Installation of a Superconducting Magnet in a Cryogen-Free Dilution Refrigerator

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\textbf{Abstract.} A cryogen-free dilution refrigerator equipped with an 8 T superconducting magnet is developed. The dilution unit and the magnet are cooled together by a common Gifford-McMahon refrigerator in the same vacuum chamber. A heat flow from room temperature terminals through a pair of copper current leads is well absorbed by thermal anchors connected to a 1st stage of the GM refrigerator. Between the 1st stage and the 2nd stage, a pair of flexible high-\textit{T}_c DyBCO coated conductors is used as a material for the current leads to reduce the heat leakage to the magnet. The dilution cycle is not affected by coexistence of the magnet, because the heat load imposed by the magnet is much less than that by the dilution unit. When a quench event happens, the temperatures of the magnet and a 4 K plate of the dilution unit rise rapidly up to 20 K, but safely recover in 18 min without causing serious trouble in the dilution process.

\section{Introduction}

In recent years, the dilution refrigerator (DR) is getting more popular among researchers for obtaining low temperatures below 1 K continuously. Besides the conventional DRs, cryogen-free DRs [1-6] have been developed by using Gifford-McMahon (GM) or pulse-tube refrigerators as the performance of these cryocoolers is improved. Some of the cryogen-free DRs are commercially available nowadays. Although they have mechanical vibration, the cryogen-free feature brings many advantages. It saves running cost and helium resources, requires less space in laboratory, and does not require skilled technique to handle liquid cryogen, and so on.

For a conventional DR, a superconducting magnet is often equipped in a liquid helium bath. The magnet and circulating helium gas are cooled independently by liquid helium. When a quench event happens, the dilution process is not affected much, because the temperature of the helium bath is kept nearly 4.2 K if the dewar is filled enough.

On the other hand, the cryogen-free DR equipped with a superconducting magnet has not been reported so far. When the quench event happens, a large amount of magnetic energy is suddenly released as a heat in the cold part of the cryocooler. The heat cannot be absorbed instantly because the cooling power of the cryocooler is limited. The temperature of the cold part rises rapidly, and the dilution...
process would be affected or the dilution system would be damaged by increased pressure of the circulating gas.

In this research, we install an 8 T superconducting magnet in the cryogen-free DR and perform test runs to evaluate how much excessive power is required for cooling the magnet and what damages result in when a quench event happens.

![Figure 1. Photograph of the DR system. Right: a gas handling system with a temperature monitor/controller and a magnet power supply. Center: a cryostat. Left: circulation pump, compressor, and helium dump.](image)

2. Structure of the DR

We used a DR system which is commercially available from LTLab, Inc. as shown in figure 1. The cryostat has a single vacuum chamber, which is divided into 3 parts. Usually the upper and the middle chambers are fixed, and only the lowest one is driven up/down by a pair of lever hoists when we get access to the dilution unit or to the magnet. We adopted such a structure design that the dilution unit and the magnet are located parallel in the vacuum chamber (see also figure 2), for saving total height and for a convenience when we change a sample that is set in the center of the magnet. The GM refrigerator (SHI, SRDK-415D) has a nominal cooling power of 1.5 W at 4.2 K.

Figure 2 shows a schematic cross section view of the cryostat. The thermal radiation shields connected to the 35 K plate (b’) and 4 K plate (c’) are not vacuum-tight. For pre-cooling the dilution unit from room temperature down to around 10 K, we introduced hydrogen or helium exchange gas of ~10 Pa into the vacuum chamber. To reduce vibration which comes from the GM refrigerator, flexible copper braids are used for thermal couplings between (b) and (b’), and also between (c) and (c’). Circulating helium gas is cooled by $^3$He vapor evaporated from still when it goes through a heat exchanger (f) [7], and is liquefied by a Joule-Thomson (JT) expansion valve (g).

The magnet coil (d) is made of NbTi superconducting wire, which produces a maximum field of 8 T at 120 A. The bore is 40 mm, the inductance is 1.7 H, and the maximum sweep rate is 1 A/s. Total weight of the magnet component including structural support and thermal links is 12 kg. Shunt diodes for quench protection are thermally anchored to the magnet component. Special attention was paid to eliminate thermal gradient in the magnet. The position of the magnet is designed to have a certain distance from the GM refrigerator so that the magnetic field does not exceed 0.2 T at the 2nd stage (c).
The current leads are designed as follows. They are made of copper (k) between room temperature terminals and thermal anchors on the 35 K plate (b'). In order to reduce thermal conduction between the 35 K plate (b') and the magnet (d), high-\(T_c\) DyBCO coated conductor (l), whose super layer is 3 \(\mu m\) in thickness, is used. Measured heat flow through this pair of superconducting leads was 0.01 W only, but it has a capability to transport an electric current up to 200 A.

3. Heat load of the magnet
To estimate the heat load of magnet and of dilution unit separately, we measured the cooling power of the GM refrigerator when the magnet is installed but the dilution unit is removed. Figure 3 shows the result of the cooling power as a function of temperature in 0 T and 8 T.

In this experiment, \(^3\)He circulation rate was around 100 \(\mu\)mol/s. At this circulation rate, the temperature of the 2nd stage became \(~3.1\) K in 0 T and \(~3.2\) K in 8 T, as shown in figure 4. As shown by two solid dots in figure 3, the cooling power is \(~0.22\) W at 3.1 K in 0 T, and \(~0.27\) W at 3.2 K in 8 T. The difference in power 0.05 W is due to a Joule heating at normal connecting parts in the magnet component. This value is 5 times more than the heat 0.01 W which is brought into the magnet by conduction through the current leads.

As a result, the heat load imposed by the magnet installation is 0.01 W in 0 T, and 0.06 W in 8 T. Subtracting these values from the cooling power of GM refrigerator in 3.1 K and 3.2 K, respectively, it is deduced that the necessary cooling power for running dilution unit is \(~0.21\) W, as shown in figure 3. From these results, it is concluded that the heat load of the magnet is much less than that of the dilution process.

4. Quench event
Figure 4 shows temporal change of the temperatures after quench which was caused by exceeding the magnet current beyond the critical value \(J_c\). The temperature of the 2nd stage increased rapidly after quench, reached 20 K in 1.5 min, and recovered slowly in 18 min. The temperature of still also increased rapidly after quench up to 1.3 K, but slightly decreased for 10 min because \(^3\)He evaporation rate became more by heating of mixing chamber, and then slowly recovered in 13 min. The temperature of mixing chamber increased rapidly up to 0.7 K after quench, but slowly settled down to the ini-
tial temperature in 30 min. The eddy current effect is much less than the energy dissipation at the diode on 2nd stage, but contrary it is more in the mixing chamber.

The pressure of returning $^3$He is normally 70 - 150 kPa, depending on the circulation rate and the impedance of the JT expansion valve. In the present run, initially it was ~150 kPa. After quench event happened, it immediately rose up to ~300 kPa, then decreased little by little and relaxed to the initial value. It took more than 1 h to recover, which is slower than the temperature relaxation. However, the pressure ~300 kPa is within a permissible level and no damage was caused in all the system.

![Figure 3](image1.png)  
**Figure 3.** Cooling power of the GM refrigerator when the dilution unit is removed. The difference between (3.2 K, 8 T) and (3.1 K, 0 T) is only ~0.05 W, which is generated by a Joule heating in the magnet component.

![Figure 4](image2.png)  
**Figure 4.** Temperature variations after quench event happened. Second stage of GM refrigerator reached 20 K just after the quench but recovered in 18 min. Still is not affected very much. Mixing chamber settles down in 30 min.

5. Summary
We installed the superconducting magnet in the same cryostat which contained the cryogen-free DR. The heat load for the magnet was less than that for running the dilution unit. The quench event did not cause serious damage to the system.

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