# Engineering design of a superconducting magnet for gravity compensation

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**Abstract.** Magnetic compensation of gravity allows for ground-based experiments to be carried out under weightless conditions at reasonable cost and without time limitation of the systems such as zero-g airplanes or drop towers. In this paper a superconducting magnet for gravity compensation is described. The magnet warm bore diameter is 382mm and the centre magnetic field is about 2T. The magnet is comprised by nine solenoid coils wound on two separated mandrels. The magnet is conduction cooled by two GM cryocoolers. The cryostat design and analysis are present in this paper, including the heat load analysis and cold mass support system design. Thermal and mechanical design of the cold mass are discussed in this paper, especially the temperature difference and the mechanical stress in the cold mass assembly. Cooling down and charging results show that the magnet can run at its design current very well.

## 1. Introduction

Cryogenic fuels will play increasing roles in the future space industry, including space transportation, deep space exploration, on-orbit propellant depots, space economy and so on. The main operations of cryogenics fuels include storage, conditioning, manoeuvrers, and transfer [1] [2]. The thermodynamics, hydrodynamics, heat transfer, and other physical phenomena associated with these operations need to be understand and predicted very well to success the project. The basic data, modelling method and study results of these complex thermo-fluid-dynamic processes happening in microgravity environment need to be collected and validated by experiments.

Magnetic compensation of gravity allows for ground-based experiments to be carried out under weightless conditions at reasonable cost and without the time limitation of systems such as zero-g airplanes or drop towers. Compared with normal electromagnet, superconducting magnets have the advantage of small footprint, higher magnetic field, and lower operating cost. Many superconducting magnetic gravity compensations have been installations worldwide. They can be divided into two types. One type is used for life science, the required $|\nabla(B^2)|$ is about ~ 3000T2/m, for gravity compensation in water or biological tissues that consist mainly of water. Another one type is used for physical sciences, the required $|\nabla(B^2)|$ is 5~1000 $T^2/m$ depend on the physics studied, usually used for gravity compensation in fluid to study the shape and motion of bubbles and drops [3]. Although many researches have been done focusing on the science

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phenomenon based on superconducting magnetic gravity compensations, little researches study the design and construct such a superconducting magnet.

We developed a gravity compensation superconducting magnet for bubbles thermo-fluid-dynamic processes in liquid oxygen. The magnet was conduction cooled by two GM cryocoolers. The basic magnetic design, the cryostat design, cold mass mechanical design and test results are presented in this paper.

## 2. Magnet parameters

According to the theory of electromagnetism, in the influence area of a magnetic field, paramagnetic (e.g. oxygen) and diamagnetic (e.g. hydrogen) materials are subjected to a volume force:

$$\vec{F}_m = \frac{\chi}{2\mu_0}\nabla(B^2)$$

Where $\chi$ is the magnetic susceptibility of the considered material, $\mu_0$ is the vacuum magnetic permeability, $B$ is the applied magnetic field and $\nabla$ is the vector gradient operator. To compensate gravity in oxygen, the value of $\nabla(B^2)$ needs to be 8.15 T2/m at 90 K [4]. This force, is proportional to density just like the weight, thus the compensation of gravity occurs independently of the state of matter. The main drawback of magnetic compensation stays in the fact that the ideal compensation in any finite volume is impossible. In practice, the ideal compensation is achieved in a single or at most several points. It is possible to approach the ideal compensation conditions within a given accuracy in any volume [4].

**Table 1.** Basic parameters of the magnet running in microgravity mode

| Coil Number | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 |
|---|---|---|---|---|---|---|---|---|---|
| Rin, mm | 218 | 218 | 218 | 218 | 218 | 256 | 256 | 256 | 256 |
| Rout, mm | 246 | 228 | 228 | 228 | 246 | 263 | 264 | 261 | 270 |
| Z1, mm | -360 | -191 | -57 | 90 | 278 | -326 | -79 | 60 | 261 |
| Z2, mm | -278 | -90 | 57 | 191 | 360 | -253 | -65 | 114 | 334 |
| Layers | 46 | 18 | 16 | 18 | 46 | 12 | 14 | 8 | 24 |
| Turns/Layer | 125 | 155 | 174 | 155 | 125 | 113 | 21 | 83 | 112 |
| Current, A | 90 | 90 | 90 | 90 | 90 | -90 | 90 | 90 | 90 |

The magnetic design parameters requirements for the superconducting magnet is $\nabla(B^2)$ = 8.15 T2/m, the central magnetic field B = 2.0 T and the warm bore is diameters D = 382 mm. Table 1 shows the design parameters of coils for this gravity compensation superconducting magnet. The magnetic system is composed by 9 co-axis coils. These 9 co-axis coils can be divided into 2 groups. The role of group 1 coils including coil 1, 2, 3,4 and 5 is to generate a uniform background field about 2T. The role of group 2 coils including coil 6, 7, 8 and 9 is to generate a gradient field. The magnet can be operated in two mode, microgravity mode running both group 1 and group 2 coils, and uniform field mode running with only group 1 coils.

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Fig 1 shows the magnetic field information of the magnets. Running at microgravity mode, there are several points can reach the required ∇(B$^2$) = 8.15 T2/m at the axis, and at the radius 20 mm surface ∇(B$^2$) in the horizontal direction is about 2% of the ∇(B$^2$) in the vertical direction.

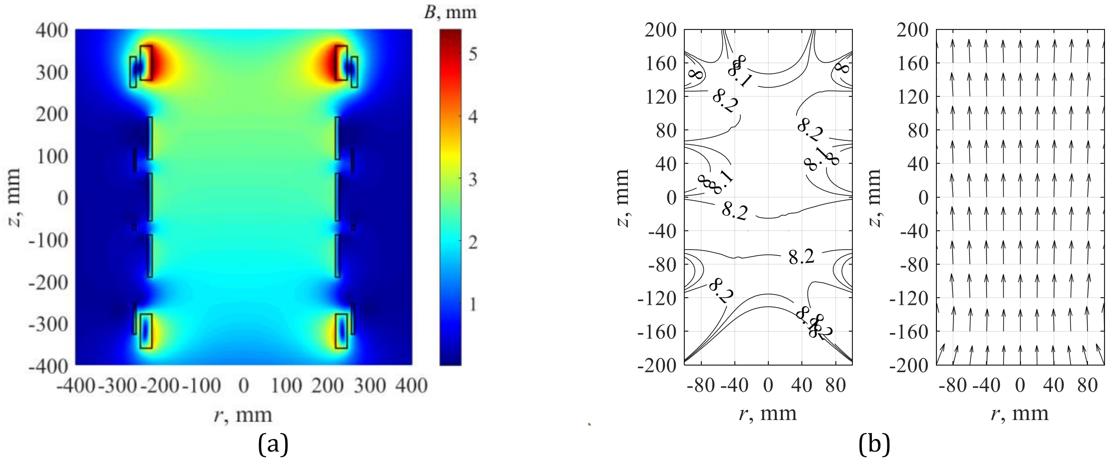



**Figure 1.** Magnetic field information of the magnet. (a) Norm of B in the space; (b) Norm and direction of ∇(B$^2$) in the warm bore

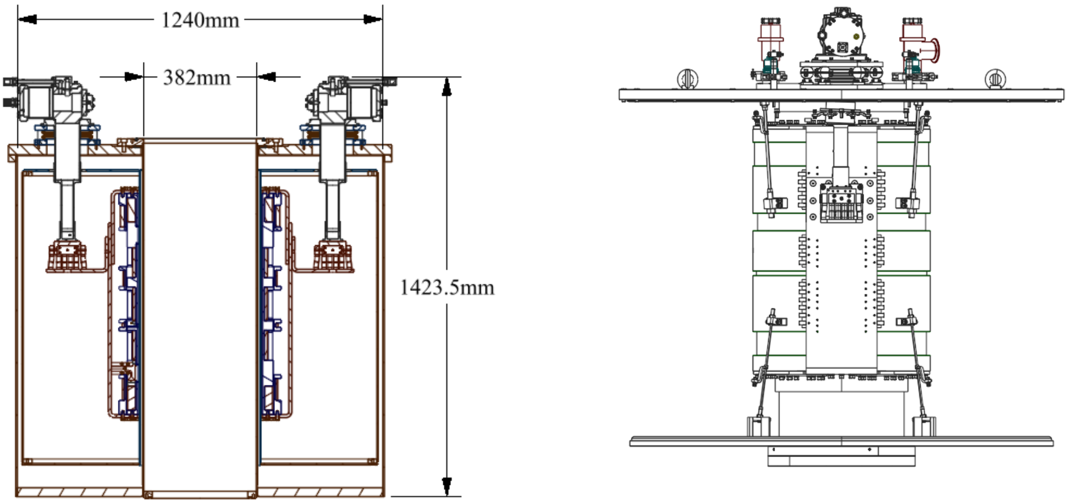



**Figure 2.** Structure of the cryostat for the superconducting magnet

## 3. Cryostat Design

Figure 2 shows the structure of the magnet cryostat. The superconducting magnet was conduction cooled to 4 K by two GM cryocoolers, BMC418 produced by BAMA CO., LTD, China. BMC418 normal cooling capacity is 1.8 W at 4.2 K and 42 W at 50 K. To decrease the effect of the cold head vibration on the experiment. Soft copper heat conduction strips were used for heat transfer between the heat exchangers of the cold head and the 4 K cold mass. And shock-absorbing rubber pad were used between the cold head and cryostat vacuum vessel. Thermal shield design at 50 K was cooled by the first stage heat exchanger of the cold head. Heat load of the cryostat can be catalogued into 4 K and 50 K two temperature level. Table 2 shows the heat load summary of the cryostat. The heat load estimation was calculated using the Fourier's Law. The temperature difference is defined as the difference between the terminal temperature and room temperature.

The cross-sectional area and length are determined from the mechanical structure. And the thermal conductivity values are sourced from the NIST database [5]. According to the heat load calculation results, the selected two BMC418 cryocoolers have big cooling margin for this cryostat.

As shown in Figure 2, the 4 K cold mass was suspended by 8 rods in the vacuum vessel. And 50 K thermal anchors were set on the surface of the rods. The cold mass support system is required to withstand self-gravity, thermal stress, and transportation acceleration loads. In all working conditions the rods are required to be at tensile stress state. The cold mass rod was made of CRFP, which has low thermal expansion coefficient at cryogenic temperature, and low thermal stress in the support system. According our calculation, considering all the working conditionings the maximal force load on the rod is about 15kN. Eight same rods were design and test with capacity of 22.5 kN.

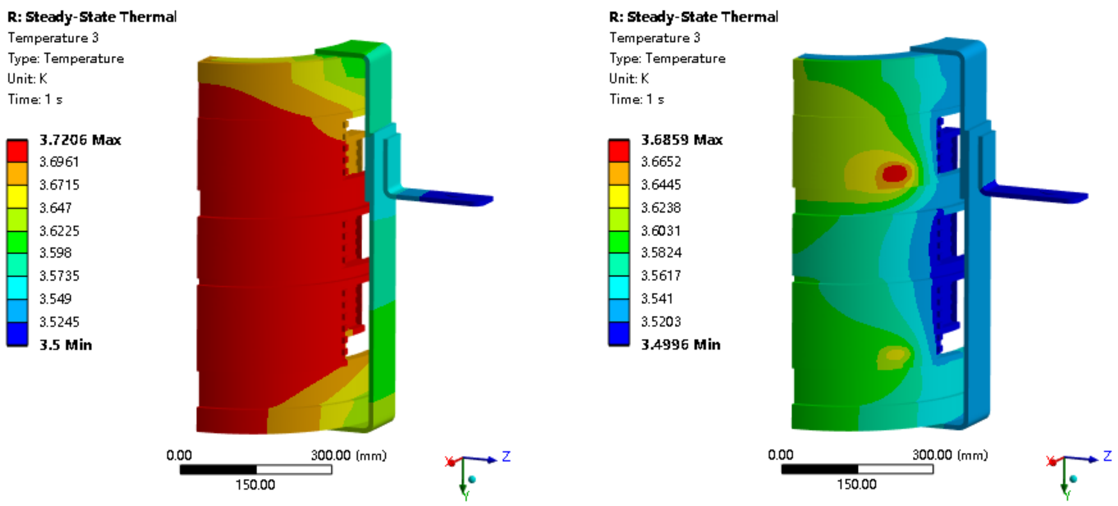
**Table 2.** Heat load estimation of the cryostat, Unit W

| Temperature | Heat load source | Value (W) | Description |
|---|---|---|---|
| 50 K | MLI from 300 K | 8.140 | MLI, Cold surface 7.4m$^2$,1.1W/m2 |
| | Thermal shield supports | 1.260 | G10, section area 4e-4m$^2$, 0.2m, 4 |
| | 50 K Thermal anchors | 5.055 | CRFP, section area 5.0e-5 m$^2$, 0.066m, 8 |
| | Normal metal current leads | 14.971 | COPPER, 90A, 1.2*ideal heat load, 3 |
| | Sensor wires | 0.057 | Phosphor Bronze, 36 AWG, 0.3m, 120 |
| | Sub-Total | 29.483 | |
| 4 K | Thermal radiation from 50 K | 0.15 | Cold surface 2.5m$^2$, emissivity 0.08 |
| | 4 K cold mass support | 0.018 | CRFP, section area 5.0e-5 m$^2$, 0.17m, 8 |
| | HTS current leads (50K – 4K) | 0.112 | CSS-0150-170,1.15* 0.065W/Pair, 3 |
| | Sensor wires | 0.001 | Phosphor Bronze, 36 AWG, 0.3m, 60 |
| | Sub-Total | 0.282 | |

## 4. Magnet Cold Mass Design

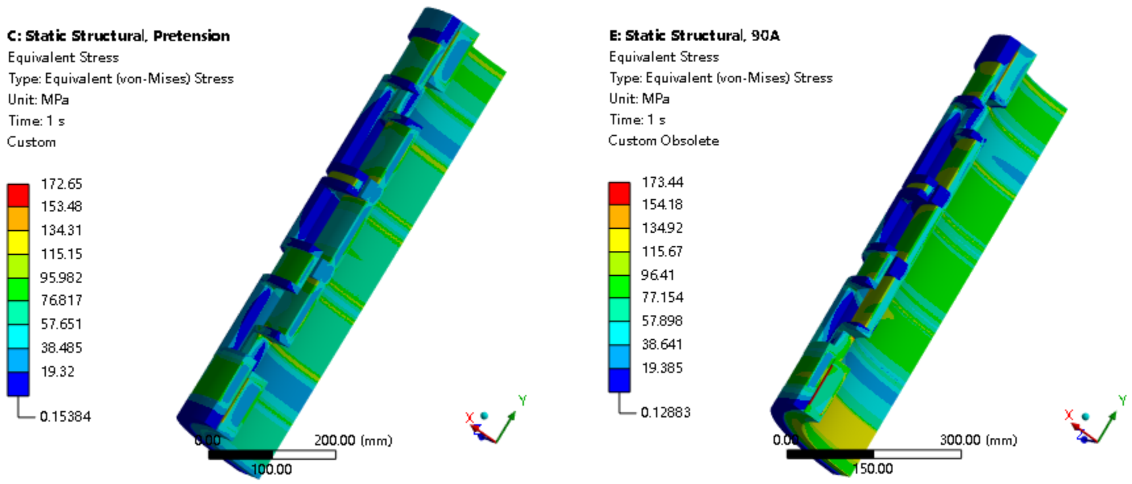
Magnet cold mass includes the superconductor windings, mandrels of 6061T6 aluminium, bounding of 6061T6 aluminium wires on the out surface of the winding, quench protection assembly and other components running at about 4 K. Group 1 coils were wound on the inner mandrel, group 2 coils were wound on the outer mandrel. The two mandrels were fixed as an assembly by the copper plates at the end plates of the two mandrels. Figure 2 shows the basic struct of the cold mass.

Cooling design of the cold mass is to lower the temperature difference or the hot spot temperature on the cold mass. The main method is to decrease the thermal resistance between the second stage of the cold head and the cold mass. Figure 3 shows temperature of the magnet cold mass. In the thermal modelling the cold head temperature is set as 3.5 K. As shown in Figure 3 (a) the biggest temperature difference is 0.22 K without copper heat conduction soft strips. Some copper soft strip links the main cold plate to the mandrels and coil bandings, as shown in Figure 1. The copper strips are made of copper RRR >100, with cross section area of 72 mm$^2$, and length of 80 mm. In our model the conduction of the copper strips was simply modelled to be a convection boundary with 3.5 K cold surface with equivalent convection film coefficient. As show in Figure 3 (b), the added coppers strips can decrease the peak temperature difference on the cold mass from 0.22 K to 0.186 K, and the temperature of the cold mass main body are decreased greatly.




(a) (b)

**Figure 3.** Temperature of the magnet cold mass. (a) without copper heat conduction soft strips; (b) with copper heat conduction soft strips




(a) (b)

**Figure 4.** von Mises stress of the cold mass at different loads (a) Room temperature pretension; (b) Room temperature pretension, electromagnetic at 90A

Mechanical design of the cold mass is to keep the stress level in every component at an allowable level and hold the superconductor at the design position not to move. The cold mass experience several phases, including coil winding phase, cooling down phase, and charging phase. In different phases, the loads conditions and stress states are different. Sever design criteria are used to check the mechanical design of the cold mass. First all the stress in every component should be lower than the allowable stress of the material. Secondly the superconducting windings should be contact to the coil mandrel at working conditions. Prestress 40 MPa and 80 MPa were applied on superconductor wires and banding wires respectively to make the superconducting wire can work well not to move. Figure 4 shows the von misses results at typical loads. According to the results in Figure 4 effects of the electromagnetic force on the stress of the cold mass is small. More attentions were paid to decrease the thermal stress in the assembly, using some technology like slip planes [6].

## 5. Test Result

The magnet has been cooldown and charged to the design current 90A several times in 2024. According to the test results, the second stage of the cold head was about 3.2 K, the measured maximum temperature of the cold mass assembly is 3.4 K, and the thermal shied is about 40 K. . All the measured temperature values were lower than their designed values, which means the cooling capacity of two BMC418 cryocooler is much larger than the heat requirement of the cryostat. This is in accordance with our heat load calculation results shown in Table 2. The eight rods cold mass supports and the cold mass assembly work well as expected. The liquid oxygen bubble behaviour in microgravity environment has been observed successfully as the superconducting magnet design aim.

## 6. Conclusion

A superconducting magnet for gravity compensation is described. The magnet is comprised by nine solenoid coils wound on two separated mandrels. The thermal and mechanical design of the cryostat and the cold mass were discussed in this paper. Cooling down and charging results show that the magnet can run at its design current very well. The capacity of the two BMC418 cryocoolers can meet the heat load with a large cooling margin for this cryostat. The magnet can provide a microgravity to study the liquid oxygen bubble behaviour successfully.

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