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JOURNAL OF APPLIED PHYSICS **118**, 044505 (2015)

Magnetic flux studies in horizontally cooled elliptical superconducting cavities

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Previous studies on magnetic flux expulsion as a function of cooldown procedures for elliptical superconducting radio frequency (SRF) niobium cavities showed that when the cavity beam axis is placed parallel to the helium cooling flow and sufficiently large thermal gradients are achieved, all magnetic flux could be expelled and very low residual resistance could be achieved. In this paper, we investigate flux trapping for the case of resonators positioned perpendicularly to the helium cooling flow, which is more representative of how SRF cavities are cooled in accelerators and for different directions of the applied magnetic field surrounding the resonator. We show that different field components have a different impact on the surface resistance, and several parameters have to be considered to fully understand the flux dynamics. A newly discovered phenomenon of concentration of flux lines at the cavity top leading to temperature rise at the cavity equator is presented. © *2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License*. [http://dx.doi.org/10.1063/1.4927519]

I. INTRODUCTION

Trapped magnetic flux in superconducting (SC) resonators contributes to the microwave surface resistance (R_s) in the form of the temperature-independent residual resistance R_0.[1]

This residual resistance due to trapped flux plays an important role in superconducting radio frequency (SRF) cavity performance, as it degrades the cavity efficiency, characterized by the quality factor Q_0. Recent studies[2–4] have shown that performing fast cooldowns, with high thermal gradients along the cavity, is vital to obtain efficient ambient magnetic flux expulsion, whereas slow and homogeneous cooling through transition leads to full flux trapping. As an example, using the fast cooling technique, residual resistances values as low as 1 nΩ in up to 20 mG magnetic field and 5 nΩ in 190 mG have been obtained with 1.3 GHz nitrogen-doped elliptical niobium cavities,[5] compared to 15 nΩ in 5 mG for slow cooling through the critical temperature T_c.[3] These examples illustrate how the cooldown procedure is crucial to maximize the efficiency of SRF cavities.

Several continuous wave (CW) accelerators currently being built worldwide (for example, X-ray FELs such as LCLS-II at SLAC[6,7]) require very high quality factors (highly efficient SRF cavities) to reduce cryogenic costs. Therefore, understanding of the cavity cooldown dynamics in a configuration that resembles the accelerator, and in the presence of magnetic field levels comparable to those obtained in shielded cavities placed in a cryomodule, is crucial in order to investigate how to minimize the surface losses due to trapped flux.

The goal of the work presented in this paper is therefore to study the impact of different external magnetic field orientations on the residual resistance when the cavity is transverse with respect to the cooling direction, similar to when elliptical cavities are placed in an accelerator. In particular, we focus on the difference introduced by the external magnetic field applied axially versus orthogonally to the cavity axis.

II. EXPERIMENTAL SETUP

In this study, we used a single cell 1.3 GHz TESLA type nitrogen doped niobium cavity, the same as used in the previous work.[3] It is worth mentioning that this cavity has achieved world record quality factors $Q_0 > 1 \times 10^{11}$ up to the highest fields of 30 MV/m at 1.5 K and with a $Q_0 > 5 \times 10^{10}$ up to 30 MV/m at 2 K.

The setup with the cavity placed horizontally in the cryostat is shown in Fig. 1. Two pairs of Helmholtz coils were placed orthogonal to each other (Fig. 1) with one parallel (a) and the other perpendicular to the cavity axis (b). In addition, four Cernox thermometers were placed on the cavity equator (orange squares in Fig. 1): one at the very bottom of the cell, one in the middle, one at the very top of the cell, and one half way in between the top and the middle ones.

The external magnetic field applied to the cavity was measured by means of four single-axis Bartington Mag-01H cryogenic fluxgate magnetometers (green rectangles in Fig. 1). Two of them were placed at the very top and aligned one perpendicular and one parallel to the cavity axis. The other two were aligned the same way but placed at the middle height of the cavity.

Several fast cooldowns were performed with the same magnitude of the ambient magnetic field of about 10 mG but different field orientations (orthogonal or axial). In order to

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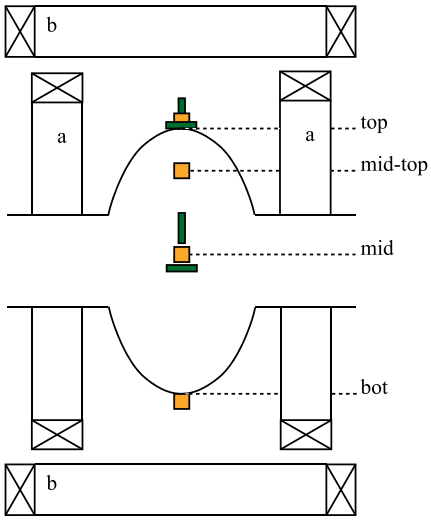

FIG. 1. Schematic of the horizontal cavity cooldown setup. Orange squares represents thermometers, green rectangles mark the fluxgates positions, and "a" and "b" label two Helmholtz coils.

obtain different thermal gradients across the cavity, different starting temperatures were chosen for these fast cooldowns.

III. CAVITY COOLDOWN DYNAMICS

In order to better understand how the cavity RF surface resistance is affected by different cooldowns, we start by discussing the dynamics with which the superconducting transition takes place along the cavity.

The fast cooldown is performed filling the cryostat with liquid helium from the bottom, establishing a thermal gradient between the top (300 K) and the bottom (4.2 K) of the cryostat. The cavity is cooled through the niobium critical temperature by the stratified gaseous helium starting from the bottom and progressing to the top of the cavity.

When the cooldown is performed with the cavity oriented horizontally with respect the cryostat axis, the boundary between the SC and the normal conducting (NC) phases will move from the very bottom to the very top point of the cell equator, rather than from one beam tube to another as in the vertical orientation.[2,3] This can cause significant differences from the vertical geometry, since now the final escaping place for flux is the equator, the most important area for RF losses.

Let us consider axial and orthogonal directions of the field to be expelled. When a magnetic field is applied axially to the cavity and sufficient thermal gradients are present during the transition, this field will be expelled from the cavity walls because of the Meissner effect, as depicted in Fig. 2(a). In the Meissner state, the magnetic field can be either confined outside of the cavity volume or it can pass through the interior of the cavity through the beam pipe. Because of the axial direction of the field, the flux lines that cross the cavity walls always have an easy path to follow during the transition, and the expulsion can be efficient. If the flux expulsion is not efficient, some flux lines may remain pinned, crossing the cavity walls and increasing the losses.

When the applied field is perpendicular to the cavity axis during the SC transition, the dynamics will be different. First, magnetic field lines will be bent because of the Meissner effect and then redistributed in three possible different ways: (i) move completely outside of the cavity, (ii) escape through the beam pipes, or (iii) go across the cavity wall if pinning centers are present, when a non-efficient expulsion occurs (Fig. 2(b)). Because of the orthogonal field orientation, the magnetic flux lines redistributed with the (ii) and (iii) mechanisms do not have any possibility to escape from the cavity inner volume except crossing the cavity walls. Assuming a sharp SC-NC interface, these flux lines will be concentrated in the normal conducting region, which will become smaller and smaller as the transition boundary advances, until they are squeezed at the very top point of the cell equator. This point of the cavity will be the last cooled below the transition temperature T_c, thereby becoming a "flux hole" from which it is not energetically favorable for flux to escape, as the only way out would be via crossing already superconducting regions.

Thus, geometry of the system could lead to an incomplete Meissner effect, even when the thermal gradient across

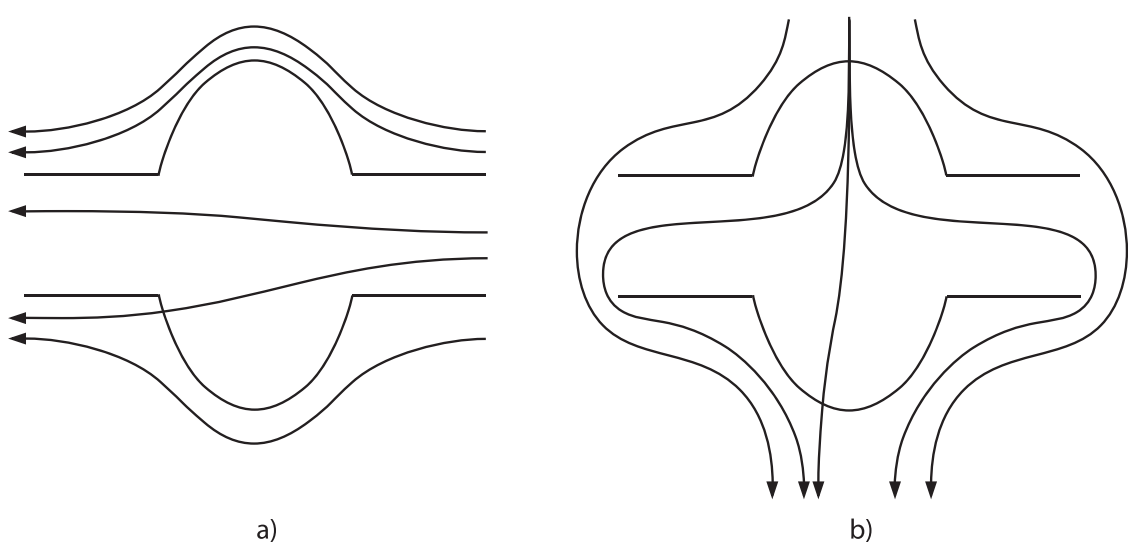

FIG. 2. Field redistribution in the Meissner state with magnetic field applied (a) axially and (b) orthogonally.

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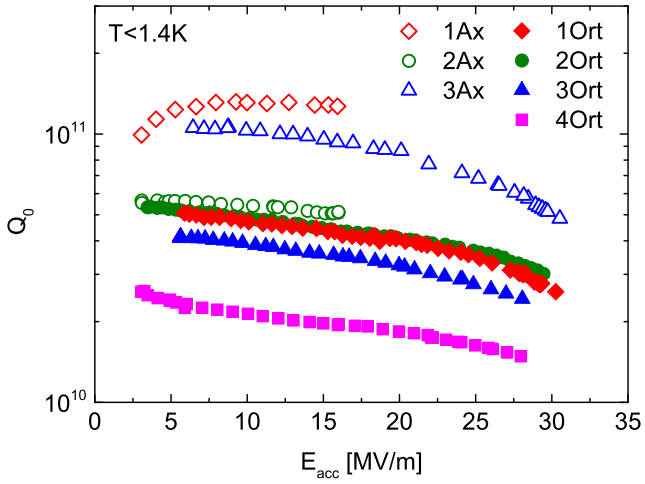

FIG. 3. Q_0 versus accelerating field E_{acc} measured at $T < 1.4$ K.

the cavity is high enough to provide efficient flux expulsion for the axial configuration.

IV. DATA ANALYSIS

RF measurements were performed at the Fermilab SRF cavity vertical test facility. The unloaded Q-factor (Q_0) versus accelerating field (E_{acc}) curves were acquired at 2 K and at the lowest temperature achievable with the pumping system, which was lower than the calibration range of the thermometers ($T < 1.4$ K). At such low temperatures, the surface resistance is dominated by the temperature-independent part (residual resistance R_0).

The Q_0 versus accelerating field curves acquired at $T < 1.4$ K are shown in Fig. 3, while the cooldown conditions of the data series are summarized in Table I. As studied in the previous work,[8] the uncertainty of the measurement of Q_0 does not exceed 10%.

The cooldowns for the data series named nAx (axial) were performed applying 10 mG of external field parallel to the cavity axis. For curves 1Ax and 2Ax, an administrative limit of 16 MV/m was set for the accelerating field to avoid quenching the cavity, which could cause an increased surface resistance due to trapped flux.

The highest quality factor was reached for the case of 1Ax: the Q-factor increases slightly at low fields and reaches 1.3×10^{11} at 16 MV/m. The 3Ax data set reveals a reduced performance with considerable degradation of Q-factor with the accelerating field, showing the typical slope due to trapped magnetic flux.[9,10] The worst performance for the axial series is found for the 2Ax data set, in which the Q-factor reaches only 5.1×10^{10} at 16 MV/m.

TABLE I. Summary of cooldown parameters and associated measured residual resistances.

Name	Field magnitude (mG)	Field orientation	Start temperature (K)	R_0 @ 16 MV/m (nΩ)
1Ax	10	Axial	300	2.1
2Ax	10	Axial	50	5.3
3Ax	10	Axial	300	2.9
1Ort	10	Orthogonal	300	6.3
2Ort	10	Orthogonal	260	6.1
3Ort	10	Orthogonal	170	7.7
4Ort	10	Orthogonal	25	13.9

The cooldowns of the nOrt (orthogonal) series were performed applying 10 mG orthogonally to the cavity axis. In general, all the curves of the orthogonal series show reduced Q-factors compared to the axial series with the field dependent Q-slopes characteristic of trapped flux. The best performance for the orthogonal series is shown by 2Ort with $Q_0 = 4.3 \times 10^{10}$ at 16 MV/m, while the lowest Q-factor values are found in the 4Ort data series, and in this case the Q-factor is 1.9×10^{10} at 16 MV/m.

The residual resistance at 16 MV/m was calculated for each cases as G/Q_0 ($G = 270\,\Omega$), since, as already mentioned above, the surface resistance at $T < 1.4$ K is dominated by the temperature independent part. Obtained values of residual resistance are reported in Table I and allow comparing the global cavity losses of each series.

Examining the axial and orthogonal data series separately, different cooldowns lead to different residual resistances, as reported previously for the vertical configuration.[1]

We suggest that two useful parameters to describe the dynamics of the cavity cooldown are the thermal gradients $\Delta T_{bot-top}$ and $\Delta T_{mid-top}$. The first one corresponds to the temperature difference between the top and the bottom of the cell at the moment when the bottom reaches T_c. The second one is the temperature difference between the top and the middle position of the cell when the latter passes through the SC transition.

The residual resistance as a function of the thermal gradients $\Delta T_{mid-top}$ and $\Delta T_{bot-top}$ for all data is summarized in Fig. 4. Looking at Fig. 4(a), the residual resistance for the orthogonal series seems to follow a linear trend with $\Delta T_{mid-top}$ thermal gradient. No particular trend is apparent for the axial series. Conversely, the linear trend of the residual resistance as a function of the thermal gradient $\Delta T_{bot-top}$ appears only for the axial series (Fig. 4(b)).

Comparing 2Ort and 3Ort, the same $\Delta T_{bot-top}$ thermal gradients are observed, but lower R_0 value is measured for 3Ort, which may be attributed to a higher $\Delta T_{mid-top}$.

Therefore, the data suggest that both mid-top and bottom-top thermal gradients play an important role in determining the residual losses. One could intuitively expect that cooling details may vary as the SC-NC boundary progresses along the cavity profile, thus thermal gradients at the SC-NC phase front during the whole period of time when the transition front progresses through the cavity matter for efficient flux expulsion.

In order to better understand this, we also investigated the SC-NC interface evolution during the full cooldown. Setting to zero, the time at which the cavity bottom passes through transition, the position of the SC-NC interface can be plotted against the time it takes moving from one thermometer position to another, as shown in Fig. 5.

It is important to emphasize that the slope of the segment connecting two points corresponds to the average speed (cm/min) of the SC-NC interface along the cell. This should

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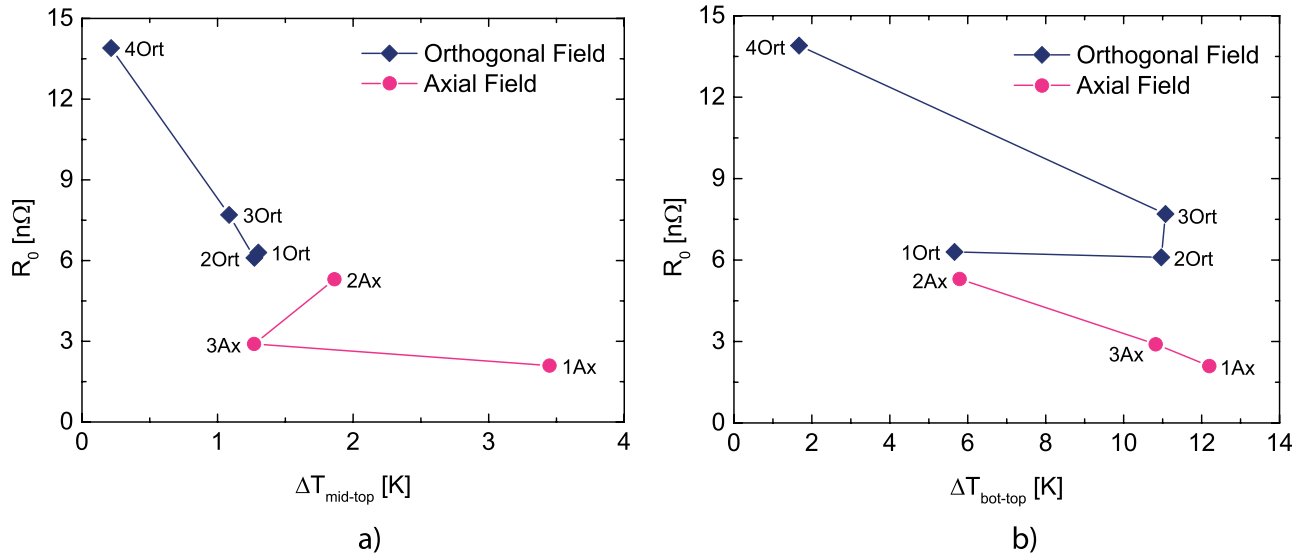

FIG. 4. Residual resistance versus (a) mid-top and (b) bot-top thermal gradients.

not be confused with the cooling speed (K/min), which, on the contrary, does not seem to be a key parameter for flux trapping.

One of the important things that we can conclude from Fig. 5 is that thermal gradients per unit length are indeed not constant throughout the movement of the SC-NC interface, but that they decrease as the boundary moves towards the top. This is perhaps an effect of the cavity starting out warm but then rapidly cooling by conduction. This could potentially cause more flux to get trapped at the top, which in the horizontal cavity case corresponds to the equator, causing greater performance degradation as compared to the vertical cavity orientation.

As an extreme case, for 4Ort, the top of the cavity passes through transition before the mid-top position. Thus, differently from all the other cases, the last point becoming SC is not the very top, and the SC transition scenario cannot anymore be described by a sharp SC-NC interface movement across the cavity, leading to the reduced expulsion efficiency. This leads to more trapped magnetic flux along all the cavity equator region, causing increased residual losses as described in the previous work.[2]

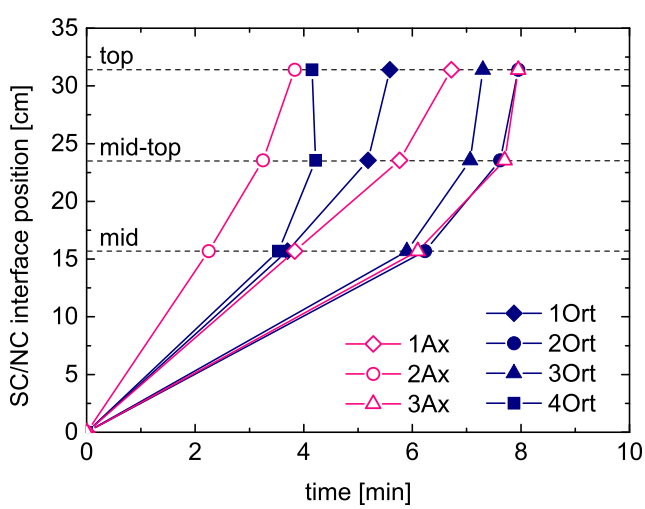

FIG. 5. Evolution of the SC/NC interface during the cooldown.

The magnetic field data acquired during the cooldown are shown in Fig. 6. The jump in the magnetic field magnitude occurs always at the SC transition temperature T_c, with some small variation from one series to another. This is likely due to the imperfect thermal equilibrium between cavity and thermometers, especially for fast cooldowns from high temperatures.

In Fig. 6(a), the ratio between the magnetic field after and before the SC transition, acquired with the vertical fluxgate at the mid position of the cavity, is shown as a function of temperature. This ratio gives an idea of the magnetic field expelled during the SC transition.[2] It is clear that for 4Ort the flux expulsion is less efficient than for the other series and more magnetic field remained trapped in the cavity walls. The same ratio B/B_0 measured by the vertical fluxgate on top of the cavity as a function of temperature is shown in Fig. 6(b) and provides information regarding the magnetic field trapped at that location. These data further corroborate the hypothesis that the magnetic field for 4Ort is homogeneously trapped instead of being preferentially concentrated at the top.

One important point to notice is that the series 3Ax and 2Ort show the same $\Delta T_{bot-top}$ and $\Delta T_{mid-top}$ thermal gradients (Fig. 4), suggesting the same flux trapping efficiency, but exhibit a factor of 2 difference in the measured residual resistance R_0. This discrepancy cannot be explained by the slight difference in the magnetic field just before the transition (12 mG for 2Ort vs. 9 mG for 3Ax) and should likely be attributed to the different orientation of the magnetic field.

In general, systematically higher residual resistances listed in Table I (lower quality factors in Fig. 3) suggest that the magnetic field applied orthogonally to the cavity axis may have a larger effect on deteriorating the cavity performance and increasing the residual losses than the axial magnetic field. This possibility will be addressed in more detail by future studies with the use of temperature mapping, an

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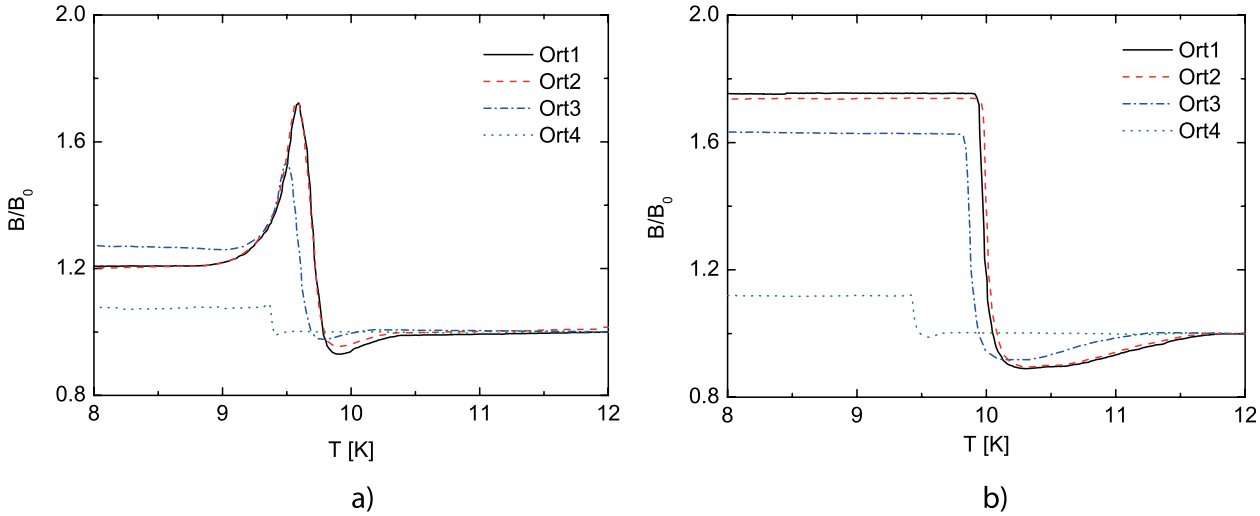

FIG. 6. Ratio between the magnetic field measured after (B) and before (B_0) the SC transition for the orthogonal applied magnetic field series. (a) B/B_0 measured with the fluxgate at the cavity mid position and (b) B/B_0 measured with the fluxgate at the cavity top position.

advanced cavity diagnostic technique to study surface heating.[11]

Data presented in Fig. 7 strongly support the "flux hole" scenario as the orthogonal magnetic field leads to local heating on top of the cavity equator, exactly where we believe the magnetic field should concentrate after the SC transition. This heating is clearly apparent at high fields in the series 1Ort, 2Ort, and 3Ort for the thermometers at the cavity top position. The temperature rise was most prominent in the 1Ort series, where the temperature starts to exceed 1.4 K at about 20 MV/m, and reaches 1.6 K at about 30 MV/m. The warming up is lower for the 2Ort and 3Ort series where it starts from about 27 MV/m reaching just 1.45 K. The absence of heating of 4Ort is likely due to the different cooldown procedure discussed previously, which does not involve the concentration of magnetic flux at the very top of the cavity, but rather flux being homogeneously trapped because of poor thermal gradients at the phase front during cooldown.

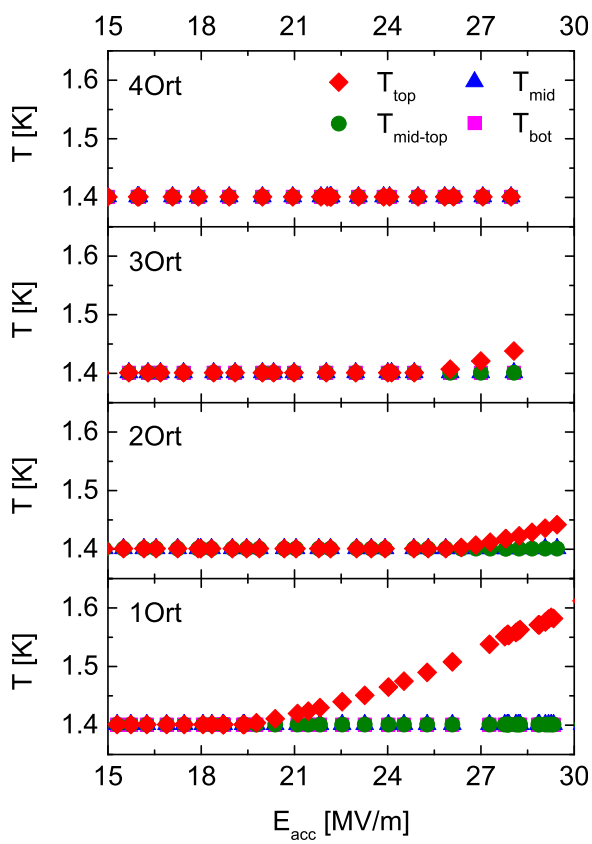

FIG. 7. Cavity top temperature variation versus the accelerating field.

Such a heating we discover on the very top position of the cavity is a newly described phenomenon for SRF cavities, and it can be viewed as a proof of the local dissipation due to concentrated trapped flux pinned on top of the cavity when cooled in horizontal configuration and in the presence of the orthogonal magnetic field.

Interestingly, the same effect was repeatedly observed during the test of the 9-cell nitrogen-doped niobium cavity TB9AES021 dressed with the LCLS-II vessel at the FNAL horizontal test facility (HTS). This cavity was instrumented with flux gates and thermometers inside the helium vessel and, as shown in Fig. 8, the thermometer located on top of cell 1 of the cavity (input coupler side) showed significant

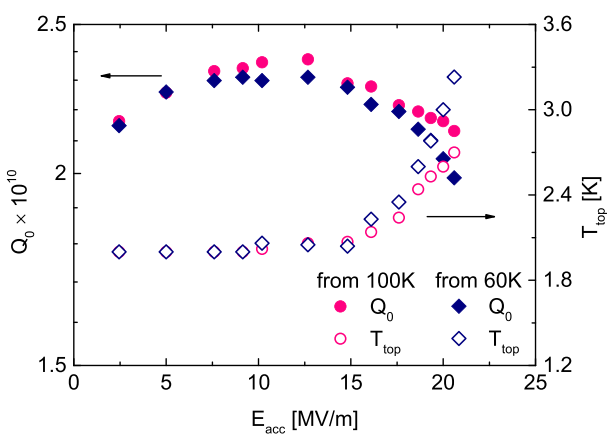

FIG. 8. Q_0 and T_{top} versus accelerating field for HTS measurements after the cooldowns from 100 K and 60 K.

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heating starting at medium field (about 10 MV/m) with the temperature reaching values larger than 3 K at above 20 MV/m. This heating had a strong effect on cavity performance causing Q_0 degradation.

As can be seen from Fig. 8, increasing the starting temperature (cooling with larger thermal gradients from 100 K) pushed the onset of heating and correspondingly improved cavity performance. These nine cell data, together with the previously presented single cell data, suggest a scenario where an orthogonal magnetic field component might be present close to cell 1 during the SC-NC transition causing a "flux hole" hot spot to appear on top of cell 1. Such an effect is an important performance limiting mechanism for superconducting cavities placed in an accelerator. Detailed results of a series of horizontal tests of nine cell nitrogen doped cavities dressed with different styles helium vessels will be presented in future works.

V. CONCLUSIONS

This paper presents the first study of a superconducting single cell elliptical cavity cooled horizontally and immersed in different magnetic field orientations. The first important conclusion is that cooling cavities in the horizontal orientation results in the thermal gradient at the SC-NC phase front, which—differently from the vertical cavity orientation cooling—significantly decreases at the later stages of the cavity transition when the top of the cavity is approached. This reduced thermal gradient at the top leads to more trapped flux in that region, and therefore an increase in RF losses, as it resides in the high surface magnetic field area. Cooldown procedure should therefore be sought in accelerators to ensure that a sufficient thermal gradient is maintained throughout the full cell profile or that the final resting place of flux is not around cavity equator. The second important conclusion is that different field orientations may have a different impact on final performance; in particular, an orthogonal magnetic field may have a larger degrading impact for RF losses than an axial component for the same efficient cooldown procedure. Finally, an important new phenomena of heating at the top of the cavity has been observed in both the single cell and dressed nine cell studies, compatible with the "flux hole" scenario, where vertical field lines become encircled by superconducting regions and highly concentrated at the very top of the cavity. This can be harmful for cavity performance in an accelerator and could lead to both Q-factor and quench degradation.

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