ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP095

DIRECT MEASUREMENT OF THERMOELECTRIC CURRENTS DURING COOL DOWN

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Abstract

In recent years there has been much discussion on thermoelectric effects and their role in flux expulsion during cool down of SRF cavities. Magnetic field is often measured to asses both flux expulsion as the cavity undergoes superconducting transition, and thermoelectric currents due to spatial thermal gradients. As a complementary view, in this paper we show direct measurement of the thermoelectric current independent from the expulsion measurement of the magnetic field. In our setup the azimuthally symmetric cavity is vertically installed and the thermal gradient is along the symmetry axis allowing to describe the cool down behavior of the thermoelectric current using simple coupled simulations.

INTRODUCTION

Typically, during cool down the cavity is exposed to a significant thermal gradient to maximize the amount of expelled ambient magnetic field. However, in bi-metal structures, the presence of such a gradient may also become a thermoelectric (TC) source of currents. In turn the induced magnetic field may be trapped which, depending on the cavity geometry and conditions of cool down, can have an impact on the residual surface resistance. The significance of this effect has been previously studied in the context of both horizontal/vertical cavity orientation in the helium tank with major work found in e.g. [1–3].

In SRF cavity studies performed at CERN we are generally interested in two cases where TC effects are relevant: cavity tests where TC currents exist between a Nb cavity and its surroundings (e.g. the supporting frame) and TC effects intrinsic to the cavity structure itself, such as in cavities based on niobium film and copper substrate. In this study we first report the result from a TC current measurement during a cold test of a 5-cell 704 MHz niobium elliptical cavity. The test was performed in one of our vertical cryostats where TC current was directly measured during the process of cool down. In the second part of the study we simulate the experiment where the thermal distribution is coupled together with the Seebeck effect and the resulting TC current is obtained as a function of the thermal gradient.

EXPERIMENT

At the vertical testing facilities available at CERN the cavity is typically supported by a frame made of stainless steel alloy *316LN* which is then mounted to the lid of the cryostat. Since cooling is applied from the bottom a temperature gradient is established along the vertical axis of the cavity. The support frame together with the flanges and the vacuum line are all made of stainless steel and are in a direct electrical contact with the cavity (Figure 1). Thus, the configuration of the typical experiment is effectively a bi-metal structure where a thermoelectric current loop can form through the metal frame (and cryostat) at its multiple points of contact with the cavity.

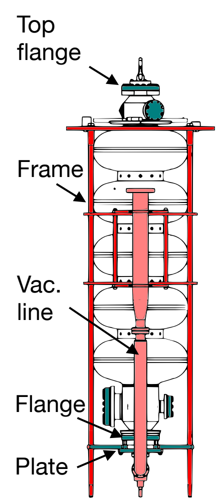

Figure 1: Scheme of the mounted cavity shown as typically tested in the vertical cryostat. All non-Nb components are depicted in color. The ones shown in green could not be electrically decoupled for the measurement reported in this study.

Setup

To be able to verify the possibility of a thermoelectric effect in our vertical setup we choose to directly measure TC current. It is hence needed to engineer the setup so that the total current is collected outside of the cryostat where it can be measured. This is done by electrically decoupling the cavity from the frame and the vacuum line by using appropriate isolating spacers. Since the circuit needs to close, we instead connect conducting wires made of copper which are attached to the flanges at the two ends of the cavity (Figure 2). The wires are then led to the top of the cryostat and are fixed to a feed-through connector so that an ammeter can be connected outside. We note that while it is impossible to decouple all the flanges attached at the various openings of the cavity they do not participate in the closed loop for the TC current. However, this is not true for the top and bottom flanges as well as for part of the supporting frame at the bottom (as shown in Figure 1 the bottom plate could not be decoupled). Since these elements are at the TC junctions we need to include them in the analysis. We also

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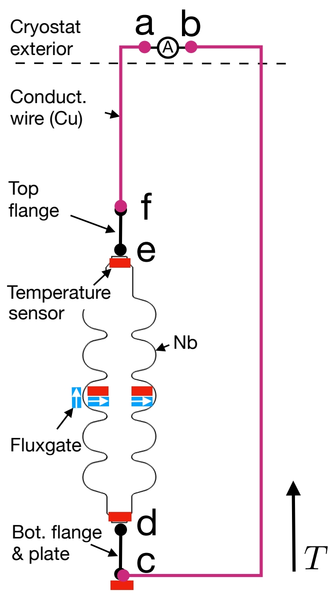

Figure 2: Simplified scheme of the TC current loop considered in the experiment. The segments f, e and d, c represent the stainless steel components which could not be electrically decoupled. Two of the temperature sensors are attached to the cavity ends (at the junctions with the flanges) and one is separately attached to the bottom steel plate itself (point c). In this way we are able to correlate in real time the temperature measured at the bi-metal junctions to the TC current. Three orthogonal magnetic fluxgates allow B-field measurement to be performed at the middle of the cavity.

note that special care is taken to decouple the heaters used to evaporate the liquid as the applied dc current can influence the measurement.

Thermoelectric effects manifest in coupling between heat and charge transport. In our case they can be accounted via Seebeck coefficient which is in the order of μV/K and gives the amount of voltage built-up between the two ends of a material exposed to a temperature gradient. For the open circuit case (ammeter disconnected) the thermoelectric voltage measured at points a, b consists of the contributions in the separate segments as labeled on Figure 2. Without loss of generality, by neglecting the temperature dependence of the Seebeck coefficient, we can write:

$$\begin{aligned} V_a - V_b =& S_C \Delta T_{fa} + S_S \Delta T_{ef} + S_N \Delta T_{de} \\ &+ S_S \Delta T_{cd} + S_C \Delta T_{bc}, \end{aligned} \tag{1}$$

where the temperature difference ΔT is indexed according to the junction points shown in Figure 2 and S_C, S_N, S_S are accordingly the Seebeck coefficients of copper, niobium and stainless steel. Since the stainless steel flanges are much shorter relative to the cavity height we will simplify by assuming: $T_f \approx T_e$ and $T_d \approx T_c$. Outside of the cryostat we are at room temperature hence $T_a = T_b$. Therefore, the voltage difference reduces to:

$$\Delta V = (T_d - T_e)(S_C - S_N). \tag{2}$$

For our direct measurement this result means that no additional thermoelectric current will be generated by measuring outside of the cryostat. The Seebeck voltage contributions generated in the wires in the region between the top of the cavity and the warm side of the cryostat will cancel since both wires are made of identical material. In order to accurately represent the temperature distribution in our simulations we try to keep the wires well-aligned along the vertical axis.

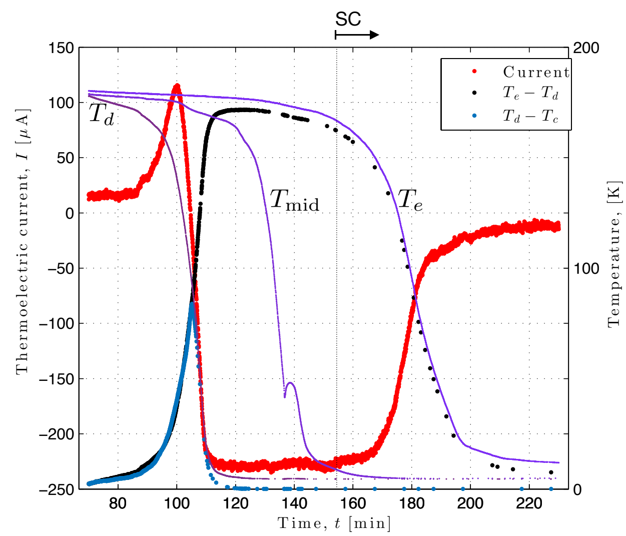

Figure 3: Thermoelectric current, temperature and temperature difference at the junctions shown as measured during cool down: T_e, T_d and T_{mid} are the temperatures measured at the top and bottom ends and at the middle of the cavity; Correspondingly $\Delta T = T_e - T_d$ and $\Delta T = T_d - T_c$ are defined along the cavity height and along the stainless steel flange found at the cavity bottom. The top arrow indicates the superconducting transition, as obtained from the magnetic flux-expulsion at the middle of the cavity.

Results

In Figure 3 we report the result for the TC current obtained from the initial cool down. As expected, when the temperature at both cavity ends is identical the measured current is close to zero. In the process of cooling temperature gradient starts forming and TC current builds-up. The maximum strength is found when the temperature difference along the cavity ($T_e - T_d$) is maximum. After this point the cavity volume starts thermalizing and the temperature measured in the middle starts rapidly falling. At $t \approx 155$ min the cavity undergoes transition which we also verify by Meissner flux expulsion (shown in Figure 5). However in this region the TC current is still somewhat unaffected and starts decreasing once the top of the cavity thermalizes – the region where the temperature gradient diminishes. An interesting feature is the peak observed at the beginning of the cool down, before the current changes sign, which results in a hysteresis behavior of the TC current as seen in Figure 4. We attribute that to the flange attached to the bottom end of

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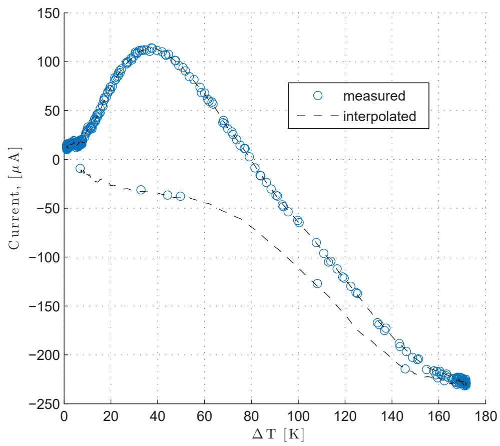

Figure 4: Measured TC current as function of the temperature difference along the cavity. Region *A* and *B* indicate correspondingly the rise of the TC current and its decay after maximum gradient is reached in the process of cool down. The missing points at the time of acquisition are shown interpolated.

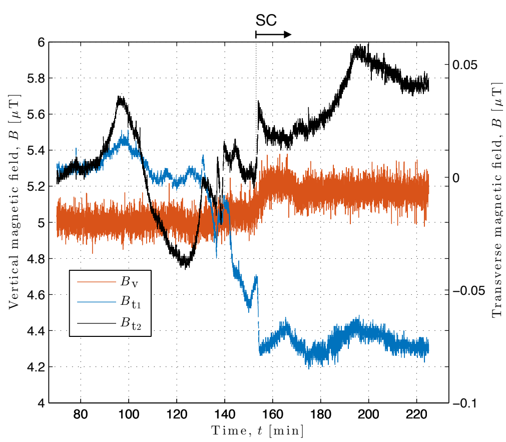

Figure 5: Magnetic field as measured during cool down. All three components are obtained near the equator at the middle cell of the cavity as shown in Figure 2. The top arrow indicates the superconducting transition, as obtained from the temperature measurement.

the cavity – as it is made of stainless steel a thermo-couple is still locally formed. Moreover, the difference in heat diffusivity with respect to Nb and the presence of mechanical contact mean that in the process of cool down non-negligible temperature gradient may in fact form. Indeed this can be confirmed in Figure 3 since the position of the temperature sensors allowed us to directly measure the gradient across the bottom flange.

For the magnetic field measurement we have three independently driven coils which allow us to control the field inside the cryostat: the transverse component of the ambient field could be reduced to ≈ 50 nT while the vertical was kept around 5 μT. In this way the magnetic field which is expelled and the one attributed to the TC effect are mutually orthogonal and can be observed reliably. To evaluate the magnetic field, for the vertically oriented TC current we can apply infinite wire approximation hence the field has radial dependence and is proportional to the enclosed current: for a magnitude of 300 μA the azimuthally oriented magnetic field, evaluated at the outside surface of the cavity equator with a radius of ≈ 0.194 m, is therefore ≈ 0.3 nT. This means that the magnetic field contribution of the TC current is negligible which in our case is because the current is measured outside of the cryostat and is subject to a relatively large resistance. The magnetic field measurement is reported in Figure 5. Although weak expulsion is expected for this particular cavity, the superconducting transition is still well visible from the vertical component. Given the low amplitude of the measured TC current the fluctuation of the transverse magnetic components cannot be attributed to the thermoelectric effect. Finally we note that the signals from the transverse components exhibit the expulsion too (the jump seen at $t \approx 155$ min) showing that the sensors were slightly misaligned.

SIMULATION

A simple way to model the thermal part of the problem is to consider that heat transport is by diffusion only. Time scale for diffusion allows us to assume that every measurement point corresponds to a stationary temperature gradient for which a steady-state TC current forms. Since cooling is applied from the bottom, the azimuthal symmetry of the problem allows us to simulate the steady TC current in 2D (Figure 6). In this case the gradient is established in the vertical direction so that the domains representing the cavity and the conducting wire are subject to the temperature distribution similarly to the experiment. The additional domains included at the bottom (T_d), at the middle junction (T_e) and at the top (room temperature) serve as boundary conditions. We model them with electrical conductivity: $\sigma \to \infty$ and Seebeck coefficient: $K = 0$, so that they do not influence the current magnitude. In this way we are able to simulate the temperature at the junctions as measured in the experiment and, at the same time, obtain the current found in the closed loop. The material constant data is taken from [4] for niobium and from [5], [6] for copper. Due to lack of material data the stainless steel domains could not be included which makes the results valid only for the region where no temperature gradient exists across the bottom flange.

Results

The above-described simulation allows us to model the dynamics of the steady TC current as function of the temperature gradient along the cavity height. In Figure 7 we show the simulated result obtained by varying T_e while keeping T_d at 5 K which is similar to the experiment. As the temperature difference decreases the TC current decreases too, where the simulation is found to describe well the steeper slope part of region B in Figure 4. However in the range $\Delta T < 55$ K the current predicted by the simulation is significantly less than the experimentally observed for which

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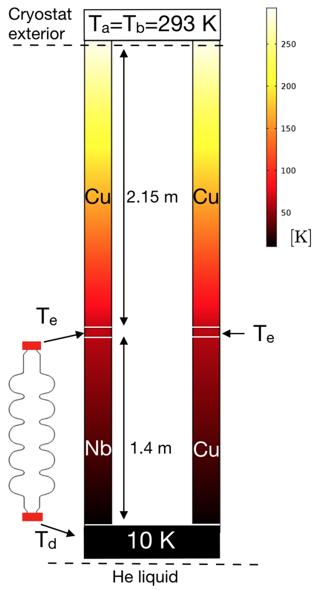

Figure 6: Scheme of the 2D simulation used to model the closed TC loop from the experiment. The temperature distribution is shown for: T_d = 10 K, T_e = 60 K and room temperature at the top of the cryostat.

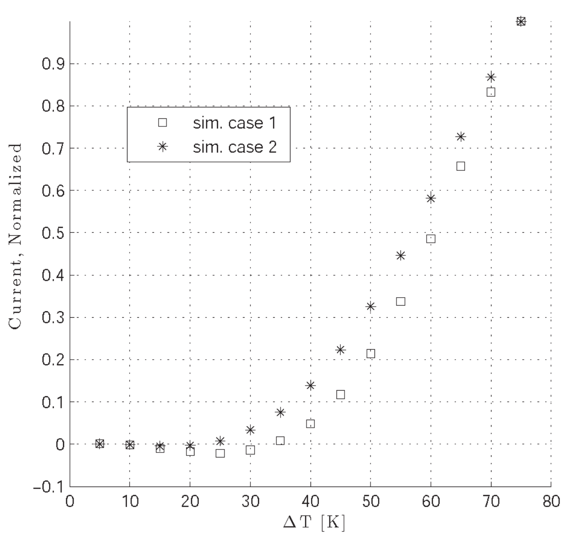

Figure 7: Simulated TC current as function of the temperature difference along the cavity height. Region B from Figure 4 is modeled. Normalization is considered for ΔT = 75 K.

two possible explanations are considered. The first is related to the purity of the copper wire – impurities in the material can alter the Seebeck coefficient which would be naturally seen at lower temperature gradients since the Seebeck voltage is dominated by copper for high gradients. This is also suggested by the simulation results – the two cases shown in Figure 7 correspond to different values for copper (with different purity) found in the literature. A foreseen modification to improve the accuracy of the simulation is to replace the copper in the experiment by titanium for which recent data exists at cryogenic temperatures. Alternative explanation for the simulated result is related to the possibility that there is additional temperature gradient across the top flange. Effectively, this would be a source of Seebeck voltage which is not accounted for in the simulation. In the future experiments it is therefore justified to also measure the gradient across the top flange.

Finally it is worth noting that having a relatively large dynamic range for the temperature in our cryostat often can make it challenging for the convergence. Therefore the simple simulation used is found to be an important advantage.

SUMMARY

In this paper we show a proof of concept for a direct measurement of thermoelectric current in the process of cooling a vertically installed cavity. The experiment shines light on how the dynamics of cool down across different materials plays a role in the formation of TC current. The complementary simulation suggests that steady current and heat diffusion are in principle sufficient to represent the problem where in our case confirmation is found for larger temperature gradients. As measuring and decoupling the magnetic field attributed solely to the TC current is difficult, this experiment is found useful as it provides a reliable way to observe the TC current and, at the same time requires minimum modification of the setup. The simulation study provides guidelines for future work related to TC effects in cavities based on niobium film and copper substrate.

ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 Research and Innovation program under Grant Agreement No 730871.

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