Development of a zero boil-off helium cryostat for superconducting magnets

Meifen Wang1, Huan Yang1, Feipeng Ning1,2, Zian Zhu1

1State Key Laboratory of Particle Detection and Electronics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
2Graduate University of Chinese Academy of Sciences, Beijing 100049, China

E-mail: wangmf@ihep.ac.cn

Abstract. This paper describes a horizontal type cryostat of a superconducting magnet with a 300mm room temperature bore. The magnet, with the diameter of 400mm and length of 815mm, is immersed in 30 liter liquid helium. Design consideration, including thermal staging of the silver/Bisco current leads, low thermal conduction mechanical support structure, and the theoretical calculation of heat load to the cryostat are discussed. And only a helium recondensing G-M cooler (40W at 50K, 1.5W at 4.2K) is used to achieve zero boil-off.

1. Introduction
Superconducting magnets have many important applications in different areas such as superconducting magnetic separators, magnetic resonant imaging (MRI) systems, and the semiconductor industry. In order to provide low temperature environment, most conventional superconducting coils have various ‘wet’ cryostats to use considerable amounts of liquid helium. But, the increasing costs of liquid helium caused by a limited natural resource on earth raise concerns about conventional cryogenic equipment. And so there is a growing necessity to develop large, low cost and reliable superconducting magnets. Fortunately, based on the 1990 cryocooler development using multi-compounded rare earth materials in the second-stage regenerator [1], a new generation of cryogenic system, called the zero helium boil off cryostat or re-condensing cryostat, is developed [2]. This system is usually designed with a small amount of stored liquid helium by inserting a 4.2K cryocooler to recondense liquid helium boil off during static operation. By reducing the size of the LHe vessel and eliminating one thermal shield, this development results in a more compact design as compared to traditional superconducting magnet systems. While zero boil off cryostats do still contain liquid cryogens, they can be viewed as having the advantages—Liquid helium costs are minimized, and the same time they have the ability to tolerant power faults without superconducting magnet quenches [3-7].

In this paper, the detailed design and construction of a zero boil off cryostat for a 5 T superconducting magnet are presented. This cooling approach can eliminate the dependence on liquid cryogen. The superconducting magnet is cooled with 30 litres liquid helium. The cryostat is designed to have very low heat leak coupled with one 1.5W GM cryocooler to allow the helium re-condensed and long, maintenance-free operation.

2. Cryostat description
A superconducting magnet is in production and will be operational at Dec. 2011 in Superconducting Magnet Engineering Center (SMEC), Institute of High Energy Physics (IHEP), Chinese Academy of Sciences. The schematic illustration is shown in Figure 1.

![Figure 1. The cryostat illustration.](image)

The cryostat is of horizontal design, consisting of an inner helium vessel which contains the main NbTi field coils. The helium vessel is supported from the outer vacuum vessel with glass fiber reinforced plastic (FRP) G10 rods. A single thermal shield surrounds the inner and outer surfaces of the helium vessel. The stainless steel vacuum vessel is 1.1 m high and 0.8 m outer diameter. The magnet, with the diameter of 400mm and length of 815mm, is immersed in liquid helium bath. The system can generate up to 5T at an operating current of 150A when enclosed in iron. The horizontal cryostat is equipped with one closed-cycle G-M refrigerators for shield cooling and helium reliquefying. The cryocooler consists of a helium compressor, a cold head and flexible connection lines. Its specification is: 40W at 50 K on the first stage and 1.5W at 4.2 K on the 2nd stage simultaneously. In order to connect to the magnet for ramping the field up and down, a pair of high temperature superconductor current leads is adopted with the aim to reduce both heat leak and Joule heating [8], [9]. The specifications of the magnet are presented in Table 1.

| items            | parameters |
|------------------|------------|
| Inner diameter   | 400mm      |
| length           | 815mm      |
| Central field    | 5T/150A    |
| inductance       | 125H       |
| Stored energy    | 1.5MJ      |

2.1. The helium vessel

The 304 stainless steel helium reservoir, which is covered with shiny aluminum foil tape, is welded and has a helium volume of 30 liters. On top of the vessel is a service tower to provide the access to the helium reservoir, which houses the current leads and the cryocoolers. Initial cooling and filling of this vessel is via the service tower. The cold head is connected with cryostat through a bellows tube, this allows for the reliquefaction of helium evaporating in the reservoir. In order to reduce the performance degradation of the cryocooler caused by the magnetic field, the cryocooler is located at the top of the cryostat [10]. The cold end of it extends into the chamber of the cryostat, and there is no mechanical contact between the second stage of the cold head and the chamber. The recondensing surface is cooled to 4.2 K directly by the second stage of the cryocooler and evaporated helium flows into the recondensing surface and returns to the LHe bath by natural convection.
2.2. The thermal radiation shield

In order to reduce radiation losses, the lower part of the chamber is surrounded by a radiation shield. The thermal radiation shield is made of aluminum 5083 with 6 mm thick. The shield is independently cooled to 40 K through the “thermal link” to the first stage of the cryocooler. Multiple layers of thin copper straps connect the cryocooler and the shield top. Both the liquid helium vessel and shield use multiple layers insulation.

2.3. The valve

At static operation, positive pressure will always be present within the helium chamber, thereby reducing the risk of ice formation. While zero boil off cryostats have many advantages compared with conventional systems, they do still contain liquid cryogens and thus properly designed pressure relief systems is necessary in case of cryocooler or cryostat failure. A pressure relief valve, and a burst disk are included in the design to ensure safety. It is also essential to vent the gas outside of the area where people are, as a dangerous quantity of helium gas could be released in one minute during quench.

3. Heat loads

The cryostat provides vacuum environment for the thermal insulation to magnet system operating at 4.2K and thermal shield system operating at 40k. The steady-state heat loads, whether radiative or conductive, are driven by the temperature difference between the vacuum vessel and the helium tank. In order to realize a zero boil-off magnet, it is a key objective to minimize environmental heat leak and thus minimize active cooling power requirements.

One important source of heat is radiation from the room temperature to the helium tank. The heat leak through the multi layer insulation (MLI) blankets was approximated using the Lockheed Equation [11] given by

\[
q = \frac{C_r (\overline{N})^{2.56} T_m (T_m - T_c) + C_s \varepsilon_{RT} \frac{T_H^{4.67} - T_c^{4.67}}{N_s}}{N_s + 1}
\]

where

\(C_r = 5.39 \times 10^{-10}\)
\(C_s = 8.95 \times 10^{-8}\)
\(\overline{N} = \) Radiation shield layer density, layers/cm
\(N_s = \) Number of radiation shields
\(q = \) Heat flux, W/M2
\(T_c = \) Cold boundary temperature, K
\(T_H = \) Warm boundary temperature, K
\(T_m = \) Mean insulation temperature, K
\(\varepsilon_{RT} = \) Room temperature (300K) total hemispherical DAM emittance
The total MLI heat load is then calculated by

\[ Q = FAq \] (2)

where

\[ A = \text{Inner surface area} \]
\[ F = \text{Degradation factor} = 1.2 \]

Moreover, a pair of silver/Bisco current leads was employed to reduce the heat leak. The heat load of the high temperature superconducting current leads is about 15 W at the operating current of 150A. The bellow pipe is employed to further reduce the heat leak from room temperature to the liquid helium vessel. The shields and the helium vessel are supported vertically and horizontally by G10 rods, G-10 is chosen for its excellent strength and thermal performance at low temperatures. The structure is strong and lightweight, and minimizes the loss of tension in the straps on cooldown. The sizing of the straps has been optimized to provide the smallest area/length ratio and still meet the structural loads. The total heat loads to the first and second stages of GM cryocooler in the cryostat are summarized in Table 2.

|                     | First stage (W) | Second stage (W) |
|---------------------|-----------------|------------------|
| radiation           | 3.20            | 0.20             |
| Supporter rod       | 4.50            | 0.05             |
| Service tower       | 9.20            | 0.10             |
| Current leads       | 15.0            | 0.10             |
| Total               | 31.9            | 0.45             |

4. Conclusions

The development of superconducting magnets has shown a strong correlation to the developments in cryocooler technology. As cryocooler capacity at 4.2 K and the maintenance interval are increased, new superconducting magnets products with the zero boil off cryostat will be developed, it is easy and safe to use. The cryostat design in this paper is being validated for the structural and recondensing regime.

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