

# T-MAPS TAKEN DURING COOL-DOWN OF AN SRF CAVITY: A TOOL TO UNDERSTAND FLUX TRAPPING

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## Abstract

During the past years a new effect has puzzled the community working in the field of superconducting RF cavities. I was found that the RF losses of the cavities are impacted by the cool-down procedures. On the flux trapping properties of superconducting cavities have been under investigation. We have measured temperature distributions of a multi-cell cavity using a T-map set-up to understand the transition to superconductivity in detail. We will report how the spatial disorder is affected by the cool-down speed and relate our findings to data on flux pinning.

## INTRODUCTION

Continuous wave mode operation of future accelerators have driven the research on achieving high quality factor SRF cavities to keep operation cost low. As the surface resistance of superconducting cavities approaches the theoretical limits parasitic effects limiting the performance came into focus of research. One interesting finding was that the quality factor of a cavity is impacted by the cool-down speed under which the cavity transits into the superconducting state.

This effect was first reported in 2011 by HZB [1]. With respect to magnetic flux pinning, they observed on samples that a slow cool-down can enable better external flux expulsion. Similar results were gained at Cornell, seeing that an initial cool-down to 4 K, followed by a thermo-cycle warming to 20 K and a slow re-cool through the critical temperature increased the quality factor significantly[2].

In contrast to this, FNAL [3] saw an increase of the quality factor of nitrogen doped cavities after a fast cool-down and claimed that – in contrast to [1]- flux expulsion is more efficient during a fast cool-down. In [4], it was proclaimed that the cool-down is more uniform during a fast cycle, which seems counter-intuitive.

As Cornell's multi-cell temperature-mapping system has unique capabilities [5], we started investigating cool-down dynamics of multi-cell cavities to get an understanding how the transition region between the normal and the superconducting state moves along the cavity.

## THE EXPERIMENTAL SET-UP

The Cornell multi-cell Temperature-map system [6] has nearly two thousand thermometers, able to cover 7 cells with 11 sensors along the perimeter times 24 azimuthal angles. The temperature sensors are 100  $\Omega$  carbon Allen-

Bradley resistor (5%, 1/8 W). To ensure good thermal contact, each sensor is pushed tightly against the cavity surface by a spring. APIEZON® type N grease, which has good thermal conductivity at low temperature, is applied to fill the gap between the sensors and the surface. Our data was taken on a TESLA-shape 9-cell cavity with the T-map place to cover the centre cells, shown in Figure 1.

In this paper, we only consider the T-map covered cells and define the cell numbers 1 to 7 from top to bottom. A read-out of all sensors takes about one minute when using 2<sup>14</sup> samples per sensor which gives an accuracy in the temperature reading of 1.5 mK at 2 K. Usually, this system is operated at a constant bath temperature to identify heating spots and/ or quench locations of cavities. Under these conditions, calibration of the resistors is done against the Cernox sensors.

To take data during a cool-down, the system had to be modified: the sampling rate had to be reduced (to get shorter sampling times) and a careful recalibration had to be done.

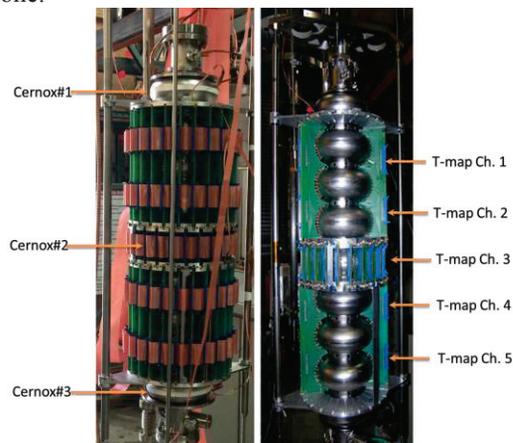


Figure 1: (Left):The multi-cell temperature-mapping system mounted on a TESLA-shape 9-cell SRF cavity. (Right): Several T-map boards have been removed to expose the cavity.

## CALIBRATION

Cornell's T-map data acquisition system usually measures the resistance of each sensor which is converted into a temperature using calibration data. During calibration, the ambient temperature surrounding the T-map resistors, measured with calibrated cernox sensors mounted on the equator of top, middle, and bottom cell, is varied and the resistance curve of each T-map sensor is taken and calibrated against the nearest cernox sensor. For Our measurement, the calibration was performed during a slow warm-up, going from 4.2 K to 50 K in about 3 hours. The maximum temperature gradient along the cavity was 0.2 K.

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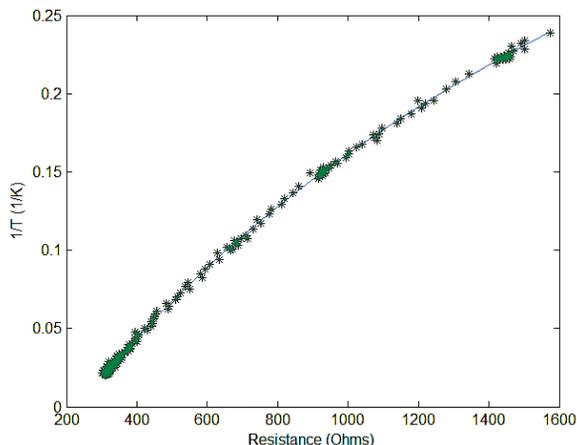


Figure 2: A calibration curve of a temperature sensor.

A typical calibration curve of a T-map sensor is shown in Figure 2. The resistance value varies from 300 Ω to 1600 Ω when the temperatures changed from 50 K to 4.2 K. The curves can be fitted by a third order polynomial and 4 coefficients are obtained for each sensor:

$$\frac{1}{T} = ax^3 + bx^2 + cx + d, \quad (1)$$

$$x = \ln(R).$$

Here,  $T$  is the temperature (as measured by the closest Cernox sensor);  $R$  is the resistance of the T-map resistor;  $a$ ,  $b$ ,  $c$ , and  $d$  are the fitted coefficients.

## T-MAPS DURING COOL-DOWN

### Slow Cool Down

For the slow cool-down, we used a short helium stinger, the end of which was above the 9-cell cavity. The cool-down took about 6 hours from room temperature to 4.2 K. Data from the Cernox and the T-map resistors was taken continuously. The Cernox sensors revealed a maximum temperature gradient along the cavity of 0.5 K.

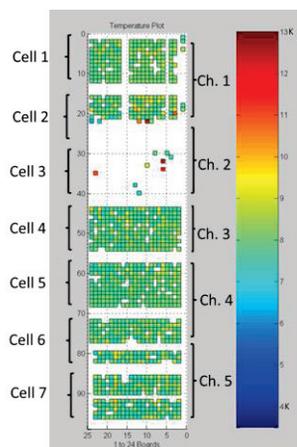


Figure 3: The T-map taken as the cavity was passing the transition temperature becoming superconducting during the slow cool down.

A temperature map, taken at  $T_c$ , is shown in Figure 3. Each T-map sensor is represented by a square with the temperature visualized by its colour. White indicates a broken sensor and we point out that no data smoothing is done in any of our T-maps. It should be noted that data channel 2 (affecting data from cell 2 and 3) was not functioning which resulted in a lack of data and some misreading in cell 2.

### Fast Cool Down

For the fast cool down, we used a long transfer line which extends its end to the bottom of our Dewar, allowing a cool-down in less than an hour. When the bottom Cernox sensor passed  $T_c$ , the thermal gradient between the top and the bottom was approximately 180 K.

As a consequence, the cavity transited the critical temperature un-uniformly, starting from the bottom. As expected, T-map revealed the cooling front moving from the cavity bottom to the top, which is depicted in Figure 4. The left diagram (1) shows the T-Map data when the cell #7 was around 50 K, the map in the middle (2) was taken 2 min later with the transition to superconductivity (tts) line between cell #7 and #6. On the right (3) of Figure 4 is data taken 2 min after (2) showing the tts-line approaching cell #5.

Our analysis will now try to quantify the spatial uniformity of the transition to superconductivity.

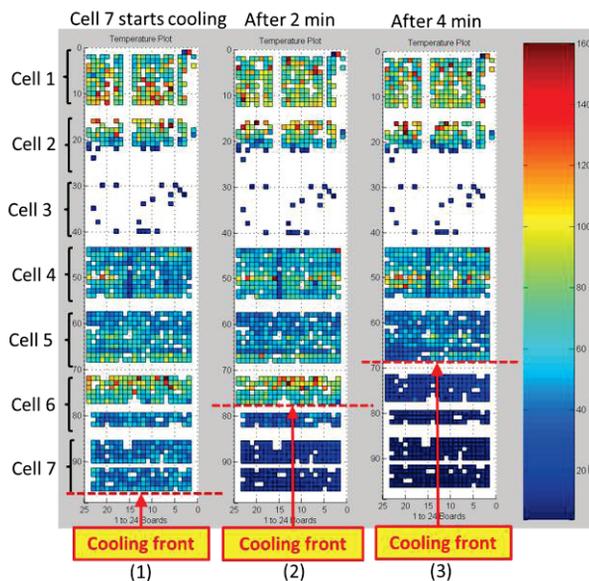


Figure 4: The T-map results showed the cooling front movement during the fast cool down.

## THE DATA ANALYSIS

Our data analysis is guided by trying to answer the question, weather a slow or a fast cool-down results in a more uniform transition of the cavity into the superconducting state. We want to study, if normal conducting islands, surrounded by superconducting area,

are more likely to develop when the cavity is undergoing different cool-down scenario.

During our analysis we found that judgments based on visual data is often misleading: on a slow cool-down, temperature spreads are small so colour-coding usually is done within a very narrow temperature scale. As a result, the T-map looks very un-uniform compared to a T-map from a fast cool-down, which is colour-coded using a much broader temperature scale. A careful comparison thus has to be done on the same scaling. The analysis presented here is guided by that idea, trying to quantify the results.

Our T-map data is a  $77 \times 24$  array. As we are interested in the transition dynamics around the critical temperature, we set a window on the data between 9 and 9.5 K. This means, we only account for temperature variations close to the critical temperature, where they may result in developing a normal conducting island.

For sensors within this temperature window, we calculated the average temperature difference to their adjacent sensors and averaged over all sensors:

$$\Delta T = \frac{1}{N} \sum_{i=1}^{77,24} \frac{1}{4} (|T_{ij} - T_{i\pm 1,j}| + |T_{ij} - T_{i,j\pm 1}|). \quad (2)$$

$N$  is the number of sensors within the temperatures window.

In Figure 5 we plot  $\Delta T$  as calculated in (2) as a function of time for the slow and the fast cool-down. It shows as a portion of the cavity becomes superconducting, the average temperature difference to the surrounding area is larger for a cavity being cooled down fast compared to a slowly cooled cavity.

As the transition to superconductivity occurs on different time scales for the fast and the slow cool-down, a more instructive way to plot the data is given in Figure 6, where the average temperature fluctuation of the surface at temperatures close to the critical temperature is plotted as a function of the temperature. As can be seen, the thermal gradient during the slow cool-down is around 0.5K-1K, which is much less than the 2.5K-3.5K seen in the fast cool-down.

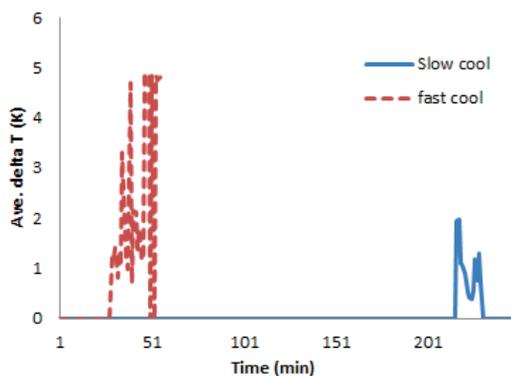


Figure 5: The average temperature fluctuation of the cavity surface within the 9 to 9.5 K window during the slow and fast cool-down.

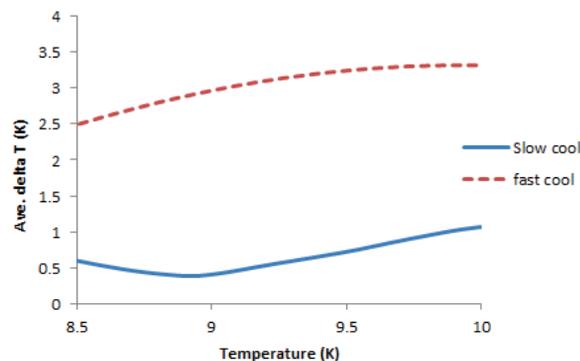


Figure 6: The average  $\Delta T$  versus temperature comparison between the slow cool and the fast cool in fine temperature scale.

## CONCLUSION

In this paper, we described how a T-map system can help understanding the cool-down dynamics for different cycles. We found visualizations in the form of Figure 3 and 4 to be sometimes misleading in judging about the homogeneity of the cool-down. As a consequence, we developed a metric, given in (2) which allows to quantify the temperature variances of the cavity as regions become superconducting. From that we conclude that a fast cool-down has larger temperature gradients at transition.

However, we see this as a first approach to quantify the cool-down uniformity. It also remains open, if smaller temperature gradients result in a smaller probability of creating normal conducting islands or vice versa- which is a topic of our on-going studies.

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