HOW UNIFORM ARE COOL-DOWNS?

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Abstract

Since the last SRF conference it has become clear that achieving extremely high quality factors of SRF cavities depends on the cool-down scenario. While some findings favor a fast cool-down, others suggest a slow cycle to be advantageous, and many variations to that have been investigated: the role of thermo-currents, the amount of ambient magnetic field and flux trapping. This paper will investigate how uniform different cool-down procedures are and if they can explain the more efficient magnetic flux expulsion.

INTRODUCTION

In the effort to produce superconducting cavities with higher Q-factors, recent experiments have been conducted to determine how different cavity cool-down processes result in different amounts of trapped magnetic flux [1-3]. Faster cool-downs have been speculated to sweep the magnetic flux out of the cavity more efficiently than slow cool-downs [1]. Furthermore, it seems unclear if this applies only to nitrogen doped cavities and large grain cavities. However, the mechanism for this effect is poorly understood and is the subject of ongoing study.

In an earlier paper, we [3] measured the movement of the transition line of a superconducting cavity using our T-Map system. Results there indicated that a slow cool-down leads to less temperature variations on the surface but gave no answer to the question if this is more likely to generate normal conducting islands that are susceptible to flux trapping.

In practice, the superconducting-normal conducting (SC-NC) interface is never completely uniform during cool-down. Defects in the niobium and thermal fluctuations perturb the SC-NC interface and increase the probability of producing normal-conducting islands, resulting in trapped magnetic flux.

As a factor that determine the uniformity of the cool-down we want to studie the size and number of perturbations to the SC-NC interface and the rate at which those perturbations shrink.

We have run simulations using ANSYS® to determine the relative size and decay time of perturbations applied to the SC-NC interface during cavity cool-down. Understanding the behavior of deviations in the superconducting phase boundary from an ideally moving cold front should help answering the question of how the cool-down rate affects the amount of trapped magnetic flux.

METHODS

Niobium Parameters

The thermal conductivity values that we used in our simulations were taken from a combination of theoretical models and experimental data. The theoretical model that we used was the thermal conductivity equation given by [4].

$$Ks(T) = \frac{Kes}{Ken}\left(\frac{\rho_{295K}}{L \cdot RRR \cdot T} + aT^2\right)^{-1} + \left(\frac{1}{De^{\frac{\alpha T_c}{T}}T^2} + \frac{1}{B \cdot l \cdot T^3}\right)^{-1}$$

$K_{es}/K_{en}\,(T)$ is the ratio of superconducting to normal-conducting electron contributions to thermal conductivity. Constant parameters are given in Table 1. This model is valid for $T < 5.8\,K$. For temperatures above $5.8\,K$, an experimental data set was used [5].

The specific heat of the niobium cylinder was assumed to follow the Debye model $C_v = \gamma\,T + A\,T^3$. Using experimental data from [6], values for the parameters were calculated as $\gamma = 0.0946\,\frac{J}{kg\cdot K^2}$ and $A = 1.28 \times 10^{-3}\,\frac{J}{kg\cdot K^4}$ (for $T > T_c$) and $\gamma = 0$ and $A = 5.01 \times 10^{-3}\,\frac{J}{kg\cdot K^4}$ for $T < T_c$.

Table 1: Parameters for Theoretical Thermal Conductivity Model, Taken from [4]

Param.	Value	Definition
RRR	400	resid. res. ratio
ρ_{295K}	$14.5 \times 10^{-8}\Omega m$	res. at 295 K
l	$50\,\mu m$	Nb phonon mfp
T_c	$9.2\,K$	Nb critical temp
L	$2.45 \times 10^{-8}\,V^2K^{-2}$	param of Eq. 1
a	$2.30 \times 10^{-5}\,mW^{-1}K^{-1}$	param of Eq. 1
B	$7.0 \times 10^{-3}\,Wm^{-2}K^{-4}$	param of Eq. 1
$1/D$	$300\,m\,K^3W^{-1}$	param of Eq. 1
α	1.76	param of Eq. 1

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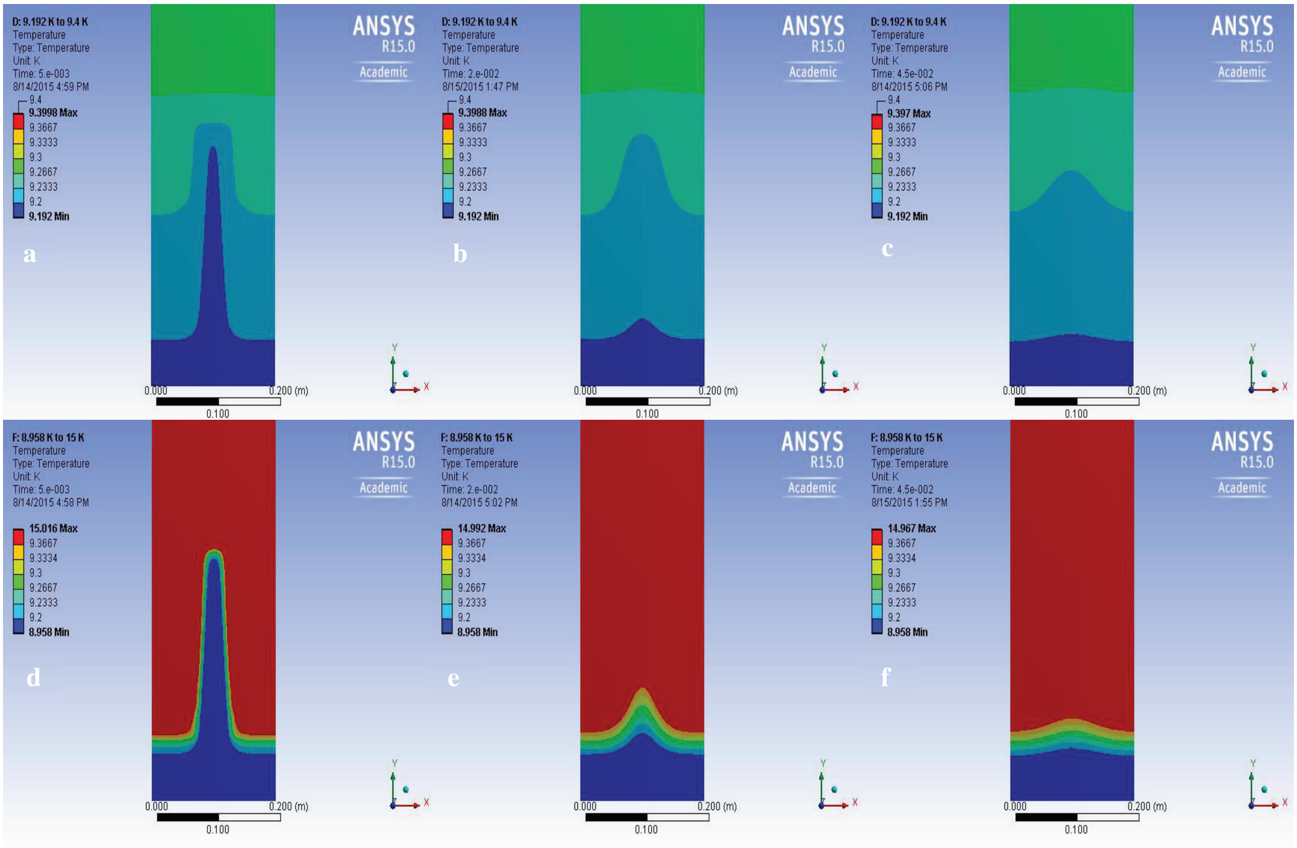

Figure 1: Niobium cylinder cool-down with $300\,mm$ initial perturbation to the SC-NC interface. a-c are slow cool-down, d-f are fast cool-down. a and d are $0.005\,s$ after the perturbation is applied, b and e are $0.02\,s$ after, c and f are $0.045\,s$ after. The size of the perturbation to the SC-NC interface at each step is: a) $251.5\,mm$, b) $27\,mm$, c) $10\,mm$, d) $244.5\,mm$, e) $27.5\,mm$, and f) $9\,mm$. The superconducting portion of the cylinder is represented as dark blue.

CYLINDER CALCULATION

Simulation Setup

A simulation was performed comparing fast and slow cool-down in a niobium cylinder. The purpose of this simulation was to measure how equally large perturbations in the superconducting phase boundary decay independently of the cavity geometry. Geometry has the potential to influence decay time results because the size of the perturbation to the SC-NC interface could expand when passing through a cell iris or could shrink when passing through a cell equator, for example. To better understand how perturbations decay independently of geometric factors we simulated cooling for the case in which the cross-sectional area is constant along the direction of cooling. The niobium cylinder simulation was set up as follows:

1. The cylinder is given an initial temperature distribution that varies linearly along the length of the cylinder. A $0.208\,K$ temperature gradient over the whole cylinder was used for slow cool-down and a $6.042\,K$ temperature gradient over the whole cylinder was used for fast cool-down.
2. The temperature at the bottom of the cylinder is fixed and heat is allowed to flow out of the bottom of the cylinder.
3. The SC-NC interface is given a perturbation of size $300\,mm$ in the middle of the cylinder.
4. The cylinder is allowed to cool and the decay time of the perturbation is measured.

Results

Figure 1 shows the temperature distribution of a perturbed niobium cylinder over time for different thermal gradients. The size of this perturbation over time is given in Figure 2.

This analysis shows that perturbations of equal size decay about as quickly for slow cool-downs as they do for fast cool-downs. As a result, no judgement can be made on the uniformity of the cool-down. The question of whether fast cool-down or slow cool-down is more uniform should then depend on differences in perturbation size for equal heat loads under different thermal gradients as a result of a more complex geometry. We will investigate this in the section below.

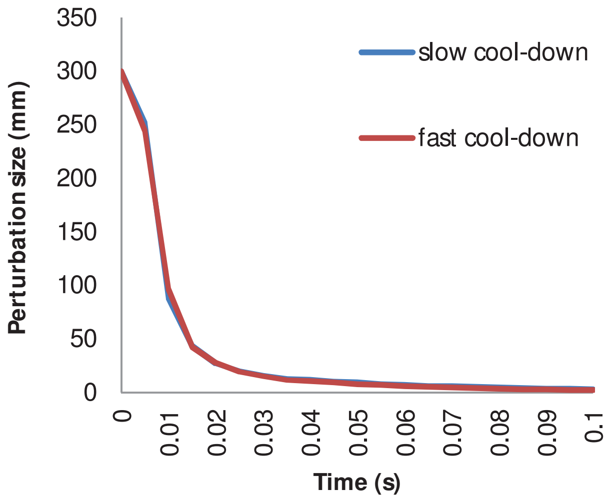

Figure 2: Decay of perturbations to the SC-NC interface of equal size and heat load in a niobium cylinder.

CAVITY CALCULATION

Simulation Setup

Simulations were performed comparing fast and slow cool-down of an RF cavity for the vertical and horizontal cool-down cases. The simulation design was as follows:

1. The cavity is given a uniform initial temperature of $15\,K$ and a constant heat flow out of the bottom of the cavity is applied to simulate liquid helium cooling. The cooling rates are approximately $3\,mK/s$ for slow cool-down and $33\,mK/s$ for fast cool-down.
2. When the equator of the first cell of the cavity reaches T_c, a heat perturbation of $0.48\,J$ is applied to a small region of the cell equator. This is done to simulate asymmetries in cool-down due to defects in the niobium or heat fluctuations.
3. The heat is applied for a short time interval and removed afterwards so that the perturbation is allowed to decay.

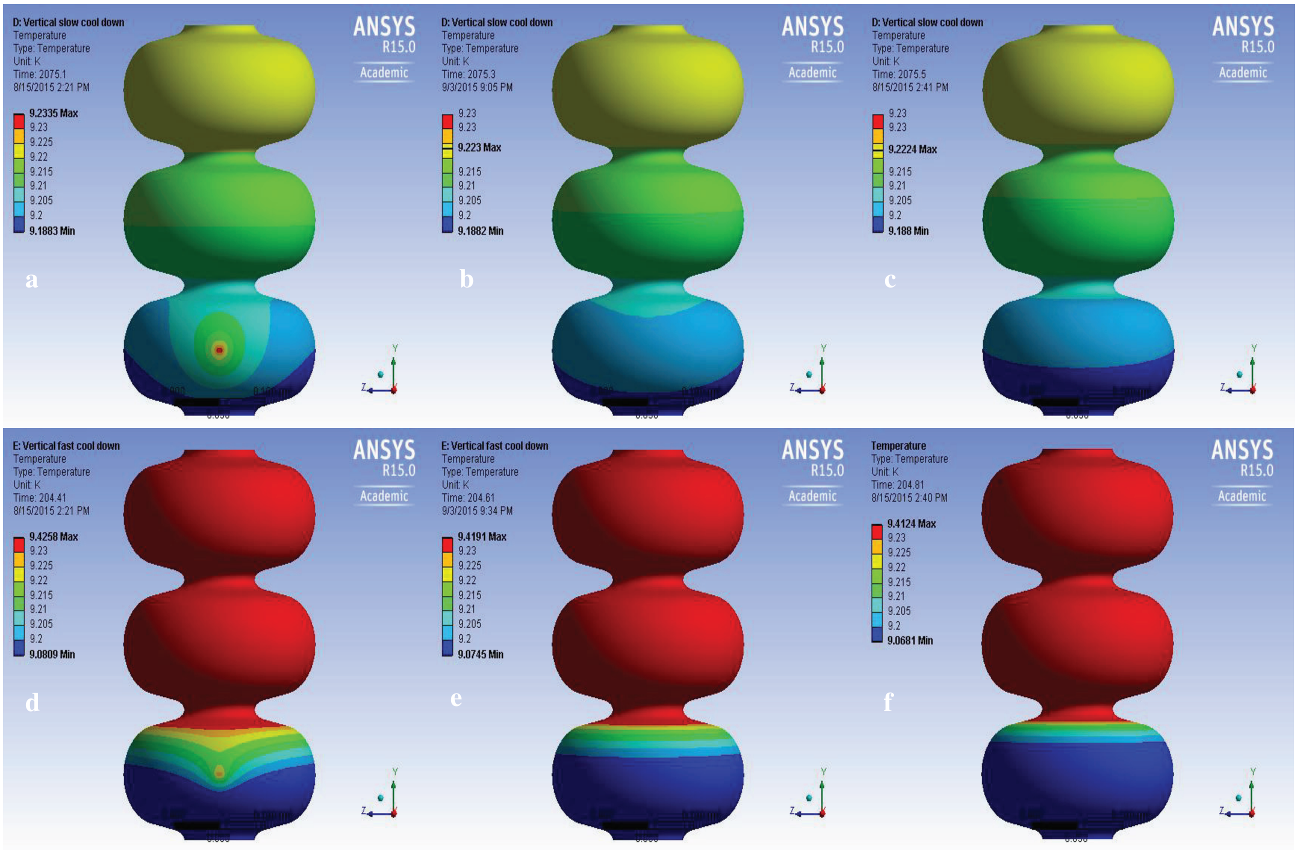

Figure 3: Vertical cavity cool-down with $0.48\,J$ perturbing heat at first cell equator. a-c are slow cool-down, d-f are fast cool-down. a and d are $0\,s$ after the perturbation is applied, b and e are $0.2\,s$ after, c and f are $0.4\,s$ after. The size of the perturbation to the SC-NC interface at each step is: a) $52.6\,mm$, b) $53.0\,mm$, c) $34.3\,mm$, d) $24.1\,mm$, e) $5.6\,mm$, and f) $3.8\,mm$. The superconducting portion of the cavity is represented as dark blue.

Vertical Cool-down Results

In the vertical cool-down scenario, equal heat perturbations were found to decay quicker for fast cool-down than they were for slow cool-down. Figure 3 and Figure 4 show how the size of this perturbation to the SC-NC interface shrinks over time.

For slow cool-down, the applied heat resulted in a perturbation in the SC-NC interface of size (length) $52.6\,mm$.

- The time for this perturbation to decay to less than $5.3\,mm$ (10%) was $1.1s$
- The time for the perturbation to decay to less than $5\,mm$ was $1.2s$

For fast cool-down, the applied heat resulted in a perturbation in the SC-NC interface of size $24.1\,mm$.

- The time for this perturbation to decay to less than $2.4\,mm$ (10%) was $0.6s$
- The time for the perturbation to decay to less than $5\,mm$ was $0.3s$

It should be noted that equal quantities of heat flow into the cavity result in different perturbation sizes. The reason for this is that the perturbing heat more easily spreads across the cavity under a smaller thermal gradient, allowing the perturbation to the SC-NC interface to grow larger during a slow cool-down than during a fast cool-down.

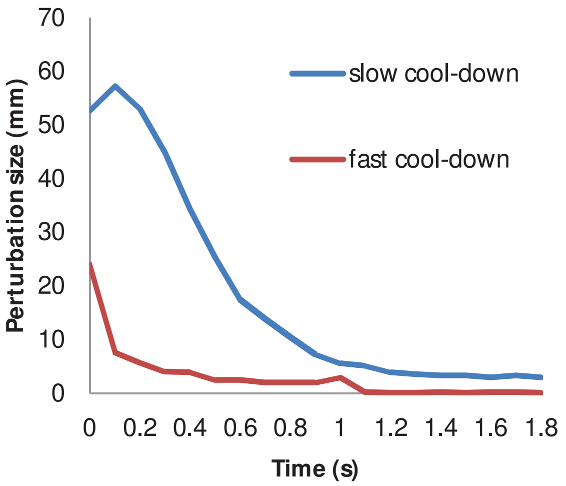

Figure 4: Size of perturbation to SC-NC interface over time for vertical cavity cool-down simulation. Deviations from smooth exponential decay can be attributed to the cavity geometry. Equal amounts of heating lead to a smaller size perturbation in the fast cool-down scenario and as a result in a faster decay.

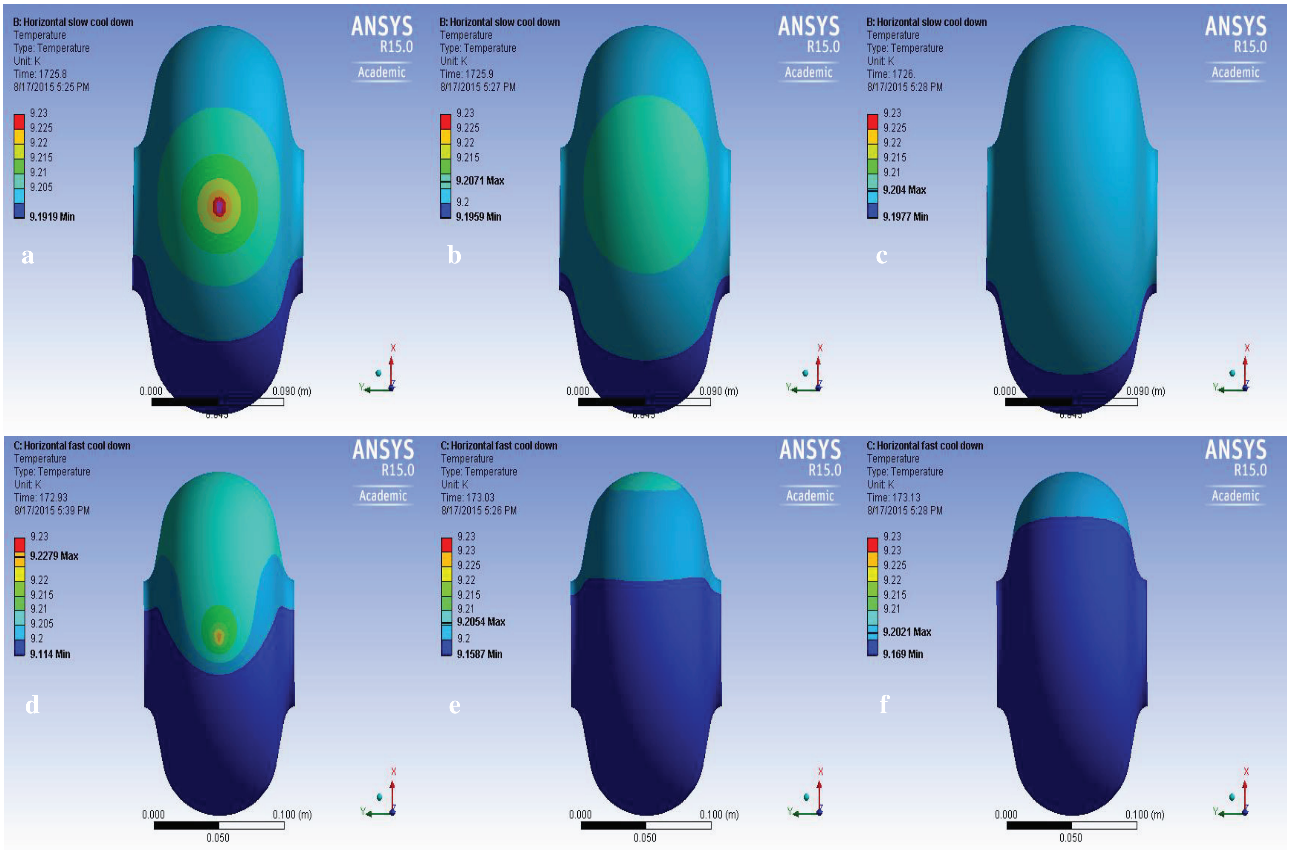

Figure 5: Horizontal cavity cool-down with $0.48\,J$ perturbing heat at the midpoint along the cell equator. a-c are slow cool-down, d-f are fast cool-down. a and d are $0\,s$ after the perturbation is applied, b and e are $0.1\,s$ after, c and f are $0.2\,s$ after. The superconducting portion of the cavity is represented as dark blue.

ISBN 978-3-95450-178-6

Horizontal Cool-down Results

Figure 5 shows how a perturbed SC-NC interface propagates through a cavity during horizontal cool-down. As in vertical cool-down, equal amounts of perturbing heat produce larger perturbations during slow cool-down than during fast cool-down. Also as in vertical cool-down, perturbations shrink quicker in fast cool-down than in slow cool-down. For instance, in Figure 5f, the SC-NC interface appears completely uniform while in Figure 5c the perturbation does not appear to have decayed at all.

CONCLUSION

ANSYS® simulations were performed to test whether the superconducting phase boundary will sweep a niobium cavity more uniformly during a fast cool-down procedure or a slow cool-down procedure. Equally large perturbations to the phase boundary were found to decay equally quickly in both large and small temperature gradients. However, cavity cool-down simulations showed that equal amounts of perturbing heat lead to larger perturbations to the SC-NC interface during slow cool-down than they do during fast cool-down. Thus, if perturbing heat fluctuations are equal during fast and slow cool-down, then fast cool-down will be more uniform and can be expected to result in less trapped magnetic flux because perturbations to the phase boundary will be larger on average during slow cool-down.

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