SIMULATION OF GEOMETRY DEPENDENT FLUX TRAPPING

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Abstract

Trapping or expulsion of ambient magnetic field has become an important factor in the performance of superconducting cavities with very high Q. As experimental data is limited, we set up a numerical field calculation model to study this effect in more details.

We will present the results of simulations describing a cavity transitioning from a normal conducting to a superconducting state in a constant magnetic field in either a longitudinal or transverse direction. This will show that the orientation of the field during cool down can affect the amount of magnetic field being vulnerable for trapping.

Our simulations will also explain, how flux trapping, partial trapping or Meissner expulsion will change the field configuration, the field remaining at the RF surface of the cavity and the field strength measureable on the outside of the cavity where usually the fluxgate magnetometers are placed.

INTRODUCTION

Residual magnetic fields, and in particular flux pinning can be a major contribution to surface resistivity of a superconducting cavity [1]. In an a-priory approach there is an easy explanation to this: Since during the transition, magnetic field cannot pass through an already superconducting region, it is possible for magnetic flux to not be expelled and eventually become trapped inside a shrinking normal conducting area in the superconductor.

As this is a purely geometric effect, the orientation of a magnetic field is suspected to be of relevance [2]. In this paper, we investigated this behavior for an ideal as well as an non-ideal superconductor under certain field configurations.

CAVITY TRANSITION SIMULATION

In order to study the configuration of the field during the cavity transition, CST® EM-Studio® was used to gain qualitative features of the transition. For this simulation, the transition of a superconducting cavity is taken to be a sharp normal-conducting/super-conducting boundary moving up cavity corresponding to a moving thermal gradient. This transition was simulated by separating a single cavity into two parts along a plane perpendicular to longitudinal axis of the cavity at varying heights (see Fig. 1). The bottom half was assumed to be a perfect electric conductor (to simulate the superconducting part) and the top half was made into a normal conducting material with no magnetic properties

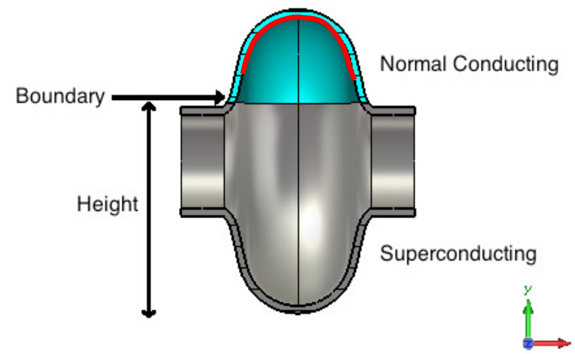

Figure 1: (a) Model of the cavity used for the cavity transition simulations. The red curve depicts the curve on which the magnitude of field will be given in the figures below.

(ensured by applying a μ-value of 1). This assumption would represent an ideal superconductor with perfect Meissner flux expulsion. A constant magnetic field with a magnitude of 1.26 μT was applied in either the longitudinal (here after referred to as +X) direction or the transverse (here after referred to as +Y) direction (see Fig. 1a).

The cavity itself had an equator diameter of 206.6 mm and wall thickness of 5 mm. Simulations were done with the normal conducting superconducting boundary at heights 28.3 mm, 103.3 mm, 143.3 mm, 178.3 mm, 188.3 mm, and 198.3 mm, measured from the bottom of the cell. At each of these heights, the field magnitude was then calculated along the inner surface at the top of cavity in order to get an understanding about the field level that are subject to trapping (see Fig. 1b).

All simulations were afterwards repeated with the bottom half portion having a μ-value of .05. This was found to correspond to a non-ideal superconductor that traps around half the magnetic field and expelled the other half.

TRANSITION SIMULATION RESULTS

Perfectly Superconducting Bottom Portion

The field configuration (see Fig. 2 and Fig. 3), and the value of the magnetic field along the inner surface of the top of the cavity (see Fig 4. and Fig. 5) are shown for both initial fields in the +X and +Y directions where the bottom portion was assumed to be a perfect superconductor with complete flux expulsion. In examining the results, the focus was primarily on two features:

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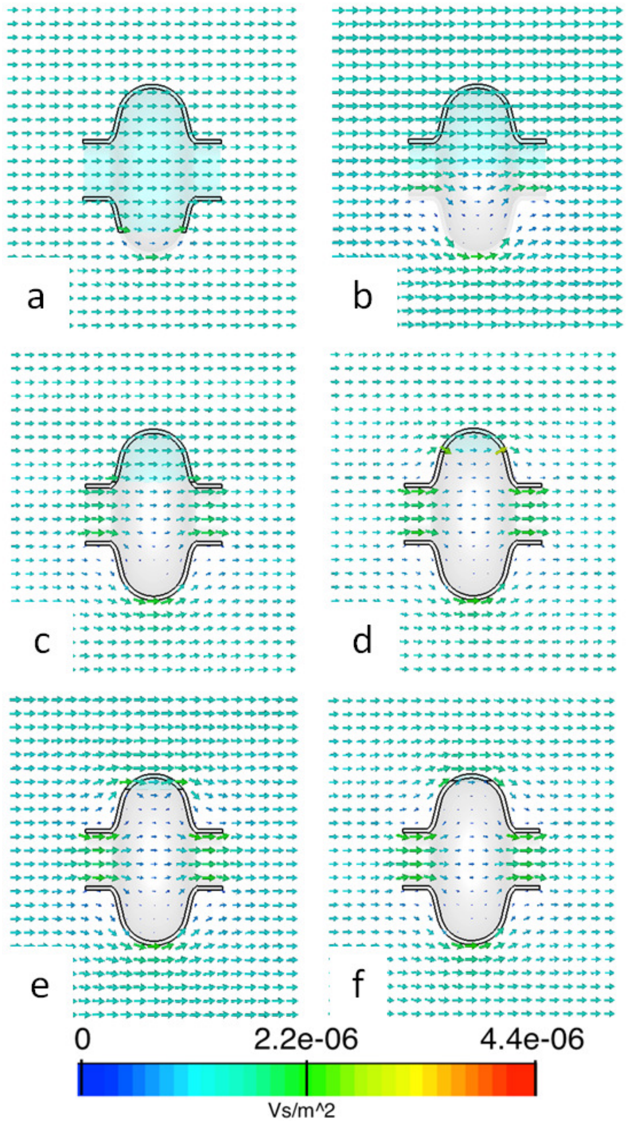

Figure 2: The field configurations at heights of (a) 28.3 mm, (b) 103.3 mm, (c) 143.3 mm, (d) 178.3 mm, (e) 188.3 mm, and (f) 198.3 mm with the initial magnetic field in the +X direction, with the bottom portion as a perfect electric conductor.

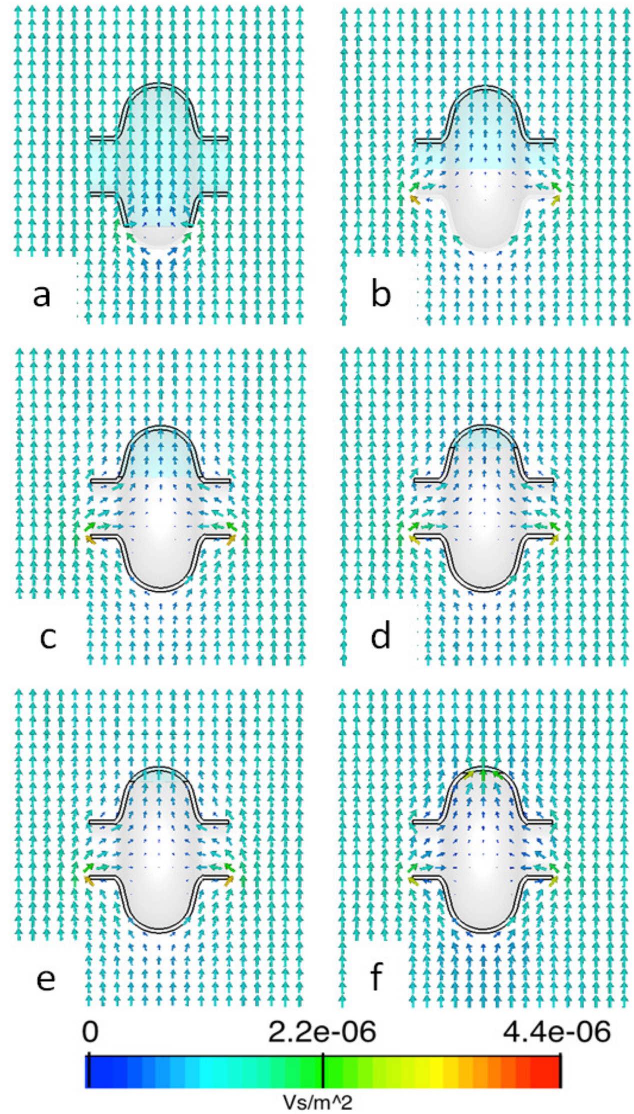

Figure 3: The field configurations at heights of (a) 28.3 mm, (b) 103.3 mm, (c) 143.3mm, (d) 178.3mm, (e) 188.3 mm, and (f) 198.3 mm with the initial magnetic field in the +Y direction, with the bottom portion as a perfect electric conductor.

how does the field enhance as it gets progressively expelled for the lower portion of the cell being already superconducting and how is this field enhancement related to the orientation of the field with respect to the transition line?

Comparing the field lines from Fig. 2 with Fig. 3 one clearly sees the asymmetry that exist when the field is radial, compared to the rather symmetric situation with the longitudinal field. For the +X direction initial magnetic field situations, the magnetic fields in the interior of the cavity are either located around the normal-conducting/superconducting boundary, or passing through the center of the cavity. Because the field in the center of the cavity is not interesting any normal conducting region of the cavity, it shall be ignored, focusing instead on the field around the boundary. As the normal conducting /superconducting boundary rises in the cavity, the magnetic field near the boundary is seen to occupy less of the interior of the cavity. In addition, since the top of the cavity remains normal conducing, there is a path for flux expulsion. This demonstrates an efficient method of flux expulsion for the cavity as it becomes superconducting.

For the +Y field situations, the magnetic field is not localized to the normal-conducting/superconducting boundary. At the 178.3 mm, 188.3 mm, and 198.3 mm heights, there is magnetic field passing through the sides of the cavity up through the normal-conducting/superconducting boundary. In this configuration, there is a superconducting ring surrounds magnetic field inside the cavity, preventing flux expulsion for geometrical reasons. It confirms that a radial field is likely to be trapped in the upper portion of the equator.

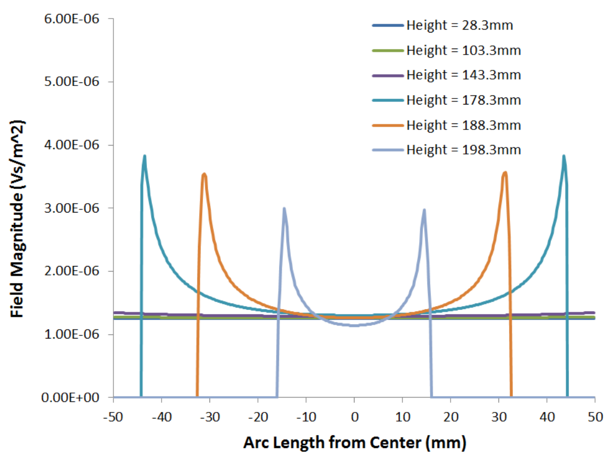

Figure 4: Measurement of field along the upper inner edge of the cavity with the initial magnetic field in the +X direction, with the bottom portion as a perfect electric conductor. Note: Height = 28.3 mm, 103.3 mm, and, 143.3 mm are all located on top of each other.

Figure 4 and Fig. 5 give field values along the RF surface of the upper half of the cell, indicating an enhancement of the radial field. These plots also show peaking fields at 178.3 mm, 188.3 mm, and 198.3 mm heights in both (+X and +Y) situations, with enhancement factors of up to 5. These enhancement peaks lay directly at the location of the normal to superconducting boundary line.

In these simulations, the +X magnetic field simulations have higher field enhancement peaks relative to the non-enhanced field than +Y the magnetic field simulations. However, for the +Y magnetic field simulations, the field enhancements become more pronounced relative to the non-enhanced field as the height increases, while the field enhancements of the +X magnetic field simulations diminish slightly. More importantly, the high enhancement values in both the +X initial magnetic field

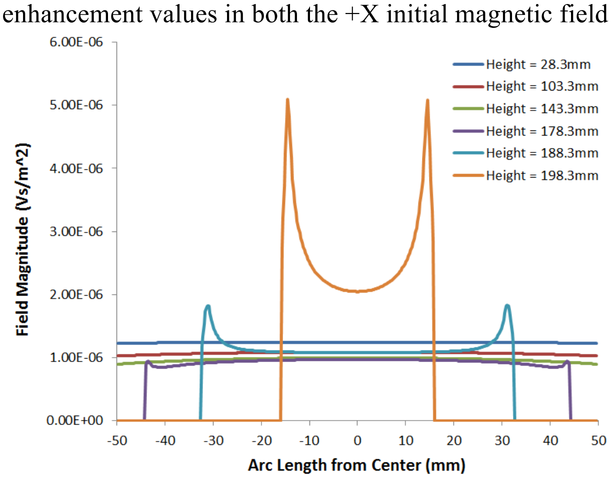

Figure 5: Measurement of field along the upper inner edge of the cavity with the initial magnetic field in the +Y direction, with the bottom portion as a perfect electric conductor.

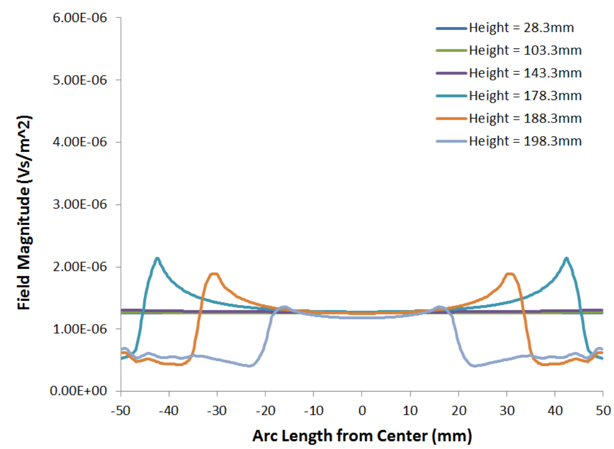

Figure 6: Measurement of field along the upper inner edge of the cavity with the initial magnetic field in the +X direction, with the bottom portion having a μ-value of .05. Note: Height = 28.3 mm, 103.3 mm, and, 143.3 mm are all located on top of each other.

and +Y initial magnetic field situations means that there will be strong magnetic fields present at the normal-conducting/superconducting boundary, as it reaches the top of the cavity.

So far, the results gained correspond to a perfect superconductor, which due to the Meissner effect would only trap flux for geometric reasons. In this scenario, a longitudinal magnetic field would be almost completely expelled, while a radial field would eventually become trapped in the upper equator.

Flux Trapping in the Bottom Portion

In the simulations reported below we now give up on the assumption of a perfect superconductor. Instead, we assume that due to surface defects and/ or impurities in the material, magnetic flux could be partially trapped.

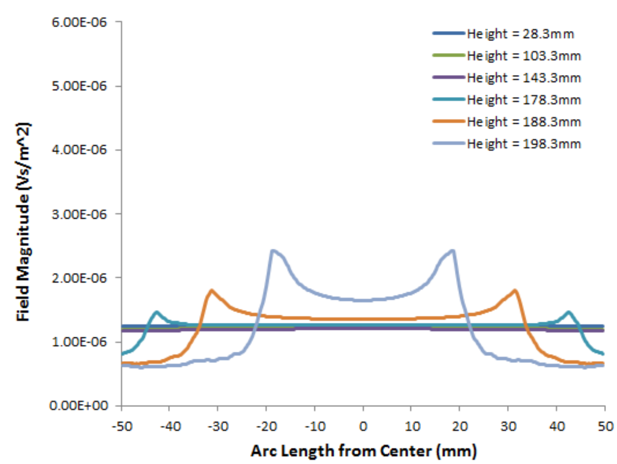

Figure 7: Measurement of field along the upper inner edge of the cavity with the initial magnetic field in the +Y direction, with the bottom portion having a μ-value of .05. Note: Height = 28.3 mm, 103.3 mm, and, 143.3 mm are all located on top of each other.

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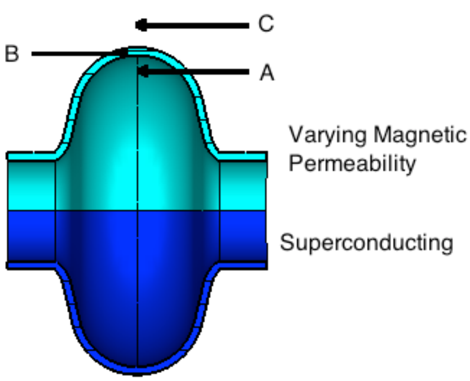
Therefore, we allotted a relative permeability of μ=0.05 to the material representing the superconductor, which to based on our calculations corresponds to roughly 50 % of flux trapping.

Under this conditions, similar results (given in Fig. 6 and Fig. 7) were found, but with less sharp field enhancements. Again, radial fields give higher enhancement factors (compared to longitudinal fields) but the enhancement is reduced by a factor of two compared to the Meissner superconductor.

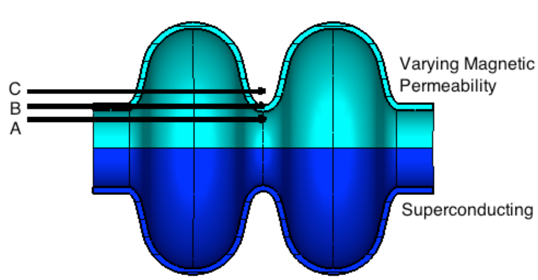
DETERMENING THE AMOUNT OF FLUX TRAPPED

As we have seen in the section above, the amount of magnetic field that exists at the RF layer of a cavity strongly depends on two factors, one being the filed orientation (relative to the superconducting transition line), the other being the amount of flux that actually is trapped as the material becomes superconducting.

The later leads to a recursive problem: as a result of the flux trapping, the field enhancement is changing, which as a result determines the amplitude of the field which is going to be partially trapped. This leads in our understanding to a lack in interpreting experimental data which usually records the change in the magnetic field measured on the outside of the cavity. Stating that the change in the field amplitude is a direct measure for the amount of flux trapped is to our understanding not fully correct.



(a)



(b)

Figure 8: Model of the cavity used for the trapped flux equator (a) and iris (b) simulations and iris (b). A is inside the cavity, B is the RF layer and C outside the cavity where a fluxgate might be piking up fields.

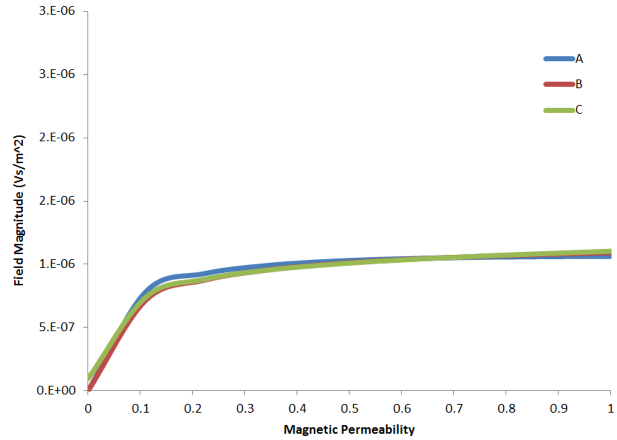


Figure 9: Magnetic Field measured near the cavity wall of the equator with varying magnetic permeability with the initial field in the +Y direction. Note: A, B, and C are on top of each other.

Therefore, we simulated the magnetic fields under the condition that the cavity has a bottom half being perfectly superconducting (which corresponds to the findings described above, namely that flux trapping most likely occurs in the upper half) and a top half that has an adjustable amount fraction of flux trapping- which is provided by different values of the. As before, a +X and +Y initial magnetic fields was applied to the cavities. The field strength was then measured along the equator, inside the cavity (A), inside the cavity wall (B), and outside the cavity (C) (see Fig. 8a).

For the measurements along the equator with the +Y initial magnetic field, the values at A, B, and C are all similar (see Fig. 9). At all three of these points, the magnitude of the magnetic field decrease as the magnetic permeability decreases. This means a radial magnetic field, measured at C gives the exact flux density at the RF layer independent from the amount of flux trapping.

For the measurements along the equator with the +X initial magnetic field, the values at A, B, and C all show

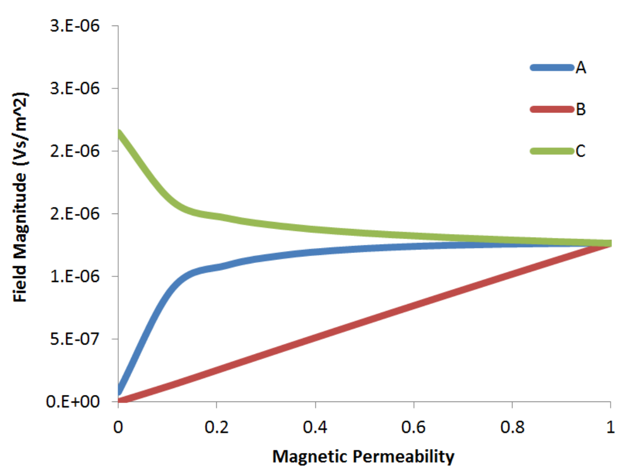


Figure 10: Magnetic Field measured near the cavity wall of the equator with varying magnetic permeability with the initial field in the +X direction.

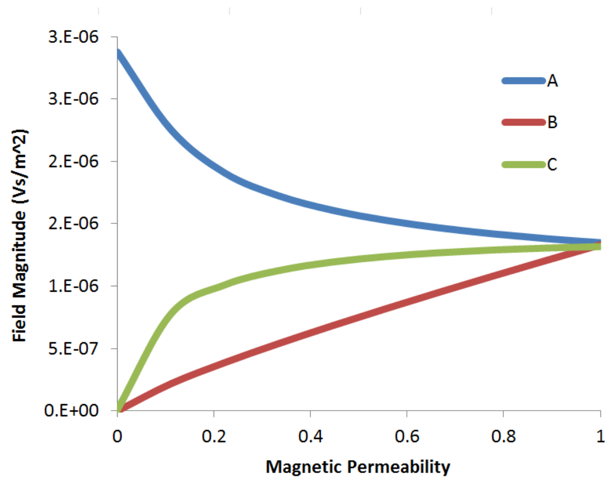


Figure 11: Magnetic Field measured near the cavity wall at the iris with varying magnetic permeability with the initial field in the +X direction.

differences (see Fig. 10). At A, the magnetic field behaves as it did in the +Y initial magnetic field situation. At B the magnetic field also decreases, but does so linearly. Most importantly, at C, the field increases as the magnetic permeability decreases. In terms of understanding the field at the RF layer, a longitudinal field behaves different from a radial field. The less flux trapping occurs in the superconductor, the smaller gets the field at the RF layer, which meanwhile is associated with a strong increase in fields measurable on the outside at the equator.

For the iris results are shown in Fig. 11 (+X) and Fig. 12 (+Y). While for the radial field the situation is similar, longitudinal fields seems to behave differently. In particular, there is more field found inside the cavity at lower permeability values with the field in the +X direction, implying there is less magnetic field penetrating the wall.

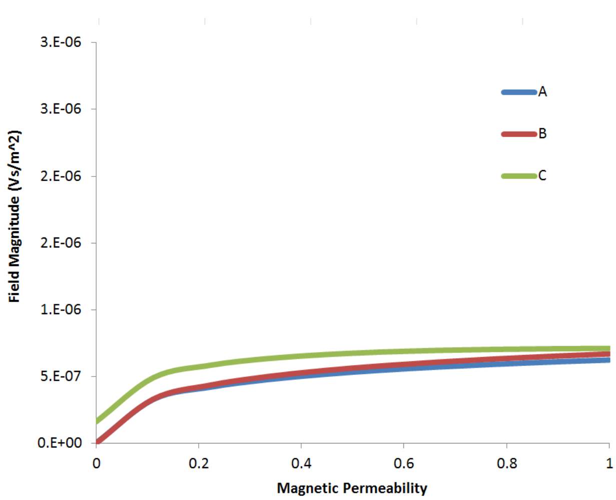


Figure 12: Magnetic Field measured near the cavity wall at the iris with varying magnetic permeability with the initial field in the +Y direction. Note: A and B are on top of each other.

CONCLUSION

The simulations that have been discussed so far show that there exists a difference between cavity transitions with a longitudinal and transverse magnetic field. In particular, there appears to be a greater possibility of flux trapping with a traverse magnetic field than with a longitudinal, as shown by the field enhancements and the lack of efficient flux expulsion. Due to this, cavities cooled in the presence of transverse magnetic fields will likely have higher surface resistances, cause by flux pinning.

We also calculated, how experimental data from fluxgates measured on the outside of the cavity, allows to estimate the amount of flux being trapped. Depending on the location and the field orientation, flux trapping can result in a slightly higher or lower reading after transition. A careful analysis of data therefore has to distinguish fundamentally different scenarios as described above.

OUTLOOK

As we have show, flux trapping is a highly non-uniform process. In the next step, we will use the field enhancement values as calculated and estimate the impact on the residual resistance of the cavity. Our hope is to being able predicting the additional resistance as a result of a given magnetic field which exist during cool-down.

ACKNOWLEDGMENTS

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