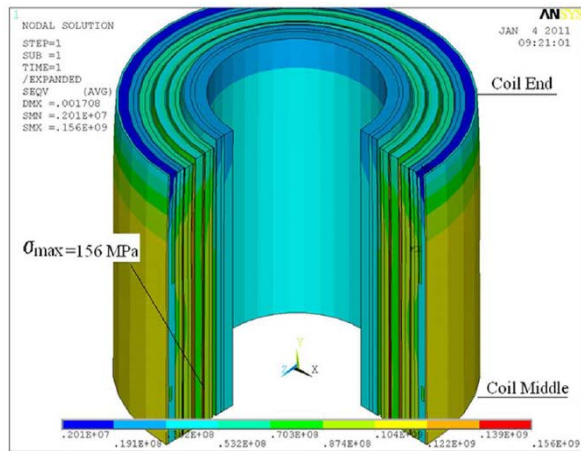


Figure 6. Hoop stress distribution.

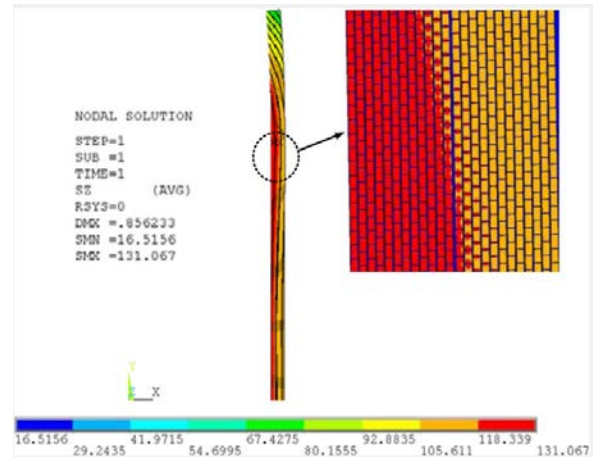


Figure 7. Hoop stress distribution with detailed model.

5. Quench protection design

A quench event may do damage to the superconducting magnet, with high temperature to burn the coil on the hot-spot, high voltage to break down the insulation of the winding and the former, and high stress to degrade the performance of the superconducting wire. For the 9.4 T MRI magnet with large amount of stored energy and large stress, it is very important to design an efficient and reliable quench protection system.

5.1. Quench simulation

A quench event may do damage to superconducting magnet, with high temperature to burn the coil on the hot-spot, high voltage to break down the insulation of the winding and the former, and high stress to degrade the performance of the superconducting wire. For the 9.4 T MRI magnet with large amount of stored energy and large stress, it is very important to design an efficient and reliable quench protection system.

A quench simulation code has been developed in IEE, CAS for the quench protection design [6]. The anisotropic continuum model (ACM) is adopted for the prediction of the quench resistances, currents, and voltages of the superconducting coils. The wire material properties and critical properties dependent on the local time-varying magnetic field and temperature are considered. The quench behaviour with respects to the coil currents and voltages is closely related to the quench sequences of coils. Since coils can be triggered to quench by the heaters, the calculation of the times that the heaters trigger the coils to quench is required. The ACM could not predict the quench starting times of the coils, and the 2D control volume method (CVM) is adopted. It models the heat conduction between the coils and the heaters. It is assumed that when the temperature of a control volume in a coil rises above its current sharing temperature T_{cs} , the quench of the coil will be triggered by the heater. In order to increase the computational speed for many attempts of quench protection design, the CVM will be altered to the ACM when a coil is triggered to quench by a heater.

5.2. Quench protection design for the 9.4 T magnet

Passive quench protection is employed for the 9.4 T MRI magnet [7]. Circuit subdivision and protection heater are used. By means of the quench simulation code, many attempts have been made for the design. In order to reduce the coil voltages, the 5 main coils are subdivided into 10 sections. The 4 compensating coils are combined into one section to keep balanced force of eddy current in the radiation shield. Each section is in parallel with a shunt resistor and a bi-directional diode. Resistance less than 0.1 Ohm of each shunt resistor is used for safe energy deposition in the resistors.

An ‘in-out-in’ heater network configuration is proposed, shown in figure 8. If any of the inner main coils initiates to quench, the outmost compensating coils will be triggered to quench by heaters first, and then the other coils will be triggered by heaters to quench. Heater strips are attached on the outside surfaces of windings, with width of several centimetres and thickness of about 0.1 mm.

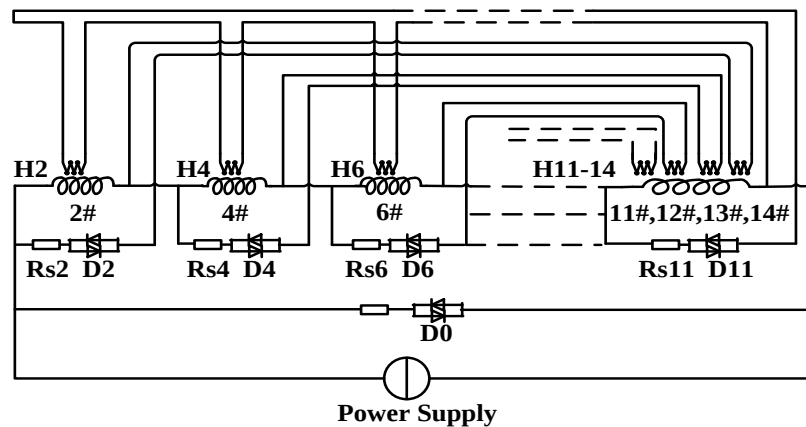


Figure 8. Protection circuit and heater network configuration.

With the optimized quench protection design, the coils are safe in the worst case that quench initiates in coil G1. The maximum coil voltage is restricted to about 600 V. The coils can withstand the maximum voltage since each coil winding passes the high potential test of 2000 V. The maximum coil hoop stress is limited below 170 MPa. In the quench simulation, the simple method of $B_z \cdot J \cdot R$ is used for fast calculation without considering any outside reinforcement of the windings. Real hoop stresses in the coils will be less than the calculated ones. The highest temperature rise is below 120 K. Therefore, the protection design can guarantee the safety of the 9.4 T MRI superconducting magnet.

The protection heater is also employed to Z2 shimming coils besides the electromagnetic decoupling of Z2 coils. The heater driven circuit for Z2 coils is coupled to the above heater network, and the Z2 coils will be protected at the same time as the main coils and compensating coils. In this way, the safety of Z2 shimming coils will be further guaranteed.

6. Cryostat design

The partial cross-sectional view of the cryostat is shown figure 9. The superconducting coils are placed in a liquid helium vessel made of austenitic stainless steel. The axis of the superconducting coils is 40 mm vertically lower than that of the vessel for a higher liquid level above the coils. The capacity of the vessel is about 6500 L, and it contains liquid helium of about 2900 L. The cold weight of about 30 tons is supported by 4 groups of rigid race-track-shaped rods. The rod is made of E-glass epoxy with very low thermal conductivity.

To reduce the thermal radiation from room temperature, an aluminium radiation shield surrounds the helium vessel. The shield is linked to two 50 K cryocoolers via soft copper braids. Multi-layer insulation (MLI) is attached on the outer surface of the radiation shield for further reduction of the thermal radiation from the outside. A stainless steel vacuum vessel contains the radiation shield and the superconducting coils. It provides high vacuum to eliminate heat convection of the gas in it. Three removable transit fixtures through each vacuum vessel end plate are bolted to the helium vessel for solid support in transportation. On the top of the vacuum vessel, a service turret locates vertically at the center. It provides for current leads, measurement leads, helium transfer pipes, liquid level meter, and quench exhaust pipe. Two GM cryocoolers Sumitomo 415D with two stages are installed in the turret. The first stage with 35 W cooling capacity at 50 K is used to cool the main current leads during the magnet charging. The second stage with 1.5 W cooling capacity at 4.2 K is for re-condensation of helium gas to realize the zero boiling-off of helium. At each side of the turret, there is a single-stage GM cryocooler Sumitomo 500B that provides 130 W cooling capacity at 50 K for the radiation shield

cooling. All cryocoolers are installed with bellow tubes to minimize the vibration from the cold heads transmitted to the internal helium vessel and radiation shield.

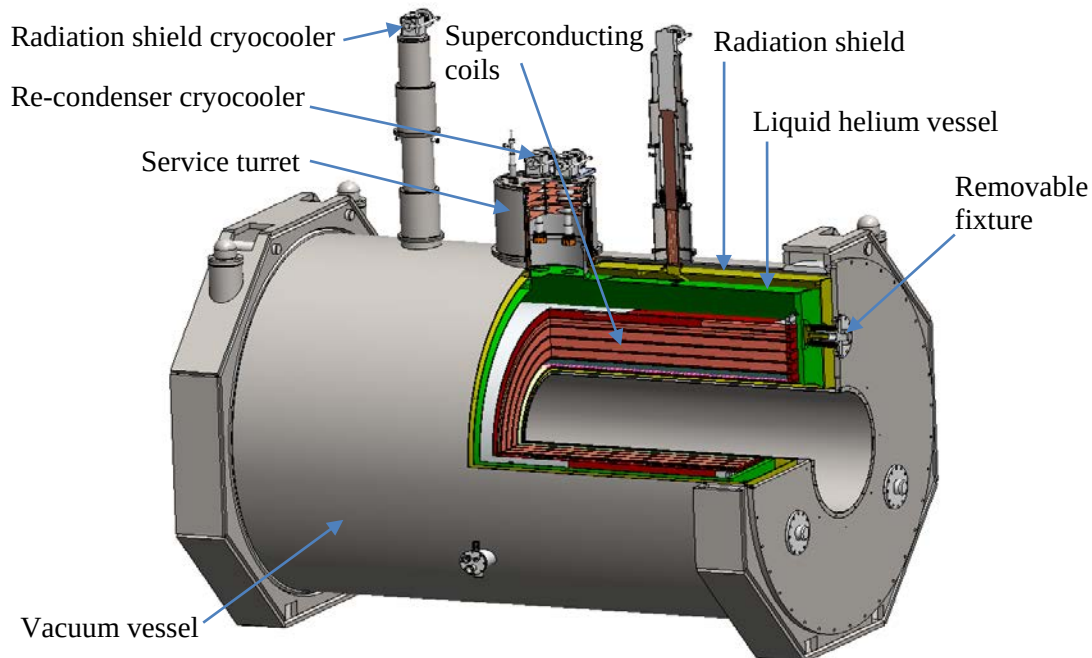


Figure 9. The cryostat of the 9.4 Tesla MRI magnet.

7. Conclusion

A superconducting magnet for 9.4 T whole-body MRI is developed in IEE, CAS. Superconducting main coils and compensating coils are designed to generate 9.4 Tesla in the central 400 mm DSV with field inhomogeneity below 5 ppm. For better field correction, the design parameters of compensating coils are updated based on actual winding results of the main coils. Thirteen groups of superconducting shimming coils are designed with the Z2 shimming coils electromagnetically decoupled from the main coils. Stress and strain analysis shows that the safety and stability of all superconducting coils is guaranteed during normal operation. Quench protection system is designed by means of a experimentally verified quench simulation code developed in IEE. The simulation results show that the safety of the main coils, compensating coils and Z2 shimming coils can be guaranteed during quench. The cryostat is designed with two kinds of cryocoolers for radiation shield cooling and helium recondensation, to realize the zero helium boiling-off.

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