Design calculations for the superconducting dipole magnet for the Compressed Baryonic Matter (CBM) experiment at FAIR*

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Calculations have been performed to design the coil case, the coil vessel, the support links and the quench protection scheme for the CBM superconducting dipole magnet. The general parameters of the magnet have been discussed in a separate contribution to this Scientific Report. The code TOSCA was used for calculating electromagnetic forces exerted on the coil, while the structural analysis was made by using the code ANSYS. The radial F_r and vertical F_y forces were calculated at 1.08 T with TOSCA as a function of the azimuthal angle of the coil. The radial force points toward the outer direction, while the vertical force attracts the coil toward the iron yoke. The integrated forces along the coil circumference are radially 60 tons and vertically 254 tons. The ANSYS calculation was based on the results of TOSCA.

Coil case

The coil case is designed considering two main functions: one is to protect the windings against magnetic forces during operation, and the other is to use the case as a container for liquid helium (LHe) to cool the winding. The volume of the LHe in the case is about 20 liters for one coil, including the LHe stored in the current leads box. The case is welded of stainless steel 316LN [1]. The minimal thickness of the case is 20 mm. The steel magnetic permeability is about 1.01 ~ 1.02. The cross section of the coil has the height of 236 mm and the width of 221 mm. The coil occupies only a part of the internal space of the case. The rest space is filled with the spacers made of NEMA G10 and an aluminum circular shim (AW6061 or AW3003). In addition, the shim provides good thermal conduction that allows to distribute the heat load caused by friction if the coil moves or cracks under the Lorentz forces. The large cross section is necessary to have a very rigid structure. The case should transmit huge vertical forces from the coil to the supports.

The case is supported by six main cylindrical supports and six tie rods. To reduce the heat flux to the helium system, the outer surface of the casing will be wrapped with 10 layers of a multi-layer insulation.

Thermal shield

The thermal shield must have good thermal conductivity, good rigidity to weight ratio, and it should be easy to fabricate and assemble. The thermal shield consists of two main pieces: the top shield and the cover. The shield has a radial cut for an electrical break. All pieces are made of copper sheets each 2 mm thick. The forced-flow cryogen for cooling the thermal shield is cold helium gas to intercept thermal radiation from the cryostat. The cooling pipes are made of a copper tube 1 mm thick having a rectangular shape with an outer dimension of 20 mm × 8 mm. To reduce the heat flux to the helium system, the outer surface of the thermal shield will be wrapped with insulation of 20 layers. The thermal shield is fixed to the main cylindrical supports.

Suspension

The cold mass is suspended from the room temperature (RT) vacuum vessel using 6 support struts and 6 tie rods. These support struts are described as “warm-to-cold” because the warm end is attached to the RT vacuum vessel and the cold end is attached to the cold mass. The suspension during the working cycle has two types of loading. When the magnet is switched off only the weight of the cold mass is applied to the suspension. In this case the vertical force is about 2000 kg. When the magnet is switched on, the vertical component of the Lorenz forces should be added to the weight of the cold mass. The maximum vertical force in this case is 254 tons. The lateral forces should not exceed a few hundred kilograms due to symmetry of the magnet. The support struts are typically compressed. Only the green parts require pre-compression while manufacturing the CBM dipole magnet. The tie rods will provide this pre-compression. The support struts have a nominal compression force of 42 tons [2]. The tie rods are tensed with the force of 500 kg.

The support strut consists of four composite tubes nested coaxially in each other and connected in series by three stainless steel tubes with Z-shaped cross section. The composite tubes are a polar wound tube with glass fibers and epoxy resin. The axial winding angle is ± 15º. Few layers have the winding angle of 90º to fix the main layers. The glass fiber composite has small thermal conductivity at low temperature. The Z-shape tubes are made of the SAE 304 stainless steel. Five layers of MLI are inserted in each gap between the tubes. The middle tube is connected with the thermo shield at the temperature of 80 K.

The tie rods are used to sustain the cold mass and preload the support struts. The tie rods, which are attached on one side to the vacuum vessel and on the other side to the coil case, are subjected to a thermal gradient from 4.5 K till room temperature. Titanium alloy Ti 5Al 2.5Sn has been chosen as tie rod material for its low thermal conductivity and high

*Supported by the BMBF, JINR Dubna, and by EU/FP7 Hadronphysics3

mechanical strength [3] The tie rods have spherical hinges on both sides. The hinge attached to the vacuum vessel is fixed with a key. The hinge on the other side has a thread for adjusting. On 1/3 of the length from the vacuum vessel it has a shoulder for a thermo bridge [4].

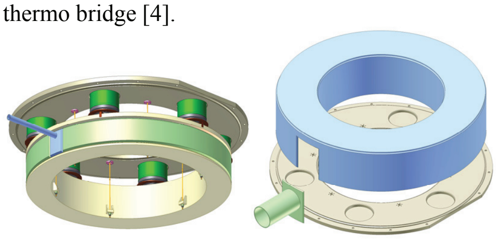

Figure 1: Suspension on the coil (left) and the vacuum vessel (right)

Vacuum vessel

The vacuum vessel seals the vacuum around the cold mass to allow the cooling system to reach the desired cryogenic temperature. The vacuum vessel consists of a support ring, a shell and a weldolet. The rest parts are made of stainless steel SAE 304 [1]. The thickness of the shell is 15-20 mm. The support ring is 48 mm thick. All parts of the vacuum vessel will be assembled by welding.

The space between the spacers is used for the liquid helium circulation. Over the spacers there is a tray made from thin G-10 Glass Epoxy laminate and covered by few layers of fiber glass fabric with epoxy resin with total thickness of 2 mm. The coil is wound inside this tray. Each layer is insulated with three layers of 0.1 mm fiber glass fabric with epoxy resin. Since the coils and conductor experience radial and axial forces of a high magnitude, the winding is required to be done at high tension of 20 kg and gaps between turns are needed to be filled with epoxy resin to restrict movement of the conductor. This impregnation should be done with a brush. The last layer should be wrapped with six layers of 0.1 mm fiber glass fabric with epoxy resin. Then aluminum banding is carried out around the coil at 200 kg tension for restricting the movement of the conductor and the coil while the magnet is energized. Aluminum banding gives more compressive stress to the coil at 4.5 K as compared to SS because of the higher thermal contraction coefficient. A special grade of Aluminum (5052 - H34) strip having high hardness and tensile strength of 267 MPa is used. The strip has a cross section of 2.5 mm x 5 mm.

Instantaneous quench

Figure 2 shows the instantaneous quench calculation results [5,6]. This calculation was done with a constant inductance of 21.9 H (L_w at 686 A). The average temperature is equal to 81 K. The resistance of quenched pole is equal to 2.6 Ohm and the maximum quench voltage is equal to 737 V. The quench detection and protection scheme is shown in figure 3.

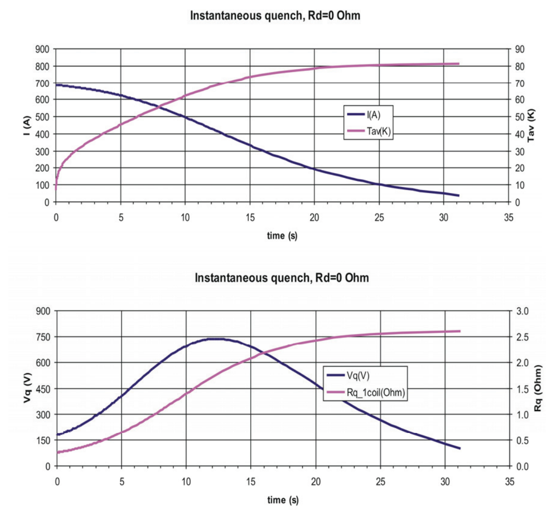

Figure 2: Instantaneous quench calculation of the CBM dipole: magnet current and average coil temperature (upper plot) and quench voltage and quench resistance (lower plot)

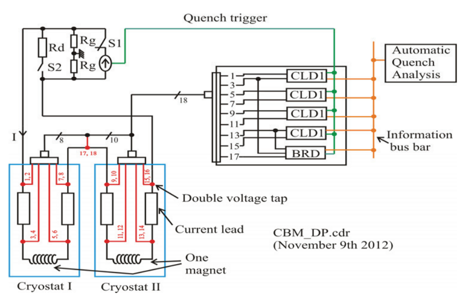

Figure 3: Quench detection and protection scheme (including voltage taps)

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