Operation and Control of Superfluid Helium in a Healthcare Device

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Abstract. While the search for novel superconductors toward higher current carrying capacities and lower transport losses in different types of superconducting wires continues, so far, there is no record of any "liquid superconductor". Superfluid helium (He-II), however, "conducts" heat without thermal resistance due to its very high thermal conductivity below its Lambda transition point. For superconducting magnets, different cooling schemes are employed using superfluid helium. These systems usually relate to internal or forced convection modes capable of transferring high heat loads. The inherent hydraulic quantum properties of He-II, like viscosity and density e.g., are therefore used in pumps (so-called fountain effect pumps (FEPs)), as described by the London equation, and enable the generation of a self-sustaining forced flow when using filters, optimized to work as "superleaks". Those pumps have successfully been integrated in large superconducting applications e.g., like fusion magnets, accelerators, or dedicated gyroscopes. All these applications primarily depend on the peculiar flow characteristics of the superfluid helium component. As of today, there is no technical application that solely relies on the high thermal conductivity of the superfluid helium film as a heat transfer medium through copper/steel interfaces at temperatures below 1 K. To fully utilize that specific physical quantum property however, the interposing superconducting film needs to be well controlled in static, as well as transient cryogenic operating conditions. In this paper we present cryogenic engineering insights of trials and tribulations faced, when implementing, containing, and operating those thin superfluid helium films in a clinical environment for a medical Healthcare platform, that takes full advantage of this unique thermal conductivity and sound properties, that superfluid helium provides.

1. Introduction

After more than twenty years since its introduction, Hyperpolarized MRI is now a well-established, molecular imaging method that allows monitoring of bodily enzymatic and metabolic changes through biochemical methods. The GE HealthCare SPINlab™ C^{13} hyperpolarizing MRI system, initially developed by GE Global Research is an essential, high-end tool for cancer diagnostic research on animals and humans, targeting different types of cancers. SPINlab™ has in particular been developed to serve as a complete stand-alone clinical system using hyperpolarization MRI technology for polarizing pyruvic acid and urea samples for detecting early stages of cancer.

Operating this 4-channel hyperpolarizing system involves lowering a small vial into a dedicated polarizing space within the bore of a 5 or 7 Tesla magnet. The vial is initially filled at room temperature with 1-^{13}C pyruvic acid and guided into the sample pot where the liquid is typically frozen and polarized at 0.8 K. Hot water of 130 °C is then rapidly injected into the vial to dissolve its solid state, maintain its polarization and inject it into a patient [1]-[4].

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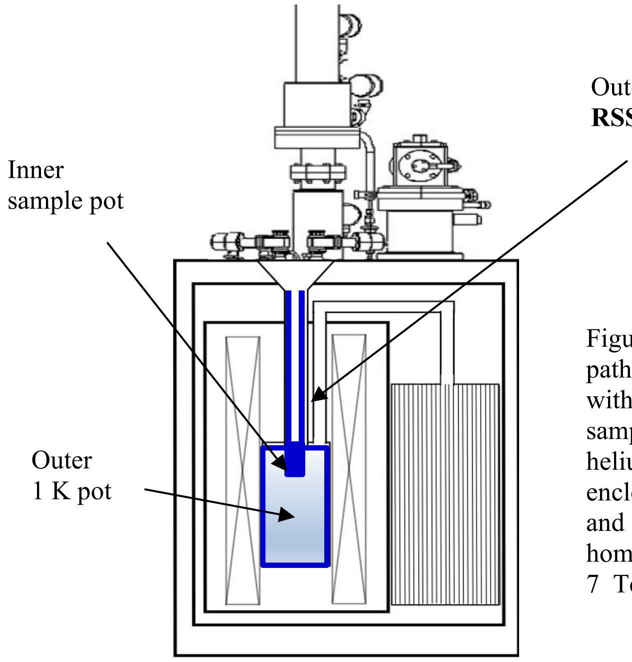
2. Design evolution

Previously, we discussed the need for shifting from a curved sample path to a more serviceable, straight sample path for lowering the vial into a superfluid helium filled 1 K sample pot [5]. This however increases the thermal burden on the sample pot.



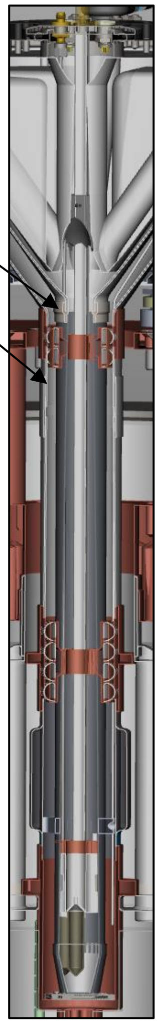


Figure 1 shows the vial travel path from top of the sleeve with its funnel to the 1 K sample pot filled with liquid helium. The outer 1 K pot encloses the inner sample pot and resides in the warm bore homogeneity region of a 5 to 7 Tesla magnet.

Figure 1. Straight sample path for lowering and accommodating 4 vials in the RSS.

The cryosystem consists of an inner "**R**emovable **S**ample **S**leeve" (**RSS**) with a sample pot at its bottom end, placed into a straight outer tube enclosing the inner tube, as shown in Figure 1 on the right. Initially, the now created interstitial space (**IS**) between outer and inner tube is evacuated but in thermal contact with the surrounding 1 K pot. Temperature sensors are placed on the external bottom side of the sample pot, on the copper 1 K pot vacuum end whereas the temperature within the sample pot is converted from the pressure measurement. See Figure 2 Case 1.

3. Superfluid helium contact modes tested

Figure 2 shows the basic, iterative design steps for vial cooling. Case 1, top left, depicts a copper sample pot solidly separated but embedded into a surrounding copper 1 K pot. In this configuration, 1 K pot and inner sample pot are independently filled of each other and remain without fluidic communication but evacuated IS). Case 2 below shows an Inconel sample pot attached to the RSS in contact with an opposing copper 1 K pot surface, separated by an additively created Inconel thermal switch [6]-[7]. The IS space is evacuated as well. In case of any vial exploding during hot water injection into the vial, helium in the switch is pumped out from the switch and the switch OFF conductance would allow one to service the RSS. For more serious events and as the switch bottom is soft soldered to the 1 K pot using Galinstan, a liquid solder, the contact can be broken when the cryostat is warmed up slightly above room temperature [6]-[7], [8]-[12]. This may sometimes be necessary in case there is contamination in the RSS tube that cannot be cleaned with standard methods.

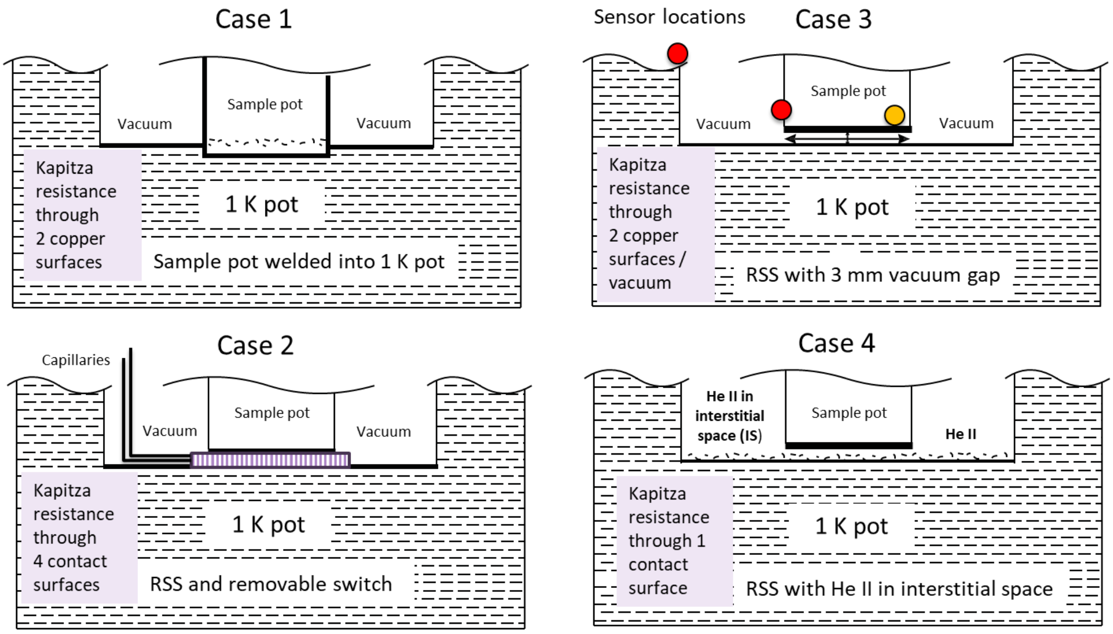


Figure 2. Development stages of RSS implementation into Spinlab "Emerald" version.

Figure 3 shows the first assembly (Case 2 in Figure 2) of the switch in its intended, previous configuration. Although offline on/off tests and thermal conductance tests of the switch were positive, we decided for further design simplification. The thought was whether it would be possible to eliminate any contact with the 1 K pot and the sample pot bottom as shown in Case 3 configuration above, right in Figure 2. If that were possible, it would give us further degrees of freedom for assembly and service. This however meant that we need to sacrifice the interstitial vacuum space.

What are the benefits assuming there is no contact at all between 2 mating cryogenic surfaces:

- Independent of material we use, copper or e.g., Inconel, the contact quality will remain the same. Irrespective of build and assembly constraints and tolerances, (we can adjust the tube axially using adjustment springs) we will maintain a certain gap of 1 to 3 mm (e.g., using a pogo stick or other to ensure gap size),
- We are free to define the required distance between both contact surfaces,
- Since both contact surfaces do not touch each other, they do not have to be aligned in parallel,
- Any surface roughness, crucial when reducing high contact resistances between both surfaces becomes immaterial,
- If there is no contact, then there is also no heat transfer from the sample pot bottom to the top of the 1 K pot and any vibrational effects are eliminated,
- This means the 1 K pot will maintain its helium level during sample pot service or outage,
- For the latter the interposer needs to be completely removable, external to the cryostat,
- In case of excessive heat input during a magnet quench event, contact surfaces would automatically separate from each other eliminating any heat transfer but recover quickly from this excessive heat load.

This leaves only one conclusion, namely that the interposer between both those surfaces must be a liquid medium that possesses the inherent capability to adapt to both contact surfaces. Furthermore, this medium has to be highly conductive to minimize any thermal gradient between both mating surfaces. The interposer has to be easily removable for service, as mentioned. Only a superconductor, in this case superfluid helium [8], [9] has those desired, thermal and thermohydraulic properties to act as a fluidic interposer depicted in Case 4, Figure 2. This meant superfluid helium needs to reside in the interstitial vacuum space.

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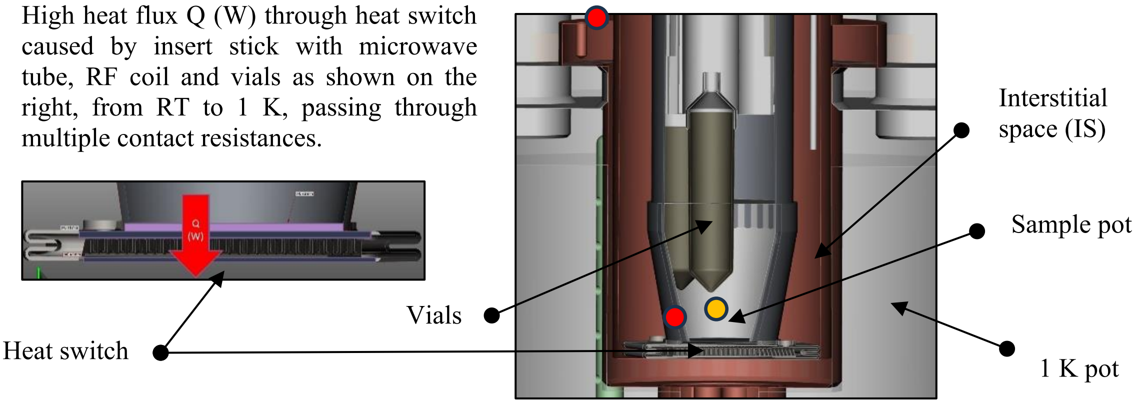

Figure 3. Case 2 with additively manufactured thermal switch and evacuated interstitial space with temperature sensors (red) and pressure sensor (yellow).

3.1. Thermal conductance of superfluid helium

Superfluid helium literature data is vague on actual conductance values. Keesom [10] states that superfluid helium thermal conductivity should be at least 800 times that of copper, 338 kW/mK, with a max. value at 1.7 to 2 K. Keller [11] mentions that He II conducts heat 1000 times better than copper at room temperature. Van Sciver gives 100 kW/mK for a heat flux of 1 W/cm^2 [12]. For Pobell [13] the thermal conductivity of ^{4}He II is infinite, or realistically 18 kW/mK @ 0.7 K (1.38 mm and 7.97 mm sized tubes). Second, the heat flow through the liquid should be without any temperature gradient as commented by Pobell [13]: "*Because the thermal conductivity of superfluid helium can be very large or infinitely large, temperature waves or entropy waves can propagate in this unusual liquid (second sound)*". Third, in the superfluid state, liquid helium also has a vanishing viscosity with Pobell [13] stating: "*The vanishing viscosity allows the superfluid helium to flow in a persistent mode as the persistent supercurrents in a metallic superconductor do*". Here we see the analogy of electrons flowing through a superconducting wire with no voltage difference whereas a superfluid flows though narrow channels with no pressure difference [14]. And fourth, there should be no bubbles in the boiling process for different thermal loads on the interface. The next, more practical question would be how superfluid helium behaves in a closed cavity in the presence of multiple transient and orientation dependent heat sources, with changing boundary and operating conditions [15]-[18]. We meticulously tested all those conditions. For the start, obviously, the total heat burden on the sample pot has to be minimized.

3.2. Thermal conductance of solid/superfluid helium sample pot interface (Kapitza conductance)

When a heat flow per unit area, Q, occurs across a solid-liquid interface, it is found to be limited by a finite conductance, h_k, which is well-defined and independent of heat transfer processes in the liquid as ΔT, the solid/liquid temperature difference, approaches the value of 0 [19], [20]. At 1 K, our operating temperature, the typical Kapitza conductance value is around 0.5 kW/(m^2·K) for copper and approx. 0.65 for Nickel. Our contact surface area (25 mm in diameter) is 4.9 x 10^{-4} m^2. This means the heat transfer for copper will be 0.245 W/K and 0.321 for Nickel (steel). Our calculations gave around 10 mW of heat load through the interface which would make the ΔT caused by the Kapitza resistance, approx. 31 mK for steel which is roughly within the 15 mK measured in our experiment. Snyder also comments that high magnetic fields up to 10 T increase the Kapitza conductance, further reducing ΔTs [19].

3.3. Minimizing the heat burden of the fluid path on the sample pot

When designing fluid sample paths for 1 K operation, thermal intercepts are mandatory to reduce the thermal conduction burden to the 1 K pot as shown in Figure 1. The thermal conduction down the tube to 1 K is reduced by reducing the tube wall thickness to 0.2 mm. Furthermore, Case 1 with its curved,

S- shaped fluid sample path works only, if the latter is bent such that any incident radiation from room temperature is not directly funneled down to the sample pot. The bent sample path however prohibits the use of an insert stick which results in a minimum heat burden to the sample pot of 1 mW. A straight sample path as shown in Case 2 and in Figure 1, requires substantial efforts for reducing thermal radiation and conduction to the sample pot. In particular, the additional so-called "insert stick" conducts heat down the sample pot. Baffles can be added, and there are many suggestions on how to design them [21], [22], like e.g., the use of multiple half disk baffles [12], [22] that however severely restrict vial travel.
Further heat sources on the sample pot are the thermal conduction of the tubing that holds the baffles, the inner microwave tubing and the RF coil holder at the bottom of the insert stick, shown in Figure 4 below. In addition, transient heat loads caused by eddy current heating during quenching effects need to be taken into account. The latter effect has been postulated and calculated by Rose-Innes [22]. In addition, continuous vial operation over time will increase the sample pot heat burden due to atmospheric air penetrating and condensing at the lower sample pot tubing. It is well known that this increases the superfluid film flow by a factor of 10, causing a thermal short to the sample pot [22].

4. Test results

First experiments were carried out with a plain baffle stick (copper disks) to understand the general behavior of the superfluid helium film without any additional heat source caused by the vial insert stick.

4.1. Baffle stick (G10) and insert stick experiments

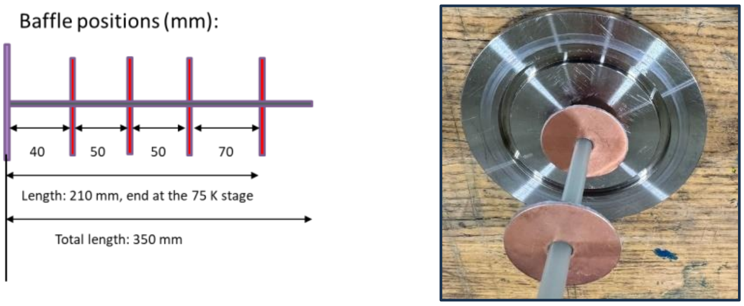

Figure 4. Baffle stick and insert stick (right).

For that, helium stored at room temperature was gradually introduced into the interstitial space as shown in Figure 2 Case 4. Helium recondensed with the 1 K pot at 4 K. A condensation cycle was then run to lower the bottom 1 K pot temperature to 1 K. We then filled the sample pot as shown in Figure 2. In On state, that is with the superfluid helium in close contact with both opposing surfaces, the temperature difference between the sample pot base and the enclosing 1 K pot was 15 mK as shown in Figure 5. Note the quiet fluid showing no temperature fluctuations, that shows the superfluid behavior one would expect.

4.2. Superfluid switch with insert stick

This insert stick comes with a microwave tube at its center as well with an RF coil and its holder at the bottom of the stick as shown in Figure 4 and Figure 6 (insert) and several temperature sensors. Vertically oriented baffles were linked to the RSS wall with copper fingers to reduce thermal radiation funneled down from the top of the insert. In this first experiment the microwave tube (3 mm inner diameter) excited thermoacoustic oscillations (TAOs) that elevated the temperatures above the superfluid phase. Figure 6 shows the typical boiling characteristics in the sample pot, now above the superfluid temperature regime.

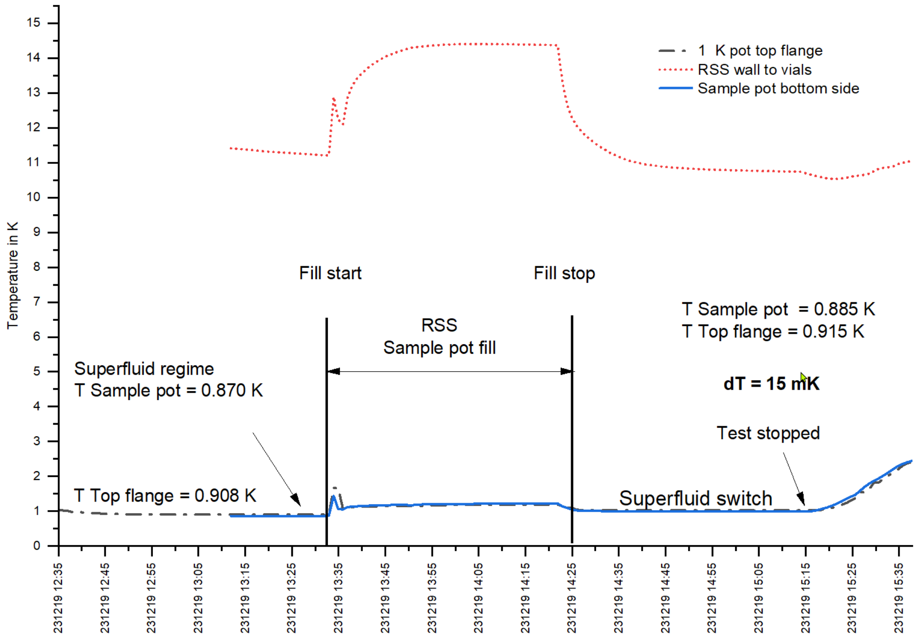

Figure 5. Baffle stick, baseline results.

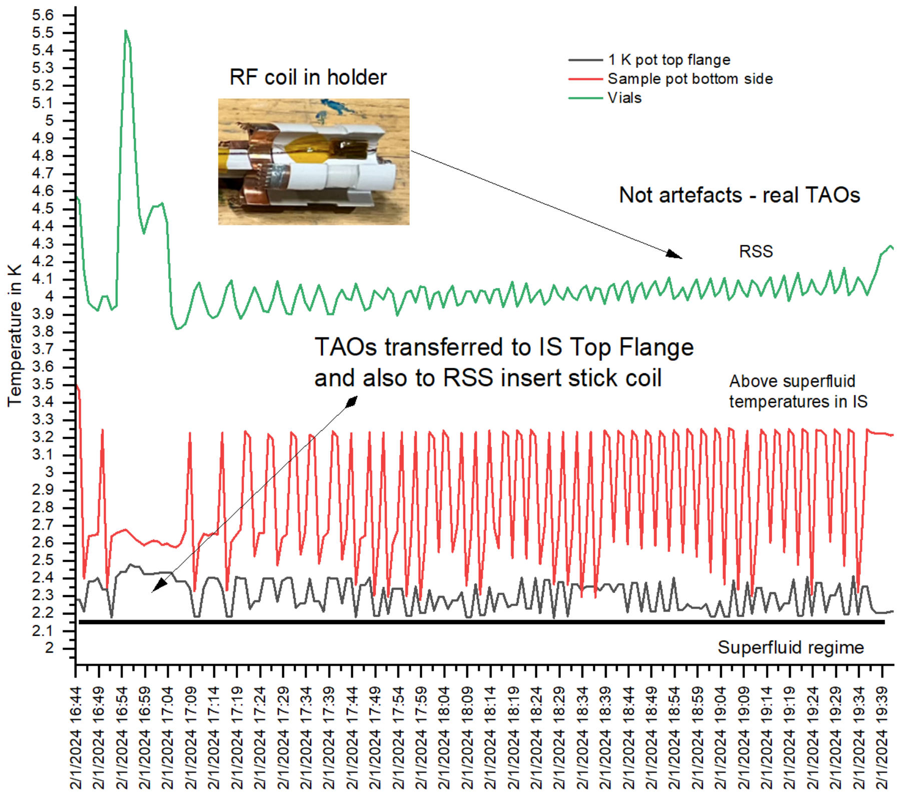

Figure 6. Reducing the heat burden on the sample pot.

4.3. Superfluid switch with improved insert stick

With an improved insert stick and reduced overall heat burden on the sample pot, base temperatures in the 1.01 K range were achieved.
This is 95 mK higher than with the plain baffle stick insert and most likely caused by sample pot contamination [22], some lower cryocooler power, higher heat load and film movement to the Kapton insulation of the conduction-cooled RF coil. A superfluid helium film will always move to any nearby heat source [23], if not knife-edge controlled. More work is under way to reduce this temperature difference to 25 mK.

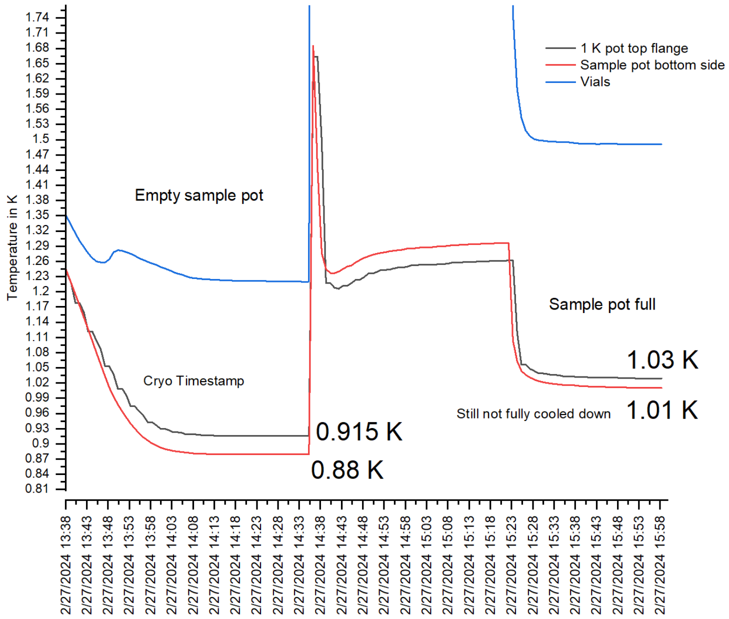

Figure 7. Baseline results with new, modified insert stick.

Summary

Superfluid helium is an important means of keeping superconducting coils at 1.8 K by exploiting the thermohydraulic properties of this quantum fluid. The latest NeuroSpin whole-body MRI 11.7 Tesla system of the Frédéric Joliot Institute for Life Sciences is cooled with superfluid helium, while the superconducting CERN Large Hadron Collider (LHC) magnets are maintained at 1.85 K. In this paper we describe the novel use of superfluid helium as a liquid and invisible interposer that can adapt to surface irregularities, different material roughness, plate parallelism and varying mutual space distances from each other (gap size), without showing a significant ΔT. Superfluid helium with its exceptional thermal conductance properties that can be switched "ON" / "OFF" at will, allows us to use this fluid as a highly efficient thermal switch, that gives the ΔTs we expect. In OFF state, the switch is completely OFF, whereas the ON state is so high that the ON/OFF ratio is so exceptionally high that this cannot be defined properly and exceeds any known solid metal-based heat switches. Kapitza resistances in our case were found to be negligible through all interfaces.

The experiments have shown that the superfluid film between the contact surfaces behaves well without runaway and can be controlled in all Spinlab standard operating modes, including service. No superleaks were detected. Repeatedly confining superfluid helium in a free, tiny gap between two opposing surfaces, was easier than thought. Auto-feeding helium from a gas bottle external to the cryostat for closing the switch (switching it "ON") using the installed fill and helium removal logistics has proven to work very well.
Other modalities, e.g., future quantum technology related cryogenic designs may greatly benefit from this type of ON/OFF switch.

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