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THERMAL MAPPING STUDIES ON Nb/Cu SRF CAVITIES

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Abstract

A thermal mapping system is one of the most useful diagnostic tools to identify the mechanisms responsible of performance degradation in superconducting radio frequency (SRF) cavities. Unlike most of the thermal mapping systems currently in operation, we want to develop a system for mapping copper coated SRF cavities. This thermal mapping system, based on contact thermometry, will operate in both superfluid and normal liquid helium for the study of thin film cavities on copper built at CERN. This paper describes the R&D studies to design and develop the system. The characterisation of thermometers and the validation of their thermal contact are presented. Thanks to the use of some heaters with the aim of reproducing the presence of heat losses in a SRF cavity, temperature profiles on a copper surface will be shown at different conditions of the helium bath. In addition, preliminary results on magnetic field sensors, based on the anisotropic magnetoresistance effect, will be reported in view of their possible implementation in the thermal mapping system.

INTRODUCTION

Since the late ’80s, CERN has pioneered development of thin film superconducting radio frequency (SRF) cavities for particle accelerators. Niobium (Nb) thin film cavities [1] on copper (Cu) have been successfully applied in LEP2 [2, 3], LHC [4] and HIE-Isolde linac [5]. However, thin film cavities historically featured a strong increase in surface resistance with accelerating field [6], resulting in a quality factor decrease (Q-slope). This is in part still unexplained and, together with the development of novel fabrication techniques and new thin film materials [7], is at the centre of an intense R&D program in the SRF community at CERN.

A thermal mapping system is one of the most useful diagnostic tools to investigate the mechanisms responsible of performance degradation in SRF cavities. This method, extensively applied in bulk Nb cavities, permits the localization of point-like and extended dissipation regions during cavity cold tests. We want to develop a thermal mapping system, based on contact thermometry, for the study of Cu coated SRF cavities in both superfluid and normal liquid helium (He). Since the thermal diffusivity of Cu at liquid He temperatures is higher than that of Nb, the detection of heat losses in thin film SRF cavities on Cu turns out to be more difficult, therefore preliminary R&D studies are needed in view of the design of the system. In addition, the implementation of a number of magnetic field sensors in the thermal mapping system is under investigation in order to monitor the magnetic field distribution around each SRF cavity under test.

The ongoing R&D studies for the design and development of the thermal mapping system are reported in this paper as follows. After the description of the experimental set-up, we present the characterisation of Allen-Bradley 100 Ω resistors, used as thermometers at low temperatures. Then, temperature measurements on Cu surfaces are examined at different heat flux values and He bath conditions. Finally, preliminary results on anisotropic magnetoresistance (AMR) sensors for magnetic field measurements are reported in this paper in view of their possible implementation in the thermal mapping system.

THE EXPERIMENTAL SET-UP

In order to characterise thermometers and their thermal contact, we used a 8 cm diameter tube in OFE Cu with a RRR of ~50 and a wall thickness of 2 mm. These features of the tube, shown in Fig. 1a, are similar to Cu substrates used for thin film SRF cavities. Two different heaters are glued in the internal surface of the tube with Stycast 2850FT epoxy, which is a high thermal conductive glue for cryogenics. One of the heaters is a thick film SMD resistor of 30 Ω at 300 K with a total area of ~1 cm^2, whereas the other one is a flexible heater in polyimide with a resistance value of 8 Ω at 300 K and a rectangular area of 9.1 x 3.8 cm^2. Thermometers are placed outside the tube and pushed towards the outer surface of the Cu tube thanks to a supporting system in Araldite MY750 and spring loaded pins (pogo-sticks) in BeCu, shown in Figs. 1a and 1b, respectively. Thermometers are embedded in an Araldite MY750 housing (see Fig. 1b) and sealed with Stycast epoxy, which is impervious to superfluid He [6]. Likewise thermometers, one Sensitec AFF755B sensor (see Fig. 1c) is placed on the outer surface of the Cu tube close to the SMD resistor. This type of sensor is based on the anisotropic magnetoresistance effect [8] and may represent a cheap solution for mapping the magnetic field around SRF cavities at cryogenic temperatures. Voltage signals of thermometers as well as the AMR sensor output are digitized by NI 9251 ADCs with a sampling rate of 1 KS/s, whereas the power supply is provided by two Keithley 2401 modules.

Different types of thermometers and various thermal contacts were tested with the Cu tube completely immersed in a liquid He bath while the internal pressure of the tube is kept at ~1×10^{-6} mbar. The Cu surface is vertically oriented during the tests. Thanks to the SMD resistor, we can reproduce point-like heat losses as those in SRF cavities. On the contrary, the rectangular heater is used to simulate extended dissipation regions, which may be present in SRF cavities, as well as evaluate different types of thermal contacts between the thermometer and the outer surface of the

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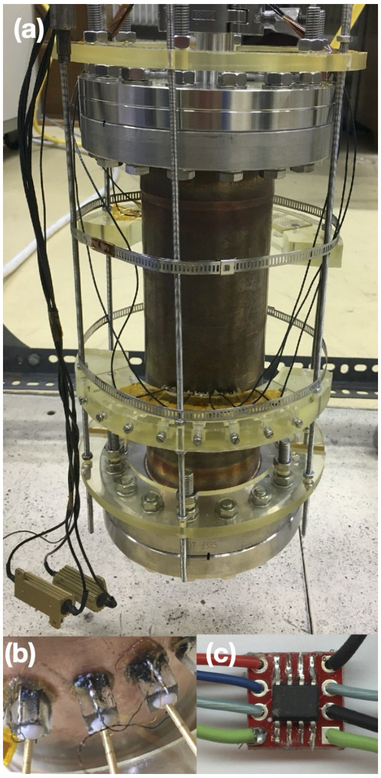

Figure 1: Photos of the experimental set-up: (a) Cu tube with the supporting system for thermometers and the AMR sensor; (b) thermometers pushed towards the outer surface of the Cu tube by spring loaded pins; (c) the AMR sensor used for magnetic field measurements.

Cu tube. The current used to fire the SMD resistor induces a local magnetic field that is detected by the AMR sensor, placed at a few millimeters away from the heater. Thanks to a NI 9472 module and a few lead batteries of 6 V, voltage pulses are used to fire heaters at different power values and for various time duration.

The experimental set-up, described in this work, gives us the possibility to characterise different types of thermometers as well as evaluate their time resolution and sensibility to the heat flux. This also allows us to understand how thermal exchange between the thermometers and the cavity wall, and the thermometers and the He bath, must be tuned with respect to each other in order to achieve a maximal spatial resolution and sensitivity of the thermal mapping system.

CHARACTERISATION OF THERMOMETERS

Different types of thermometers have been systematically characterised at low temperatures. In this work, we only report the performance of Allen-Bradley 100 Ω resistors that turned out to be the most promising in the temperature range between 1.9 K and 4.2 K.

We tested Allen-Bradley 100 Ω resistors with the 4-wire sensing method in order to obtain precise values of their resistance at low temperatures. During tests, the current of thermometers was set at 10 µA because previous studies have shown that their self-heating becomes negligible for currents lower than 25 µA [9]. The temperature of the bath is measured by one calibrated Temati carbon ceramic sensor, immersed in the He bath and used as reference. Figure 2 shows the calibration curve of 6 different Allen-Bradley 100 Ω resistors from 1.9 K to 4.2 K. The resistance of these thermometers at 1.9 K is 6−8 times higher than that at 4.2 K, ensuring a satisfactory sensitivity in this temperature range.

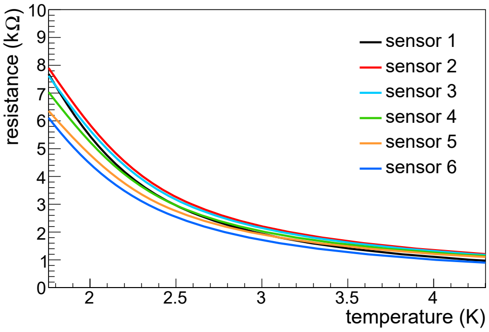

Figure 2: Calibration curves of 6 different Allen-Bradley 100 Ω resistors in the range between 1.9 K and 4.2 K.

As already reported in the literature [10], the resistance of Allen-Bradley resistors slightly changes each time they are cooled from room temperature to cryogenic temperatures. We estimated that the variation of resistance from one thermal cycle to the next can even induce uncertainties on temperature measurements higher than 150 mK. Therefore, a calibration procedure has to be implemented in the final design of the thermal mapping system in order to calibrate all thermometers each time the system is cooled down to cryogenic temperatures.

All temperature measurements in the following have been carried out with Allen-Bradley 100 Ω resistors previously calibrated at low temperatures.

Thermal Contact

A dedicated study on the thermal contact resistance between thermometers and the Cu surface of the tube has been carried out in order to increase the sensibility of thermometers as much as possible. Different solutions were tested in order to increase the thermal conductivity of the interface between the thermometers and the Cu surface. For simplicity, we only report a comparison between two different configurations: in the first configuration, thermometers are pressed against the Cu surface with only spring loaded pins and nothing is present in the interface, whereas in the second configuration the compression of pogo-sticks is unchanged but a layer of Apiezon N grease is added in the interface. In order to compare the different types of thermal contact, some thermometers are installed in one of the two configurations, previously described, in contact with the outer surface of the Cu tube and in correspondence of the rectangular heater. A direct comparison of the thermometer responses is possible thanks to the use of the rectangular heater with a total area of 9.1 x 3.8 cm^2 which ensures that the temperature of the Cu surface, where the thermometers are in contact, is uniform as the heat flux of the heater is uniform except near its edges.

If Apiezon N grease is not present in the interface, no temperature increases are detected by thermometers at 1.9 K (superfluid He), 2.4 K and 4.2 K even when the heater is fired for more than 30 s at 1.5 W/cm^2 which is the maximum value that we can reach in the experimental set-up. On the contrary, a temperature increase is detected in all three He bath conditions if Apiezon N grease is present in the interface. Indeed, the Apiezon N grease reduces the thermal contact resistance and partially shields the thermometers from the liquid He [6], permitting direct measurement of a fraction of the surface temperature at 1.9 K, 2.4 K and 4.2 K.

In addition to the He bath conditions of 1.9 K, 2.4 K and 4.2 K, we also carried out some tests in subcooled He where the bath is at ~3 K while the pressure in the cryostat is intentionally kept equal to the atmospheric pressure (~1×10^5 Pa). The overpressure suppresses bubbles in the bath and, as a consequence, the cooling capability of the He bath is much lower than that without overpressure. This generally increases the temperature of the outer surface of a SRF cavity in presence of heat losses, and the thermometer response turns out to be much higher in a subcooled He bath, as discovered by H. Piel [11]. Figure 3 shows the responses of two thermometers in subcooled He (~3 K and ~1×10^5 Pa) with and without Apiezon N grease in the interface when the heater is fired at 1.5 W/cm^2 for 10 s. Unlike the cases at 1.9 K, 2.4 K and 4.2 K where a temperature increase of the surface can be only detected thanks to the use of Apiezon N grease, the direct measurement of a fraction of the surface temperature in subcooled He is possible even without grease. Indeed, the signal of the thermometer with Apiezon N grease corresponds to a temperature increase of ~1 K, as shown in Fig. 3, whereas it is reduced by ~50% if no Apiezon N grease is present in the interface. As a consequence, the temperature of the cavity surface can be satisfactorily measured in subcooled He without Apiezon N grease, but the thermometer response in this configuration turns out to be lower than that with Apiezon N grease.

TEMPERATURE MEASUREMENTS ON A COPPER SURFACE

Thanks to the SMD resistor used as heater to simulate point-like heat losses as those in SRF cavities, temperature profiles on the outer surface of the Cu tube are measured at different heat fluxes and He bath conditions. Figure 4 shows temperature measurements as a function of the distance from the heater. These measurements have been carried out at different heat fluxes, ranging from 0.5 W/cm^2 to 4.0 W/cm^2, at 1.9 K (superfluid He), 2.4 K, 4.2 K, and in subcooled He with a bath temperature of ~3 K at ~1×10^5 Pa. The range of heat flux is within the values expected in a SRF cavity under test between 1.9 K and 4.2 K. All temperature measurements in Fig. 4 are taken with Apiezon N grease in the interface between the thermometers and the Cu surface.

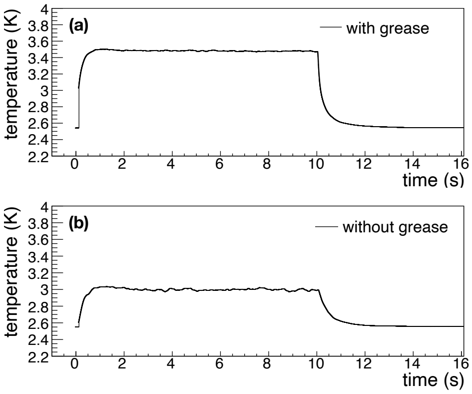

Figure 3: Signals of two thermometers in subcooled He (~3 K and ~1×10^5 Pa) with and without Apiezon N grease in the interface when the rectangular heater (9.1 x 3.8 cm^2) is fired at 1.5 W/cm^2 for 10 s.

For a fixed value of heat flux, the temperature profile on the outer surface of the Cu tube in superfluid He at 1.9 K turns out to be much lower than that at 4.2 K, as shown in Figs. 4a and 4b. At 4.0 W/cm^2 the temperature measured by the thermometer in correspondence of the heater is ~100 mK while it becomes ~3 times higher in normal liquid He at 4.2 K. This is mainly due to the extremely high cooling capability of superfluid He. In addition to temperature measurements at 1.9 K and 4.2 K, Fig. 4c shows the profile of temperature just above the He λ-point, precisely at 2.4 K. At this temperature of the He bath, the temperature profiles turn out to be generally higher than those at 4.2 K by a factor of 3 to 4, whereas in subcooled He they are in general 5−8 times higher in comparison to those at 4.2 K for low heat fluxes (<2.5 W/cm^2) and only 3−5 times higher for high heat fluxes (>2.5 W/cm^2), as shown in Fig. 4d.

ANISOTROPIC MAGNETORESISTANCE SENSORS

The magnetic field distribution around thin film SRF cavities may give additional information on their performances during cold tests. Indeed, the influence of the magnetic field, which might be trapped during the transition of a superconducting cavity from normal state to superconducting, on cavity performances is well-documented in literature. This has been also observed in Nb film cavities on Cu, tested at CERN [12], as well as in most recent tests carried out at the CERN Cryogenics Lab [13]. For this reason, monitoring the magnetic field distribution around each SRF cavity under test might play an important role. Therefore, the implementation of a number of magnetic field sensors in the thermal mapping system is under investigation.

We characterised one Sensitec AFF755B sensor based on the anisotropic magnetoresistance effect [8]. Previous studies have demonstrated that this type of AMR sensor works well in cryogenics [8, 14]. In addition, these sensors

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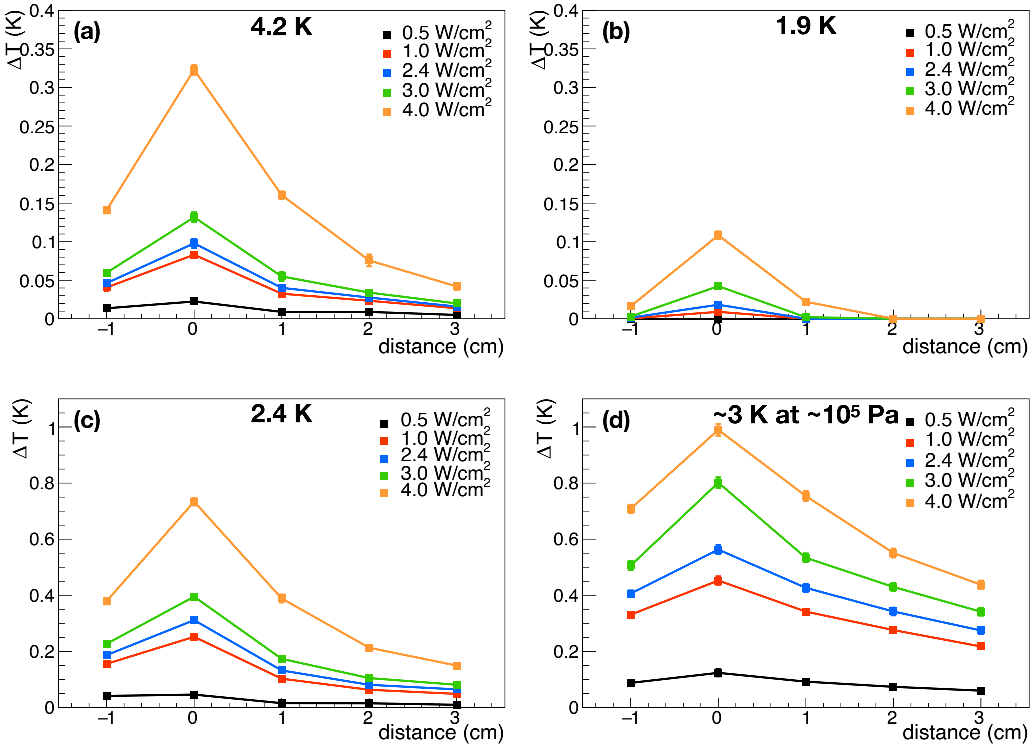

Figure 4: Temperature profiles on the outer surface of the Cu tube as a function of the distance from the SMD resistor, used as heater and glued in the internal surface of the tube (at distance = 0 cm). Measurements are carried out: (a) at 4.2 K, (b) in superfluid He at 1.9 K, (c) at 2.4 K and (d) in subcooled He at ~3 K with an overpressure of ~1 × 10^5 Pa. Some statistical error bars are hidden by markers.

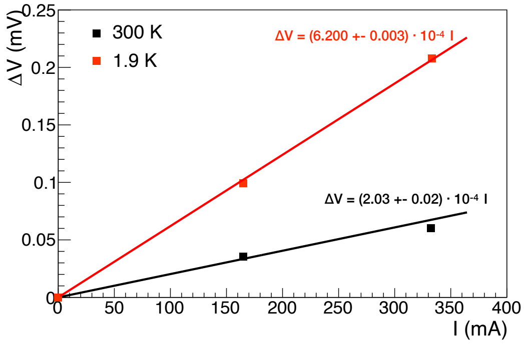

Figure 5: Voltage response of the AMR sensor as a function of the current in the SMD resistor at 300 K and 1.9 K. Statistical error bars are hidden by markers.

are small and cheap, giving us the possibility to integrate a large number of them in the thermal mapping system under development. However, AMR sensors allow us to measure the magnetic field in one dimension, therefore the detection of a local change in the absolute value of magnetic field requires the use of three AMR sensors near each other and oriented in the three spatial dimensions.

In order to test the AMR sensor, we placed it on the outer surface of the Cu tube at a few millimeters away from the SMD resistor. The sensor is completely immersed in the liquid He bath and measures the increase of magnetic field induced by the current for firing the SMD resistor. Figure 5 shows the voltage increase in the sensor response at different values of current in the SMD resistor. The sensibility of the AMR sensor at 1.9 K turns out to increase by a factor of 3 in comparison to that at room temperature. This is in good agreement with experimental data in the literature [14]. We did not observe changes in the sensibility of this sensor at 1.9 K after four thermal cycles. Figure 6 shows how the sensor response changes in voltage from 1.9 K to 4.2 K when the SMD resistor is fired with a current of ~100 µA. An increase of the sensor response from 0.06 mV to 0.08 mV has been observed around the He λ-point at ~2.2 K. Indeed, the sensor sensibility remains quite constant in superfluid He while it turns out to increase by 20% at ~2.4 K, and then slightly decreases at higher temperatures. Additional tests on a large number of AMR sensors are required in order to confirm this observation as well as to be sure that the sensibility of AMR sensors does not change after several thermal cycles.

CONCLUSIONS

A thermal mapping system specially designed for Cu coated SRF cavities is under development. This system, based on contact thermometry, will operate in both superfluid and normal liquid He and will allow us to localize heat losses in thin film SRF cavities for studying the mechanisms responsible of performance degradation. In addition, the

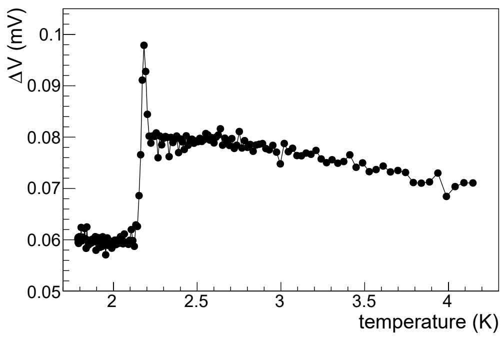

Figure 6: Voltage response of the AMR sensor as a function of the bath temperature when the SMD resistor is fired with a current of ~100 µA.

possibility to implement a number of AMR sensors to monitor the magnetic field distribution during cavity cold tests is under investigation.

In this paper, we presented the characterisation of Allen-Bradley 100 Ω resistors used as thermometers at liquid He temperatures. The use of Apiezon N grease plays a crucial role to lower the thermal contact resistance between the thermometers and the Cu surface and to partially shield the thermometers from the liquid He. Indeed, the use of this grease allows us to measure the temperature of Cu surfaces in superfluid He (at 1.9 K), at 2.4 K, at 4.2 K and in subcooled He, whereas quite satisfactory measurements without grease can be only obtained in subcooled He.

Temperature profiles on Cu surfaces have been measured at different conditions of He bath and different heat fluxes. In superfluid He, the temperature profile at a fixed heat flux value turns out to be much lower than that measured in normal liquid He. The temperature profiles at 2.4 K are generally higher than those at 4.2 K by a factor of 3 to 4 while they are 3 to 8 times higher in subcooled He, depending on the heat flux.

In view of implementing magnetic field sensors, one AMR sensor has been characterised. The sensibility of the sensor in superfluid He (at 1.9 K) is ~3 times higher than that at room temperature, while it turns out to further increase by 10−20% from 2.4 K to 4.2 K in comparison to 1.9 K. In addition, no changes in its sensitivity at 1.9 K has been observed after a couple of thermal cycles. However, a systematic study on a large number of AMR sensors is needed to confirm these results.

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