MAGNETIC FLUX EXPULSION IN HORIZONTALLY COOLED CAVITIES *

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Abstract

The cool down details of superconducting accelerating cavities are crucial parameters that have to be optimize in order to obtain very high quality factors. The temperature all around the cavity is monitored during its cool down across the critical temperature, in order to visualize the different dynamics of fast and slow cool-down, which determine considerable difference in terms of magnetic field expulsion and cavity performance. The study is performed placing a single cell 1.3 GHz elliptical cavity perpendicularly to the helium cooling flow, which is representative of how SRF cavities are cooled in an accelerator. Hence, the study involves geometrical considerations regarding the cavity horizontal configuration, underling the different impact of the various magnetic field components on the surface resistance. Experimental data also proves that under established conditions, flux lines are concentrated at the cavity top, in the equatorial region, leading to temperature rise.

INTRODUCTION

During the cool down of a superconducting radio-frequency (SRF) cavity some magnetic flux may be trapped in the cavity walls. This trapped magnetic field causes additional losses, therefore it is important to minimize this contribution for radio-frequency (RF) applications [1].

This is particular significant in case of particle accelerators in continuous wave (CW) that need low dissipated power (high Q-factors) in order to minimize the cryogenic cost during the operation [2].

The trapped flux contribution can be minimized by maintaining large thermal gradient along the cavity surface [3, 4] during its cool down through the critical temperature (T_c). Fast cool downs guarantee large thermal gradients, especially when the starting temperature is much higher than the critical temperature. Slow cool downs with starting temperature close to T_c promotes instead the magnetic flux to be trapped.

In this paper we studied the cool down details of a cavity placed perpendicularly to the helium cooling flow (horizontal cool down) and for the first time a T-map system was used to map the temperature around the cavity during the cooling.

This study reveals that after a slow cool down the heating is more uniformly distributed around the cavity than after a fast cool down. Also, cooling the cavity with magnetic field component orthogonal to the cavity axis leads to a localized heating on top of the cavity equator.

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EXPERIMENTAL SET-UP

The cavity used for the study presented in this paper is a single cell 1.3 GHz TESLA type nitrogen doped niobium cavity, the same studied in previous works [4, 5].

For this experiment the cavity was instrumented with: two pairs of Helmontz coils orhtogonally placed to each other, four single-axis Bartington Mag-01H cryogenic fluxgate magnetometers and four Cernox thermometers. The thermometers (orange squares in Fig. 1a) were placed on the cavity equator, in the following positions: bottom, mid, mid-top and top. Two fluxgates magnetometers (green rectangles in Fig. 1a) were installed one perpendicular and one parallel to the cavity axis at the top position, while the others were placed with the same directions of the previous ones but at the mid position.

The cavity was also instrumented with a T-map (Fig. 1b), an advanced diagnostic technique which allows to measure and map the temperature all around the cavity [1]. The FNAL T-map system consist on 570 thermometers installed on 36 boards that are assembled around the cavity every 10 degrees each. Every board counts 16 thermometers. In the experiments discuss in this paper the T-map system is used for two different reason: 1) to detect the temperature all around the cavity during the cavity cooling below its critical temperature and 2) to measure the temperature around the cavity during the RF measurement.

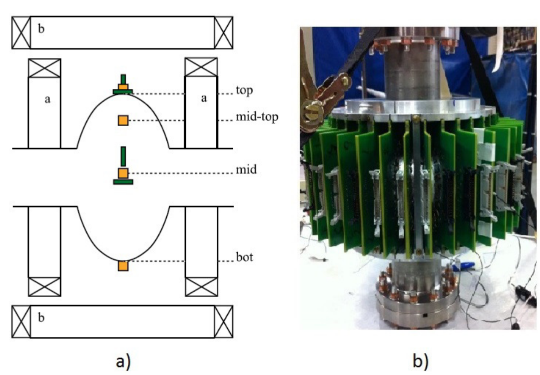

Figure 1: a)Sketch of the cavity instrumentation: four thermometers (orange squares), four fluxgates magnetometers (green rectangles), two pairs of Helmontz coils. b) Picture of the T-map system assembled on the cavity.

The cavity was cooled in horizontal configuration varying the following parameters: magnitude and direction of external magnetic field, speed (fast or slow cooldown) and starting temperature.

HORIZONTAL AND VERTICAL COOLDOWN DYNAMICS

Elliptical SRF cavities are usually tested in vertical cryostats before being dressed and tested into an horizontal cryostat which resemble the cavity during the operation in particle accelerators.

In Fig. 2 a scheme of vertical and horizontal cool down configurations is sketched. In both cases, when a fast cool down is performed, helium cold vapor is injected from the bottom of the cryostat, so the cavity will be cooled following the helium vapor flow, from the bottom to the top.

When the cavity is cooled in vertical configuration the bottom iris is the first region of the cavity becoming SC, followed by the equatorial region and by the upper iris.

In horizontal configuration the bottom of the equator reaches the critical temperature first, then the transition propagates through the iris and the mid region of the equator, and the upper region of the equator will be the last.

Since the equatorial region contributes more to cavity losses than other regions, the major advantage of the vertical configuration compare to the horizontal one is that the equator region becomes superconducting all at the same time, minimizing the probability of trapped flux at the equator.

Analyzing instead the differences in terms of direction of the external magnetic field, when the cavity is exposed to axial magnetic field, it can ideally expel all the magnetic flux during both vertical and horizontal cooling configurations. Perhaps this is not valid anymore when the magnetic field direction is transverse to the cavity axis.

The equatorial region at the top of the cavity will be indeed the last area becoming superconducting, so the magnetic field concentrated in that normal-conducting region will be completely surrounded by superconducting material and will not be energetically favorable to escape even after the SC transition (Fig. 3).

This region on top of the cavity equator, will constitute a "flux hole" in which the flux will be trapped as a consequence of geometrical effects, independently on the thermal

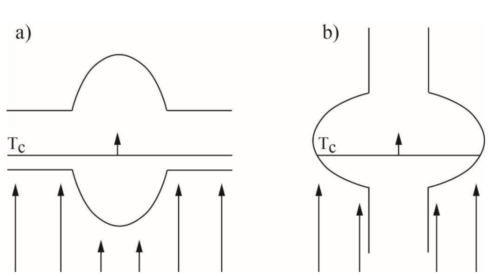

Figure 2: Schematic of the horizontal (a) and vertical (b) cavity cool down.

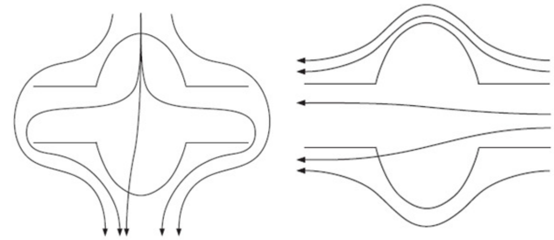

Figure 3: Field redistribution in the Meissner state with magnetic field applied a) axially and b) orthogonally.

gradients which drive the flux expulsion during the fast cool down [5].

MAGNETIC FLUX DISTRIBUTION AFTER PERFECT MEISSNER EFFECT

In order to quantify the amount of trapped magnetic field we need to know how the magnetic field arranges outside the cavity in case of perfect Meissner effect, i.e. when total magnetic flux expulsion is reached. When the perfect Meissner effect occurs the magnetic behavior of the superconductor became the same as a perfect diamagnet.

The software COMSOL® was used to simulate the magnetic flux distribution outside the cavity geometry, treating it as a perfect diamagnet. The simulation was performed with both axial (parallel to the cavity axis) an orthogonal (orthogonal to the cavity axis) magnetic field.

The results of the simulations are shown in Fig. 4. When axial magnetic field (along the x-axis) is applied to the cavity, the ratio between the field after (B_{SC}) and before (B_{NC}) the SC transition is about 1.8 at the cavity equator (Fig. 4 (a)). The cylindrical symmetry of the system implies that the magnitude of the field after the SC transition is the same along all the equator.

In case of orthogonal field instead (along the y-axis), the magnetic field distributes differently along the xy plane and the xz plane. The magnetic field at the equator mid position (xz plane) will be now different than the one at the equator

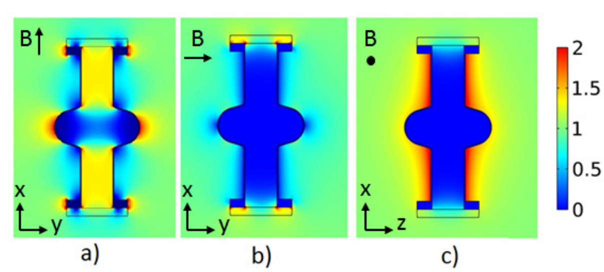

Figure 4: COMSOL simulation of the ratio B_{SC}/B_{NC} after the superconducting transition, treating the SC cavity as a perfect diamagnet. In (a) is simulated the case of axial magnetic field (along the x-axis), in (b) and (c) the case of orthogonal magnetic field (along the y-axis) with the view along the xy-plane and the yz-plane respectively.

ISBN 978-3-95450-178-6

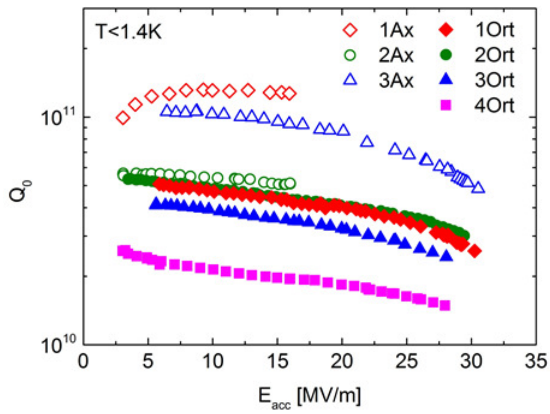

Figure 5: Q_0 versus accelerating field measured at $T < 1.4$ K.

bottom and top positions. The ratio B_{SC}/B_{NC} is around 1.4 at the equatorial mid position (Fig. 4 (c)), and tends to 0 at the bottom and up position of the cavity equator ((Fig. 4 (b)). This means that when the magnetic field is measured at the top or at the bottom of the cavity equator after the SC transition, the ratio B_{SC}/B_{NC} directly estimates how much magnetic flux is trapped in that region.

DATA ANALYSIS

The RF measurements were performed at the Fermilab SRF cavity vertical test facility (VTS) after several cool downs with about 10 mG of magnetic field applied, axially (series named with Ax) or othogonally (series named with Orth) to the cavity axis.

The Q_0 versus accelerating field curves acquired at $T <$ 1.4 K are shown in Fig. 5. The uncertainty of the measurement of Q_0 is about 10% [6].

For curves 1Ax and 2Ax the measurements were stopped at 16 MV/m to avoid quenching the cavity.

Examining the data series axial and orthogonal individually, it appears that different cool downs lead to different residual resistances, as reported previously for the vertical configuration [3]. Comparing instead the results obtained with axial and orthogonal field applied, all the curves of the orthogonal series show reduced performance compared to the axial series.

As mentioned in the previous paragraph, the goodness of the magnetic flux expulsion during the transition can be verified from the ratio between the magnetic field measured before (B_{NC}) and after (B_{SC}) the SC transition.

The magnetic field data acquired during the cool downs are shown in Fig. 6. Looking at the magnetic flux expulsion in different regions of the cavity equator during one specific cool down, it is clear that the expulsion varies from one region to another. This means that different amount of magnetic flux is trapped in different regions of the equator during the horizontal cool down.

The fact that the equator does not reach the SC transition all of a sudden is one of the main disadvantage of the orthogonal cooling. As a consequence is indeed more difficult to fully expel all the magnetic flux comparing with the vertical cooling.

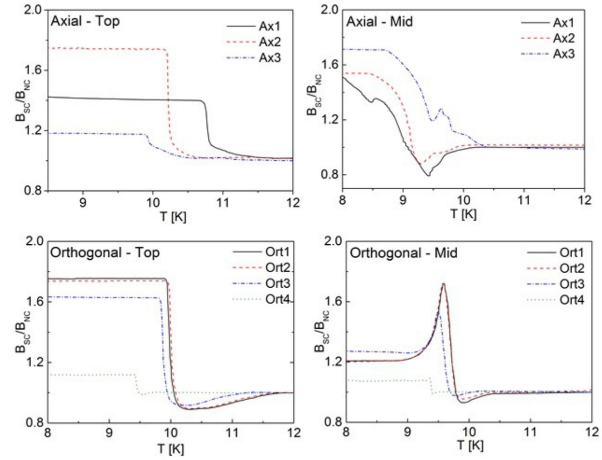

Figure 6: Ratio between the magnetic field after and before the SC transition. The graphs reported this ratio for both the axial and the orthogonal series and for moth the mid and top positions.

Looking specifically at the orthogonal series, it is important to remember that in case of orthogonal field the ratio B_{SC}/B_{NC} measured at the top position should goes to zero in case of perfect flux expulsion (Fig. 4) and should be around 1.4 at the mid position. From Fig. 6 appears clear that all the orthogonal series but 4Orth trapped the field preferentially on top, in agreement with the flux hole scenario.

The temperature as a function of the accelerating field acquired during the RF measurements with the four thermal sensors attached at the bottom, mid, mid-top and top cavity position, are shown in Fig. 7. During the acquisition of

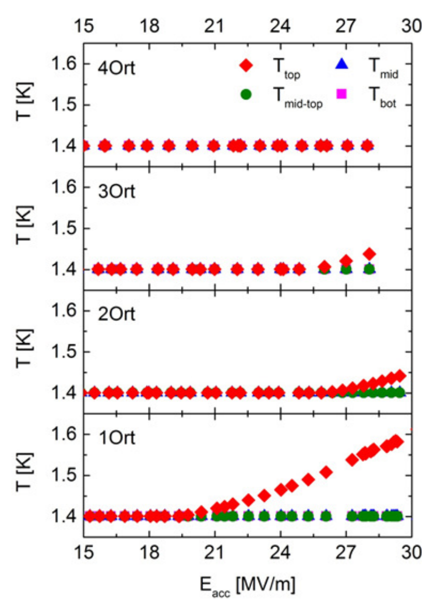

Figure 7: Temperature variation versus the accelerating field.

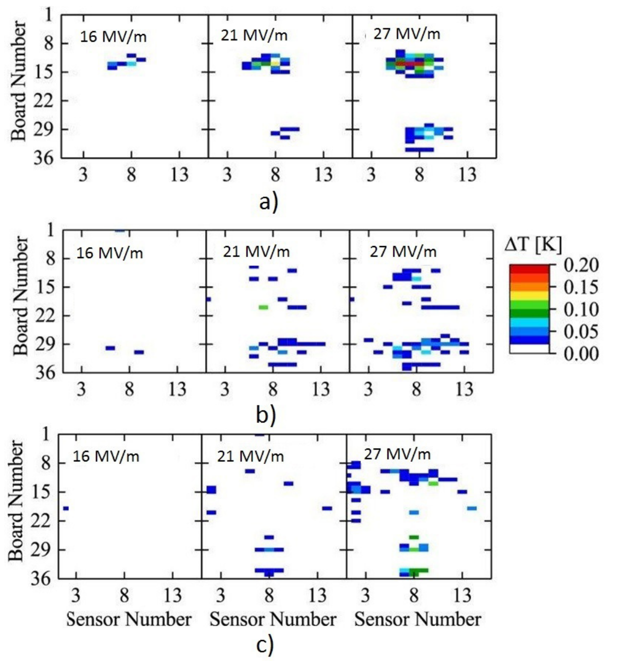

Figure 8: T-map acquired at low, medium and high accelerating field after different cool down with 20 mG of applied magnetic field. a) fast cool down with orthogonal magnetic field, b) slow cool down orthogonal magnetic field, c) fast cool down with axial magnetic field.

the series 1Ort, 2Ort and 3Ort the thermometers at the top position warmed up at high field, as shown in Fig. 7. The absence of heating of 4Ort is in agreement with magnetic field data which indicates that during that specific cool down the orthogonal magnetic field was not preferentially trapped on top.

The peculiarity of this series is that the cool down was not fast enough to cool the cavity from the bottom to the top as in all other cases. In this case indeed the mid-top position reached T_c before the top [5]. Therefore the magnetic field was probably trapped more uniformly on the cavity walls, without being concentrated on top. This data series show also lower Q-factor values than all the others, in agreement with a scenario in which more magnetic flux is trapped in the cavity.

In order to further verify this phenomenon, some measurements with T-map were acquired. The results are summarized in Fig. 8. Here the T-map acquired after some cool down with 20 mG of applied magnetic field, orthogonal or axial to the cavity axis are reported. Also in this case a temperature rising on top of the cavity (board 16, sensor number 8) was found only after fast cool down with orthogonal magnetic field applied (Fig. 8 a). The temperature rising was visible even at low field (16 MV/m), and become prominent at high field.

In addition

During these series of measurements some multipacting appears around 20 MV/m, and this is probably the reason for the heating at the bottom of the cavity (board 31, sensor number 9) at medium and high fields.

MAGNETIC FLUX EXPULSION: SLOW VERSUS FAST COOLDOWN

In order to clarify the difference between the dynamics of slow and fast cool down, the T-map system was used to detect the temperature all around the cavity during both types of cooling. The T-maps acquired during the fast (a) and the slow (b) cool downs are reported in Fig. 9.

The four T-maps showed for each cool down are representative of the beginning, the evolution and the end of the cavity cooling through the SC transition. In order to emphasize the interface between the normal-conducting and the superconducting phases, for temperatures below $T_c = 9.2$ K the map color is white, representing the superconducting (SC) phase.

During the fast cool down the interface between the normal-conducting and the superconducting phases appears sharp: the transition starts from the bottom of the cavity and propagates sharply through the top. At the end of the cooling the interface becomes broader and some islands of normal-conducting phase appears at the top.

This sharp interface is maintained during almost all the fast cool down by the large thermal gradient at the NC-SC interface.

The slow cool down dynamic appears from the beginning very different than the fast cool down. Superconducting phases start to nucleate randomly on the cavity surface. Once their temperature is stabilized below T_c, they starts to growth more and more till, at the end of the cooling, several NC islands surrounded by SC phase are randomly distributed on the cavity surface.

These macroscopic islands of NC phase might be responsible of the complete magnetic flux trapping observed during the slow cool down. The magnetic field which is free to penetrate into these NC regions is not allowed to escape from the material even after the superconducting transition is complete because, being surrounded by SC phases, the field does not have any energetically favorable path to follow during the expulsion.

Since these NC regions are randomly distributed all over the surface, the magnetic field is expected to be trapped rather uniformly on the cavity surface during the slow cool down.

CONCLUSIONS

In this paper the differences between fast and slow cool down were for the first time visualized by means of a T-map system. From the RF measurement and the T-maps acquired, it is possible to conclude that in the case of slow cool down the presence of NC region surrounded by SC phases during the transition helps to uniformly trap the magnetic flux all over the cavity surface, increasing the cavity losses.

The sharp NC-SC transition during the fast cool down allow to maintain large thermal gradient at the interface and

ISBN 978-3-95450-178-6

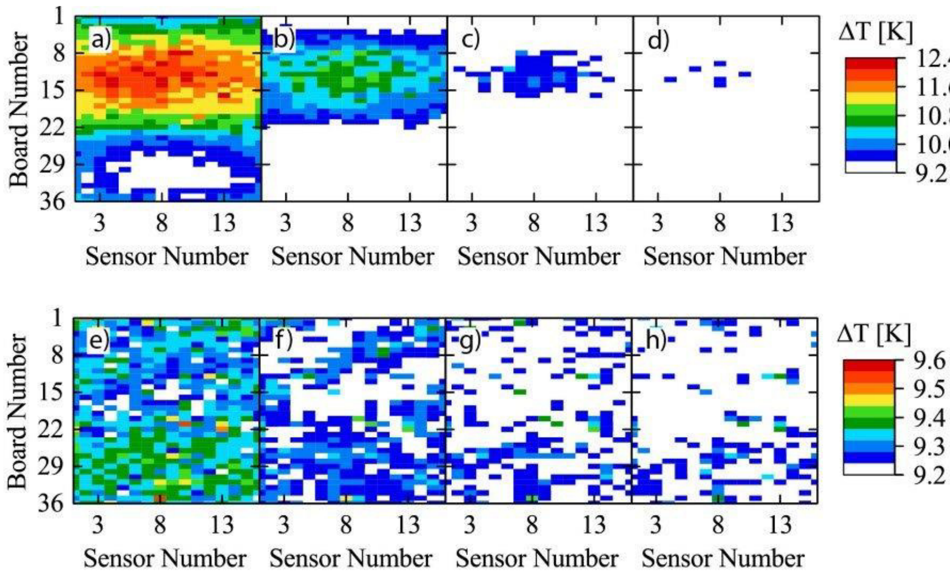

Figure 9: T-maps acquired during the fast (a,b,c,d) and the slow cool down (e,f,g,h).

help the magnetic field expulsion. This transition occurs from the bottom to the top of the cavity implying that the last point becoming superconducting is the top of the cavity equator. When the cavity is cooled fast and exposed to orthogonal magnetic field component, the field remain trapped in this region just because of geometry of the system. It is therefore important to consider that in case of large external magnetic field, the trapped flux might increase considerably the cavity losses and decreasing the Q-factor.

Considering all the different aspects we can conclude that the fast cool down is better than the slow cool down also when the cavity is horizontally cooled. Slow cool down always trap more than fast cool down.

When the cavity is horizontally cooled the magnetic flux expulsion is facilitated during the fast cool down but, comparing to the vertical cool down, it is more difficult to fully expel the external magnetic field.

The main limitation of the horizontal cool down is indeed that thermal gradient at the NC-SC interface at the cavity equator varies during the cooling, increasing the probability of trapping flux.

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