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Gas gap heat switch for a cryogen-free magnet system

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Abstract. Cryogen-free superconducting magnet systems (CFMS) have become popular over the last two decades for the simple reason that the use of liquid helium is rather cumbersome and that helium is a scarce resource. Some available CFMS use a mechanical cryocooler as the magnet's cold source. However, the variable temperature insert (VTI) for some existing CFMS are not strictly cryogen-free as they are still based on helium gas circulation through the sample space. We designed a prototype of a gas gap heat switch (GGHS) that allows a thermal management of a completely cryogen-free magnet system, with no helium losses. The idea relies on a parallel cooling path to a variable temperature insert (VTI) of a magnetic properties measurement system under development at Inter-University Accelerator Centre. A Gifford-McMahon cryocooler (1.5 W @ 4.2 K) would serve primarily as the cold source of the superconducting magnet, dedicating 1 W to this cooling, under quite conservative safety factors. The remaining cooling power (0.5 W) is to be diverted towards a VTI through a controlled GGHS that was designed and built with a 80 μm gap width. The built GGHS thermal performance was measured at 4 K, using helium as the exchange gas, and its conductance is compared both with a previously developed analytical model and a finite element method. Lessons learned lead to a new and more functional prototype yet to be reported.

1. Introduction

Strong magnetic fields are achieved by using superconductor magnets, where usually a liquid helium bath is needed. Liquid helium is not only expensive but it is also a limited resource: a helium shortage could jeopardize future energy projects, such as the long-term development of fusion [1]. The development of reliable cryocoolers with quite high cooling power at low temperatures, along with environmental resource issues leads to a trend of substitution of liquid helium baths for mechanical cryocoolers as a cold source.

Cryogen-free superconducting magnet systems (CFMS) including a variable temperature insert (VTI) along with a cryocooler (CCR) are now available, however the cooling of the sample holder is still achieved using a helium flow to the system.

The inclusion of a gas gap heat switch (GGHS) would eliminate the need for a helium open circuit. The superconducting coil is cooled down with a CCR and the same cooler can be used in parallel to cool the sample holder down, as shown in Figure 1.

The operation of a GGHS is extensively described in a previous work [2]. It is a device that switches between high and low thermal conductance, separated by some orders of magnitude, by acting on a cryopump. In this work we developed and built a prototype of a heat switch to



be implemented at the Inter University Accelerator Centre (IUAC) according to thermal and mechanical requirements of the magnet cryostat coupled with a 1.5 W @ 4.2 K Gifford-McMahon CCR [3].

The VTI must operate from 4 K up to room temperature, drastically reducing the conductance from the VTI to the CCR, *i.e.* turning such a switch OFF shall allow the VTI to be opened to room temperature while the superconducting magnet is still working, as long as it never surpasses its current sharing temperature. The necessary condition to avoid quenching is to provide 1 W at 4 K, under quite conservative safety factors. The remaining cooling power (0.5 W) is aimed to be diverted towards the heat switch which is thermally coupled to the sample holder through a thermal link.

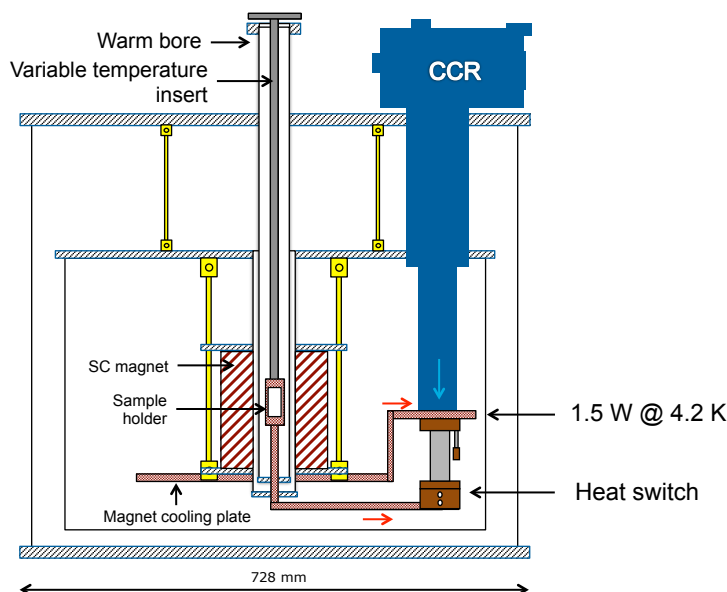


Figure 1. Schema of the magnet cryostat along with the heat switch thermally coupled to the CCR and to the VTI through a thermal link.

2. Design and construction

The built prototype has a classical geometry, as schematized in Figure 2. Mainly, it consists of a copper cylinder block coaxial to a copper tube-like block, separated by a $\approx 100 \mu\text{m}$ gap. We chose this gap width to prevent mechanical complications.

We built a $100 \mu\text{m}$ thin stainless steel supporting shell (SSSS) that encases the copper blocks, ensuring a closed volume and the centering/alignment of both blocks. This thickness is also a compromise between mechanical rigidity of the assembly and obtaining a relatively high thermal insulation between the switch blocks.

The amount of gas in the gap of a heat switch is managed using the sorption properties of an activated charcoal: the GGHS benefits from a compact and small closed system. The switching is made upon heating/cooling of a cryopump. A resistive heater is coupled to the cryopump for heating it up while cooling is achieved by conduction through the capillary that leads to the cold block. Cooling the cryopump down leads to gas adsorption: the thermal conduction through the rarefied gas becomes residual and the OFF state is reached. Heating up switches to the ON state, where the conduction is made through the dense gas in viscous regime. Our cryopump was filled up with 45 mg of Prolabo[®] activated charcoal.

The thermal conductance of the switch assembly in the ON state depends on the gap width, the exchange surface of the blocks and the gas properties. In the OFF state it mostly depends on the shell geometry and the properties of the stainless steel.

The analytic approach for the thermal conductance, in first approximation, was that the copper blocks and the gas inside the gap are connected in series; these elements are in turn connected in parallel to the SSSS, more details are available in [2]. Gas and solid material conductivity data was obtained from [4–6].

When opening the sample holder to the room temperature a low thermal conductance (OFF state) between the switch blocks is desired. We defined the geometry of the SSSS upon that condition, *i.e.* between 4–300 K the supporting shell should not conduct more than 0.5 W. For safety reasons we built a SSSS that conducts about 80% of the imposed limit (54 mm length, 25 mm diameter, 0.44 W).

For the OFF state a thermal conductance of $90 \mu\text{W/K}$ was calculated (for a $\Delta T \leq 4 \text{ K}$ at $T = 4 \text{ K}$), while 246 mW/K was obtained for the ON state using helium as the exchange gas. This corresponds to an ON/OFF ratio of 2.7×10^3 .

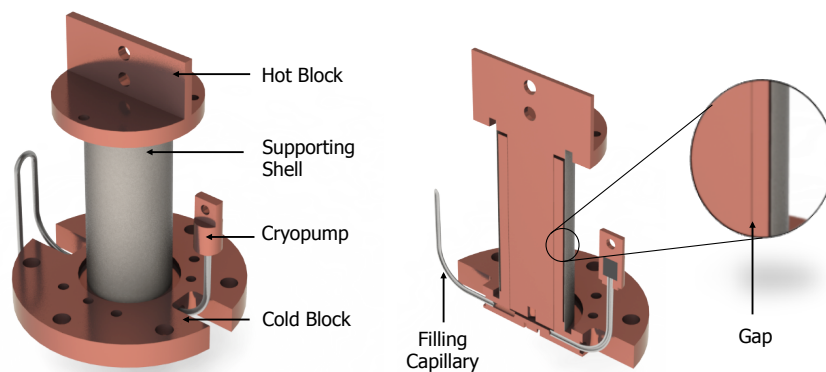


Figure 2. The switch prototype as designed with SOLIDWORKS™.

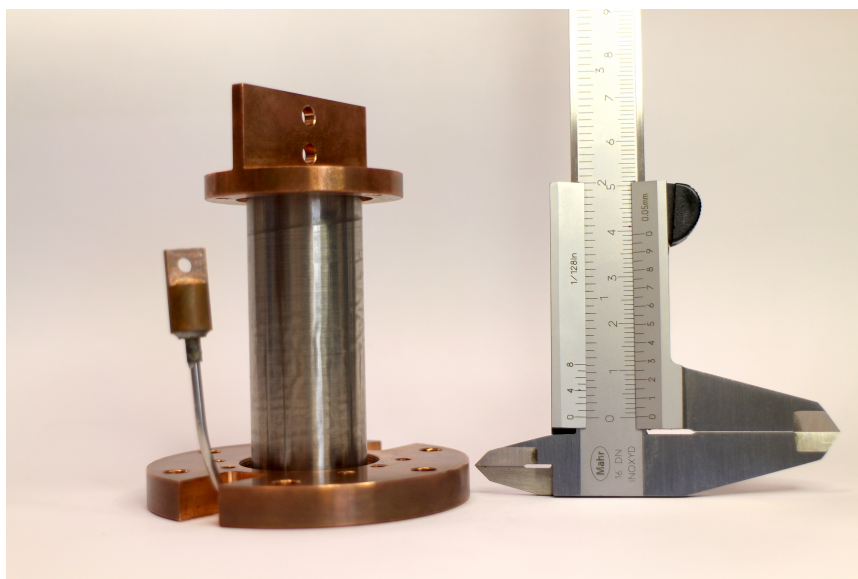


Figure 3. Photo of the gas gap heat switch (vernier caliper for scale). The switch has a height of 85 mm, mass of 510 g and a gas volume of 3.2 cm^3 .

3. Results and discussion

We used helium as the exchange gas for this switch prototype. It was filled up at room temperature with different charge pressures (1000, 106 and 12 mbar) in order to check the independence of the thermal conductance with pressure in the viscous regime.

To characterize the switch at low temperatures we used a two-stage G-M cryocooler with 1 W @ 4.2 K, thermally coupling the cold block to its second stage. Incremental power was applied to the hot block while keeping the cold block at a constant temperature, 4 K in this case. In the OFF state the switch was also characterized in dynamic mode. This was done while taking into account the hot block's heat capacity and the cooling rate.

The characterization of the ON state allowed us to obtain the gap width by comparison with the previously validated model [2], see Figure 4.

We expected a gap width of 100 μm , however we conclude to have 80 μm . This discrepancy could be ascribed to the complicated manufacture of such pieces with small tolerances.

The ON curve was expected to produce a pressure independent conductance, as long as the viscous regime was attained: from our calculations the viscous regime is achieved for charge pressures higher than 85 mbar. Our results show that the viscous regime is established for the selected pressures, even for the lowest one, at 12 mbar where the mean free path is within the same order of magnitude as the gap width. 290 mW/K was found at 4 K as the experimental thermal conductance for $\Delta T \leq 4$ K in this state (linear fit from the experimental data)¹.

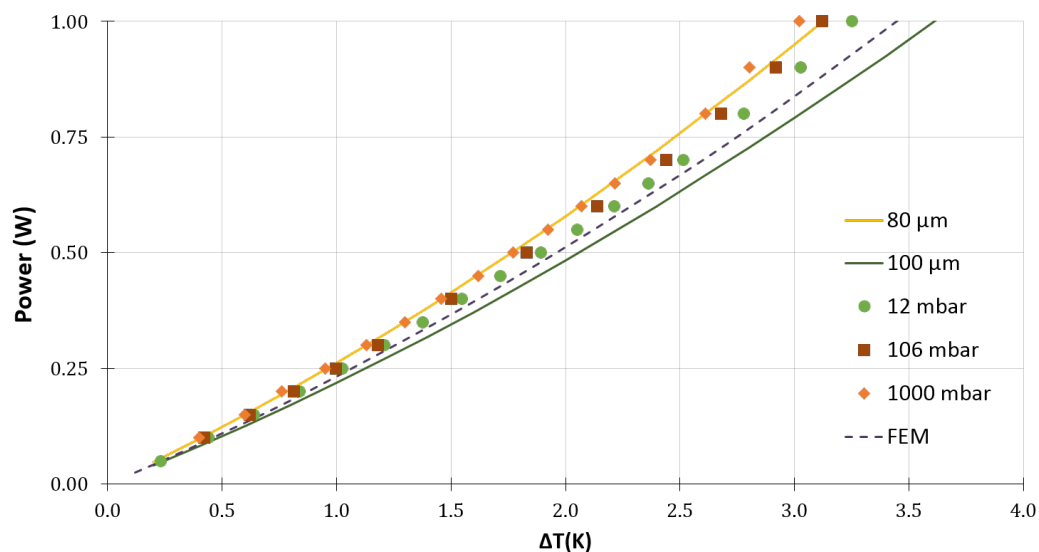


Figure 4. Thermal power through the switch *vs.* ΔT in the ON state with helium for different charge pressures. Lines represent the analytic curves obtained with our thermal model, dots are for experimental results and dashed lines the numeric approximation using finite element method (FEM) for a gap width of 100 μm .

The association in series of the copper blocks and gas is valid if the heat flux is constant along the whole geometry. Given the GGHS's geometry, it is visible that such series association is not possible, because the heat flow on the copper blocks varies along its length and because the heat flow in the gas is perpendicular to the copper, see Figure 5. Nonetheless, it was shown that the effective length of the copper block to be considered is half the geometrical length as

¹ For a gap width of 80 μm we obtain an analytic thermal conductance of 296 mW/K.

long the thermal resistances are similar [2], which is valid for small temperature differences or low applied thermal power: these considerations were used in our analysis and a finite element method (FEM) was used (with SOLIDWORKS™ Simulation) that allowed us to validate our thermal model.

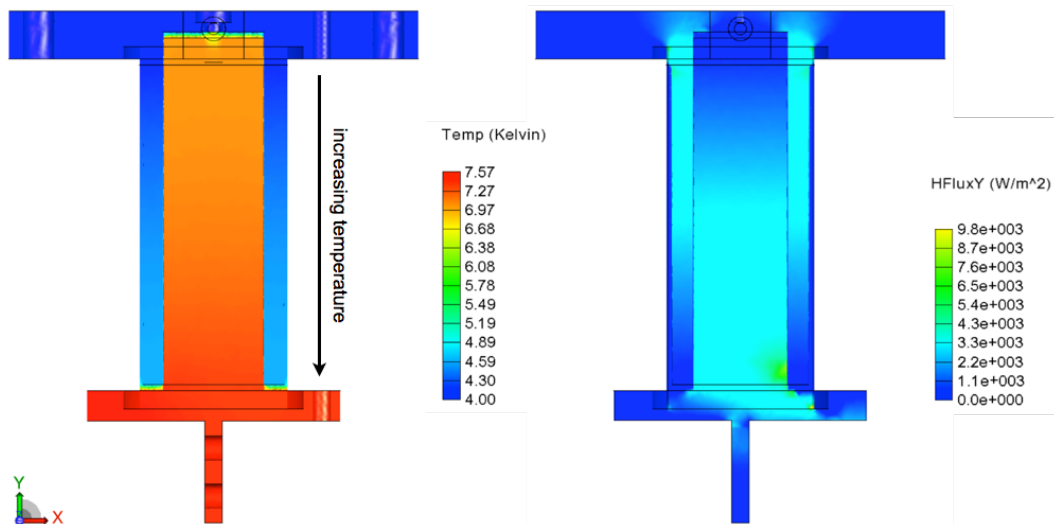


Figure 5. From left to right, thermal plot and heat flux (y direction) of the GGHS in the ON state with 1 W through the switch.

As for the OFF state, the results are shown in Figure 6. The thermal model and the FEM show a good agreement with the obtained experimental data. Also, the characterization of this state confirms that there is no physical contact between the blocks and the SSSS has the expected thickness. The analytical thermal model does not include radiation heat transfer, although the FEM does include it (an emissivity of 0.1 for polished copper was considered [7]).

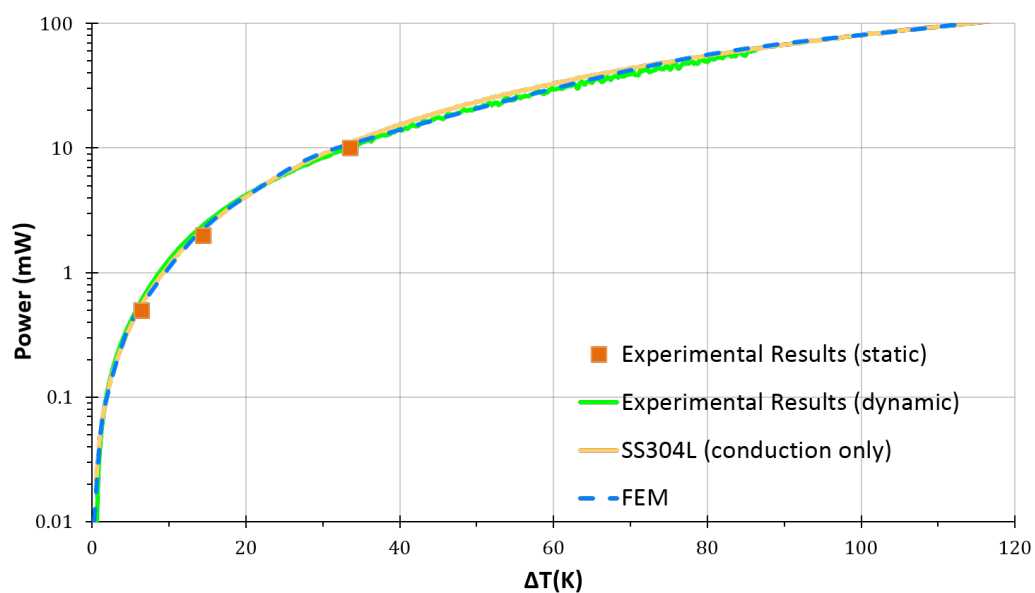


Figure 6. Thermal power through the switch *vs.* ΔT in the OFF state.

We obtained an experimental thermal conductance of $90 \mu\text{W/K}$ at 4 K for $\Delta T \leq 6$ K. The FEM results allowed to observe no thermal conduction in the gas gap since all the heat flows through the shell, see Figures 7 and 8. The temperature of the hot block is below the 300 K limit.

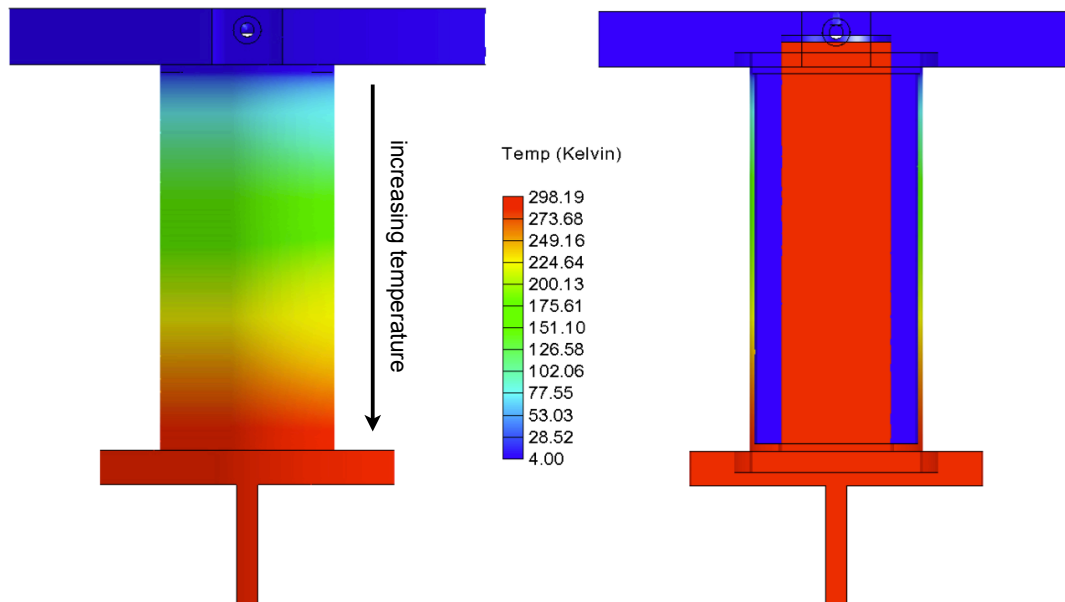


Figure 7. Thermal plot of the GGHS in the OFF state with 500 mW through the switch. On the right a section view of the GGHS.

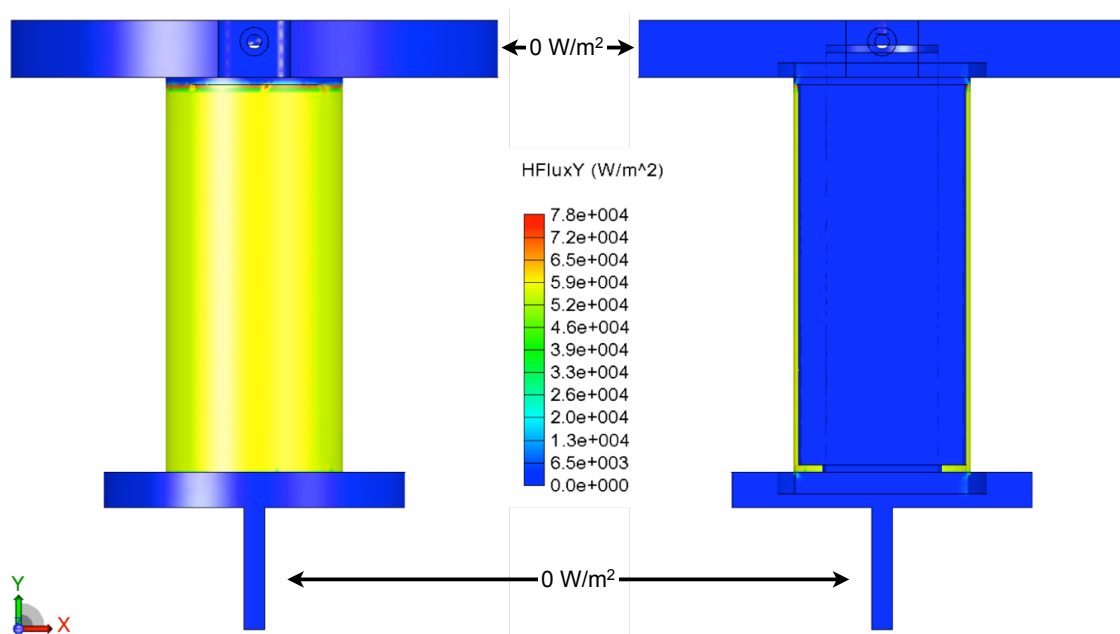


Figure 8. Heat flux (y direction) of the GGHS in the OFF state with 500 mW through the switch with one block at 4 K and the other at ≈ 300 K. On the right a section view of the GGHS.

4. Conclusions

A gas gap heat switch was designed, built, assembled and tested at 4 K upon the requirements established as per IUAC cryogen-free magnet properties setup.

An estimated gap width of 80 μm was obtained, with the GGHS showing two extreme thermal states. An ON thermal conductance of 290 mW/K was measured with helium and an OFF state of 90 $\mu\text{W/K}$, resulting in an ON/OFF ratio of 3.2×10^3 at 4 K. The experimental results are in close agreement with both the calculations using a simple thermal model and those obtained with finite element method.

The good agreement between the calculated and measured values enables a useful extrapolation for several and new applications, such as the one described in this document, where a completely cryogen-free magnet system is envisaged.

Acknowledgements

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