Feasibility study of parallel conduction cooling of NbTi magnet and sample probe in a cryogen-free magnet system

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Abstract. The conduction cooling of both a 6 T superconducting magnet along with a sample probe in a parallel configuration is addressed in this work. A Gifford-McMahon (GM) cryocooler is directly cooling the NbTi magnet, which aims to be kept at 4 K, while a gas-gap heat switch (GGHS) manages the cooling power to be diverted to the sample probe, which may be swept from 4 K up to 300 K. A first prototype of a GGHS was customized and validated for this purpose. A sample probe assembly has been designed and assembled with the existing cryogen-free magnet system. The whole test setup and components are described and the preliminary experimental results on the integration are presented and discussed. The magnet was charged up to 3 T with a 4 K sample space and up to 1 T with a sweeping sample space temperature up to 300 K while acting on the GGHS. Despite some identified thermal insulation problems that occurred during this first test, the overall results demonstrated the feasibility of the cryogen-free parallel conduction cooling on study.

1. Introduction

The work here described intends to obtain a cryogenic magnetic system with a sample holder insert to be cooled down purely by conductive heat transfer using the cooling power of a 4.2 K cryocooler. Commercial cryogen-free magnet systems (CFMS) are available with variable temperature inserts (VTI), using one cryocooler as the magnet cold source. However, when commercial CFMS includes a VTI they aren’t, cryogen-free as they are mainly based on circulation of helium gas through the sample space. Generally, the circulating helium gas is cooled by the conduction-cooled heat exchangers connected with both the stages of the cryocooler. The motivation of a cryogen-free VTI system for a CFMS is to avoid cumbersome cryogen circulation process and handling. Our aim is to eliminate that flow and provide cooling power to the sample space by regulated conduction, using the cryocooler and a thermal switch for
a parallel cooling. It will make the VTI system a ‘cryogen-free’ in a true sense.

A previously described gas-gap thermal switch prototype [1] has been tested in a CFMS [2]: the cold finger of a 1.5 W @ 4 K GM cryocooler coupled to a NbTi superconducting 6 T coil, was also coupled to the cold block of a gas-gap heat switch that diverts the cooling power to a sample probe as depicted in Figure 1. The conducting state of the gas-gap heat switch (GGHS) may be varied from 0.3 W/K in its ON state to 90 µW/K in the OFF state at 4 K. The OFF conductance was designed so that in the most extreme temperature gradient (4 K – 300 K), the diverted power does not exceed 0.5 W, leaving 1.0 W of cooling power for the coil as a safety margin.

Figure 1. Schema for the parallel cooling tested.

Preliminary tests were performed in this parallel cooling source configuration both for the initial cooldown, for the magnetic field ramping and for the sample warming up under magnetic field, test results and discussion being presented in this paper.

2. Methods

A helium GGHS as depicted in Figure 2 was used for parallel integration tests in a CFMS with a sample probe. The main characteristic of switch is the intrinsic limiting thermal power of 500 mW in the OFF state under a 4 K — 300 K gradient, other characteristics being described in detail in reference [1]. The GGHS was directly bolted to the cryocooler’s cold finger from its larger copper block (Cold Block), and a thick copper braid links the other copper block (Hot Block) to the sample probe. The superconducting NbTi magnet can be observed at the center of the whole setup in Figure 3, linked to the cryocooler through an S-like shaped copper bar.
The limitation on the thermal switch conductance was customized under conservative estimation of the cooling power needed for the magnet itself: the 1.5 W at 4 K cryocooler will divert up to 1/3 of its cooling power to the sample probe, so the magnet will be within safe thermal margin. For that limitation to be applied the switch must be in its OFF state with a cold cryopump. A smaller thermal gradient between sample space and cold finger existing, the switch conductance may be regulated by warming up a cryopump, hence releasing helium gas to the gap between copper blocks.

Two calibrated silicon diodes were attached to the heat switch, one on the hot block and another on the cryopump. A 1 \( \Omega \) resistor is also attached to the cryopump and powered by a Lakeshore temperature controller in order to regulate the conductance of the switch. Cernox temperature sensors are fixed with the magnet surface, magnet cooling plates, 2nd stage of the cryocooler and thermal radiation shield of the magnet system.

![Figure 2](image2.png)

**Figure 2.** GGHS integrated in the cryofree magnetic system.

![Figure 3](image3.png)

**Figure 3.** IUAC setup with the GGHS prototype for parallel cooling management preliminary tests.
Instead of an axial insert for the sample, for ease of assembly, an eccentric supporting structure was adapted to the existing magnetic system: a sample base and a sample probe tube were there installed. The hot block of the GGHS and the sample base are thermally connected through the four copper braids as shown in Figure 3. The length of each copper braid is about 35 cm and the cross sectional area of each copper braid is ~20 mm². Sample base is mechanically supported with the top lid of the thermal shield using G10 strips. A sample probe made of OFHC copper is brazed to a stainless steel tube and a 20 Ω resistor is attached to the sample probe along with a calibrated silicon diode temperature sensor. The bottom surface of the sample probe (25 mm x 25 mm) is thermally connected to the top surface of the sample base by mechanical pressed contact. A spring loaded bolted mechanism is attached with the top of the sample tube to ensure good thermal contact with the base using a thin layer of Apiezon N grease at the interface. The whole parts share the same vacuum chamber.

3. Results

The whole system was cooled down from room temperature (300 K) to 3.2 K in magnet surface temperature, taking 16 hours to reach equilibrium (Figure 4). The magnet surface and the GGHS’ cold block reach equilibrium in 13 h and by then the cryopump was already cold enough so it turns the switch onto its low conducting state — warming up the cryopump (25 K in this data) is needed in order to further cool down the sample probe. Once the switch starts conducting, the temperatures of the hot block, sample base and sample probe start decreasing while the already cooled parts warm up as a response to the thermal load from the warm sample side.

![Figure 4.](image-url) CFMS’s system cooling down temperatures as measured in different parts. The “OFF state” bar points out the cryosorption of the gas inside the switch corresponding to the detachment of “hot block”, “base for sample holder” and “sample probe”. The “ON state” bar points out the heating up of the cryopump and consequent reattachment of “hot block”, “base for sample holder” and “sample probe” temperatures.
The temperature of the sample probe reaches 9.6 K after four and a half hour. The steady state temperature of the sample probe is higher than expected. At the same time the steady state temperature of the hot block of the switch is about 5.9 K and the sample base temperature is about 7.4 K. Hence, there is a temperature drop of 1.5 K between hot block and the sample base. Similarly, there is a temperature drop of 2.2 K between sample base and sample probe. The temperature difference between hot block and sample base is due to the poor thermal conduction through the copper braids along with the heat load coming from the sample probe support tube. The temperature difference between the sample space and the sample base is related to the poor thermal contact between two surfaces, which is due to surface irregularities. Parasitic heat loads like conduction heat, radiation heat to the sample probe needs to be minimized to reduce the steady state temperature of the parts.

The steady state temperature of the 2nd stage of the cryocooler is 3.22 K, which is 0.32 K higher than the steady state temperature of 2nd stage achieved prior to the installation of GGHS. Similarly, the steady state magnet temperature (3.58 K) is 0.40 K higher than the steady state temperature of the magnet prior to the installation of GGHS. These excess temperatures result from the new heat loads introduced with the GGHS and the sample probe.

![Figure 5](image_url)

**Figure 5.** CFMS temperature profile while energizing the magnet with the GGHS in ON state.

Once the whole system attained the low temperature stability the magnet was energized up to 3 T in 1 T (17 A) steps, with the GGHS at its ON state. **Figure 5** shows the dynamic thermal profile of the different components during magnet energizing with 2 A/min sweep rate. The magnet's temperature
(orange curve) initially rises slightly as long as the charging of the magnet goes on. Once the current and magnetic field stabilize, the magnet’s temperature stabilizes to 3.7 K, while using the parallel path conduction introduced by the GGHS. Although there are no significant temperature changes at the cryocooler’s 2nd stage, the inter-lead joint temperature also increases due to the higher joule heating loads through the current leads. This temperature rising pattern of the magnet and inter-lead joint indicates a probable crossing of the magnet’s current sharing temperature and eventual quench if charged to a higher field.

![Figure 6. CFMS parallel tests using the GGHS for cooling a sample space while keeping the magnetic field.](image)

A third kind of tests was performed, rising the sample space temperature while keeping the magnetic field at 1 T (Figure 6). The sample space temperature is then firstly ramped up to 60 K using a Lakeshore temperature controller and the GGHS in the ON state. Magnet parts and sample parts all raise their temperatures, although the magnet is still quenching safe. At 60 K the heat applied to the cryopump is turned off, the cryopump starts cooling down (brown line) and eventually turns the GGHS to the OFF state. The sample space resumes its controlled raising up to 300 K, while the magnet parts stabilize to a colder temperature, with the GGHS in its lowest conductive state. The 300 K on sample space is reached while the magnet surface reaches 4.2 K. Even if this temperature is not risky, no higher than 1 T magnetic field was tested.

Although successful performed tests, it was found that the system was delivering more parasitic thermal power to the heat switch, namely to the cryopump, than desired. Indeed it can be seen in previous
plots that the cryopump does not cool further than 8 K and consequently is turns too easy to warm it up which turns ON the conductance of the GGHS as a consequence. An intervention on the thermal insulation of the parts was found needed before further tests.

4. Conclusions

A completely cryogen free (and gas flow free) conduction cooling magnet system with a sample probe has proved to be feasible. A parallel controllable conducting path that relies on a gas gap heat switch was established, linking the cryocooler’s cold finger to a sample space. Controlling the cryopump’s temperature allows to manage the diverted cooling power delivered by the 1.5 W at 4 K cryocooler. Cooling down a sample space with the same cryocooler that was before exclusively dedicated to the magnet was successful. Magnetizing the system up to 3 T was successful. Once magnetized at 1 T the sample space warmed up to 300 K without jeopardizing the magnetic environment.

References

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