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MAGNETIC FLUX EXPULSION IN TRIUMF'S MULTI-MODE COAXIAL CAVITIES

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Abstract

The external magnetic flux sensitivity of SRF cavities is an important characteristic of SRF accelerator design. Previous studies have shown that n-doped elliptical cavities are very sensitive to external fields, resulting in stringent requirements for residual field and cavity cool-down speed. Few such studies have been done on HWRs and QWRs. The impact of applied field direction and cool-down speed of flux expulsion for these cavities is poorly understood. This study explores the effect of these cool-down characteristics on TRIUMF's QWR using COMSOL ® simulations and experimental results.

This study seeks to maximize the flux expulsion that occurs when a cavity is cooled down through its superconducting temperature. Flux expulsion is affected by the cool-down speed, temperature gradient, and orientation of the cavity relative to an applied magnetic field. It was found that for a vertically applied magnetic field the cool-down speed and temperature gradient did not have a significant effect on flux expulsion. Contrarily, a horizontal magnetic field can be nearly completely expelled by a fast, high temperature gradient cool-down.

INTRODUCTION

The effects of cool-down speeds [1], temperature gradients [2, 3], and applied magnetic field orientations [4] on flux expulsion have been studied for 1.3 GHz elliptical cavities. It was found that for elliptical cavities fast cool-downs and large temperature gradients lead to more flux expulsion. A previous study on the effects of magnetic sensitivity on field orientation for a quarter wave resonator (QWR) cavity was performed by Lounguevergne and Miyazaki [5]. The influence of cool-down speeds and temperature gradients have not been previously evaluated for TEM mode coaxial cavities.

Two possible interpretations of the role of temperature gradient and cool-down speed have been proposed by Romanenko [1]. One is that in a fast cool-down, the superconducting phase front efficiently sweeps out magnetic flux, whereas as slow cool-down leads to normal conducting "islands" in the cavity and it is not energetically favorable for the flux in these islands to be expelled. Another hypothesis is that the superconducting phase front created by fast cool-downs with large temperature gradients is able to de-pin magnetic flux vortices. This paper examines the impact of cavity cool-down speed, temperature gradient, and magnetic field orientation on flux trapping in a QWR as informed by COMSOL simulations.

METHODOLOGY

The cavity used in this study is the TRIUMF QWR [6]. A unique feature of this cavity is that it lacks beam ports because it is intended for use as a test cavity [7]. This QWR is made entirely of niobium. There are four ports on one end of the QWR which can be seen in Fig. 1. These ports are used for vacuum connections, rinsing, and mounting to the pick up antenna and variable RF coupler. RF is coupled to the electric field. The frequencies of interest for the TEM resonant modes of the QWR are 217 and 648 MHz. The field distribution for these modes is shown in Fig. 2.

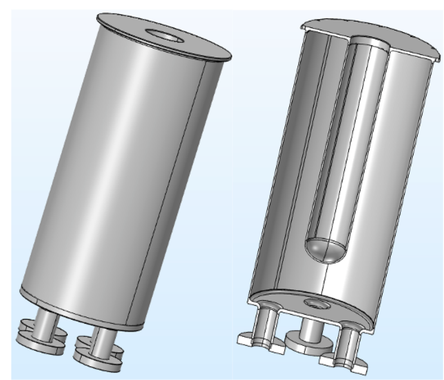

Figure 1: 3-Dimensional computer model of the QWR: Full cavity (left) and cut out (right). This model was generated using COMSOL Multiphysics ®.

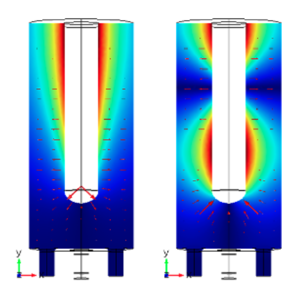

Figure 2: Field distributions for the QWR. Image courtesy of Ref. [6].

In order to perform experiments, the QWR is lowered into a cryostat along with Helmholtz coils, fluxgate probes,

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and temperature sensors. The magnetic fields applied to the cavity are controlled with three pairs of Helmholtz coils which surround the cavity and are pictured in Fig. 3. These fields can be controlled independently for all three spatial dimensions by changing the currents in each pair of Helmholtz coils [8]. The magnetic fields near the cavity are measured using commercially available Bartington Single Axis Fluxgate Magnetometers [9], also referred to as fluxgate probes. Three fluxgate probes are placed in the center of the inner conductor, and one is placed on the end plate, as shown in Fig. 4. The fluxgate probes independently measure the magnetic fields in all three spatial dimensions. The cavity temperature is measured using two Cernox™ sensors located at the top and bottom of the cavity.

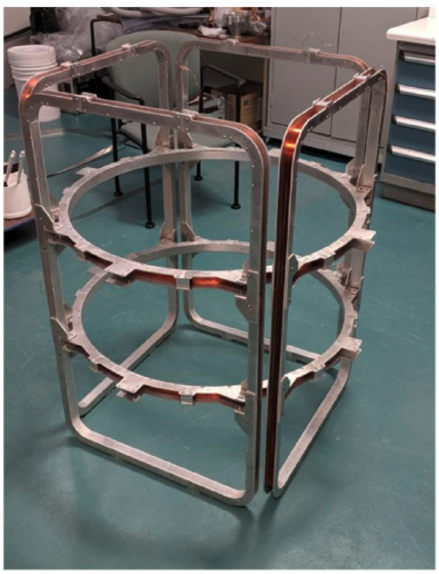

Figure 3: Photo of Helmholtz coils.

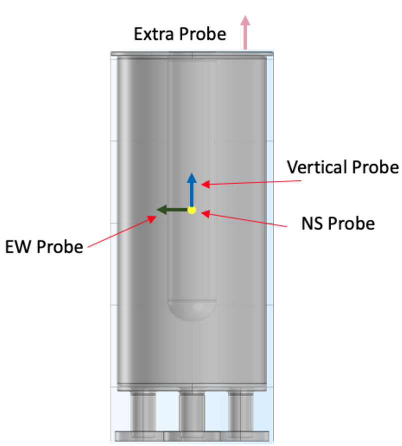

Figure 4: Locations and directions of fluxgate probes.

The cavity is cooled down to superconducting temperatures by pumping liquid helium into the cryostat. Cooling the cavity down from room temperature takes roughly one hour. During the cool-down the fluxgate probe and temperature readings are monitored in real-time using a Labview program that also controls the currents in the Helmholtz coils.

The parameters of interest for this study are the cool-down speed, spatial temperature gradient, and applied magnetic field direction. The cavity was cooled down through its critical temperature at faster or slower rates by increasing or decreasing the flow rate of liquid helium into the cryostat. The baseline cool-down used for comparisons in this experiment is called a zero field cooled (ZFC) test. ZFC means that the cavity was cooled down at a fast speed with the background magnetic field as close to zero as can reasonably be achieved. This is done by using the Helmholtz coils to compensate for background fields such as the Earth's ambient magnetic field.

During field cooled tests the cavity is cooled down through its critical temperature with external magnetic fields of 40 μT applied in either the vertical or horizontal direction using the Helmholtz coils. For the vertical and horizontal directions, the magnetic field lines are parallel or perpendicular to the cavity's axis, respectively, as shown in Fig. 5. These cool-downs are performed with either a fast or slow cooling rate. The fast cool-downs always have a high temperature gradient, and vice versa. The results of these cool-downs show how well or how poorly the cavity expels magnetic flux with different cool-down speeds, temperature gradients, and field orientations.

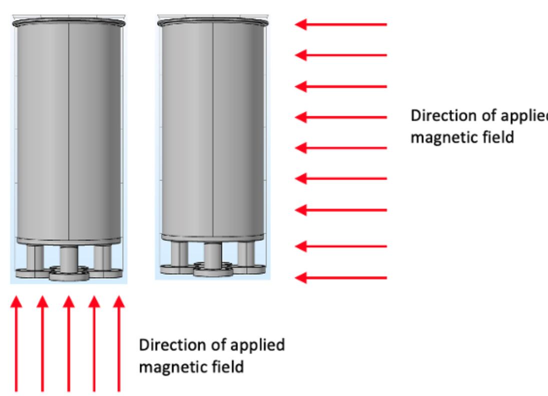

Figure 5: Arrows showing the directions of the horizontal (right) and vertical (left) applied magnetic fields relative to the cavity.

Once the cavity reaches a temperature of 4.2 K, fixed temperature measurements of Q_0 as a function of B_p are done up to the quench field in continuous wave. The surface resistance can then be computed using the equation $R_s = G/Q_0$. However, this surface resistance is not accurate for the TRIUMF QWR due to the field dependence of R_s and a non-uniform magnetic field distribution. To account for this, a method was developed by Delayen [10] to extract the field dependence of R_s. This method has been implemented for the surface resistances reported in this paper.

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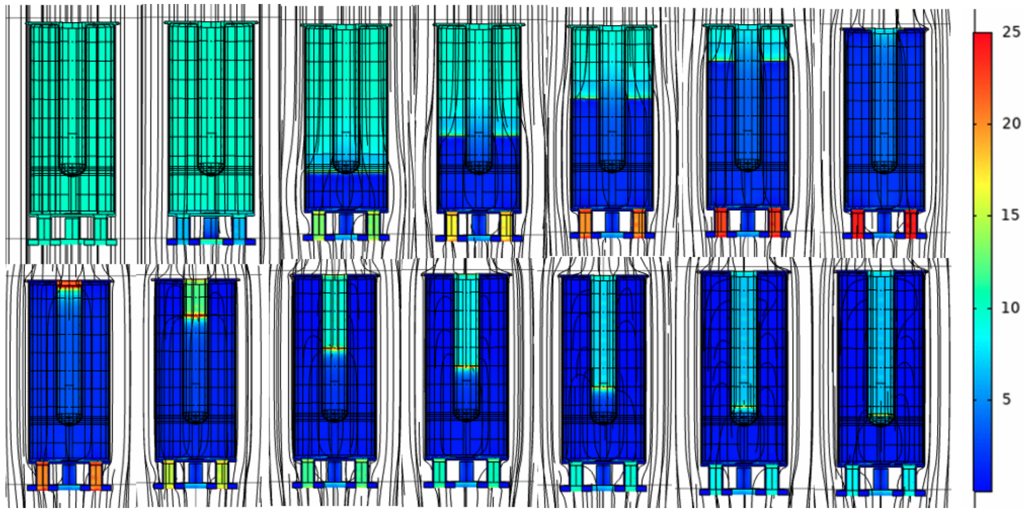

Figure 6: Time dependent COMSOL ® simulation of 10 µT applied to the QWR in the vertical direction. The heat map on the right shows the magnetic flux in µT.

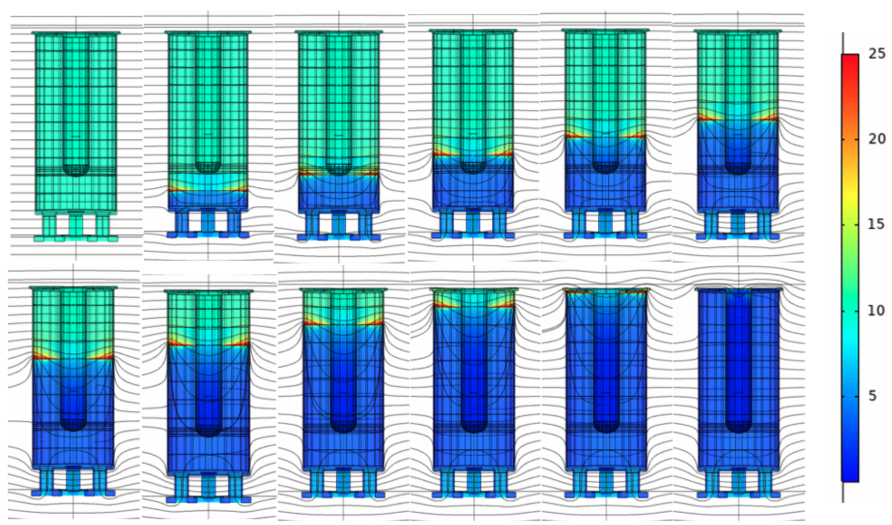

Figure 7: Time dependent COMSOL ® simulation of 10 µT applied to the QWR in the horizontal direction. The heat map on the right shows the magnetic flux in µT.

COMSOL CAVITY SIMULATIONS

COMSOL simulations were performed on the QWR in order to better understand the movement of flux during the superconducting transition. A three dimensional model of the QWR was made in COMSOL to the same geometrical dimensions as the actual cavity. To simulate a superconducting state, the cavity material is assigned a relative permeability of nearly zero. Time dependent simulations aim to replicate the movement of a superconducting front that moves continuously along the cavity surface as it is cooled down.

The time dependent COMSOL simulations are done by changing the relative permeability of the cavity sequentially given a prescribed cooling time evolution. To accomplish this, the cavity is sliced into horizontal sections which are changed from non-magnetic to diamagnetic material sequentially in the presence of an applied magnetic field. Simulations of the QWR cooling down with a vertical and horizontal applied field are shown in Figs. 6 and 7, respectively. In the simulations the outer conductor is cooled from bottom to top, followed by the inner conductor which is cooled from top to bottom, which is the same cool-down sequence undergone by the real QWR.

For the vertical simulation, the superconducting phase front can be seen moving up the outer conductor on the top row of Fig. 6, and then down the inner conductor on the bottom row. Near the end of this simulation some flux remains trapped in the tip of the inner conductor.

In contrast, for the horizontal simulation the flux gets pushed up the outer conductor, but not down the inner conductor. The image at the bottom right of Fig. 7 is what COMSOL shows for the entire cooling of the inner conductor, thus no flux is moved once the outer conductor is superconducting regardless of the state of the inner conduc-

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tor. This is thought to be due to the outer conductor shielding the inner conductor for the horizontal field orientation.

COMSOL simulates a diamagnetic material, which is similar to a perfect superconductor in that it has zero magnetic permeability and magnetic flux cannot penetrate this material. However, real superconductors are imperfect and flux can be trapped in pinning centers or weaknesses in the superconducting topology, which is difficult to simulate.

RESULTS AND DISCUSSION

In this paper, the results of different cool-downs of the QWR are presented. The QWR was cooled down through its superconducting temperature at fast and slow speeds with high and low temperature gradients in the presence of a 40 µT vertical or horizontal applied magnetic field. Numerical characteristics of the cool-down speeds and temperature gradients are summarized in table 1. The magnetic fields in the center of the inner conductor were measured during the cool-downs. For the vertical field cooled case, there was no significant difference in measured flux expulsion for the fast and slow cool-downs. However, for the horizontal field cooled case, the fast cool down led to much more flux expulsion than the slow cool-down.

Table 1: Cool-Down Characteristics

Characteristic	**Vertical**		**Horizontal**	
	Fast	**Slow**	**Fast**	**Slow**
Cool-down time [min:sec]	2:07	3:40	2:09	3:30
Top cool-down speed [mK/min]	6120	219	5200	233
Bottom cool-down speed [mK/min]	6770	250	6680	251
Temperature gradient [K/m]	53	2.2	51	2.2

For the plots in Figs. 8–11, the magnetic fields are represented by dashed lines and plotted on the left vertical axis in µT, while temperatures are represented by solid lines and plotted on the right vertical axis in Kelvin. The horizontal red line marks the critical temperature of niobium, 9.2 K. The black and gray solid line represent the temperatures of the bottom and top of the cavity, respectively.

Measurements of the fluxgate probe and temperature sensor readings for the fast and slow vertical field cool-downs are shown in Figs. 8 and 9, respectively. The blue dashed line labeled Vertical B field corresponds to the vertical magnetic field, and is set at 40 µT before the superconducting transition. Neither cool-down shows significant flux expulsion. It is likely that flux is being trapped in the inner conductor for both cool-downs as shown in the COMSOL simulation in Fig. 6.

For the horizontal field cooled case the fast cool-down results in considerable flux expulsion, as can be seen in Fig. 10. The yellow dashed line labeled NS B field represents

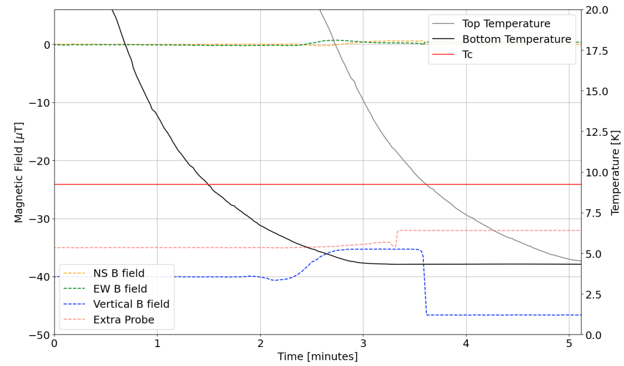

Figure 8: Fluxgate probe readings and cavity temperature plotted over time for a fast cool-down with a vertical applied magnetic field of 40 µT. A field enhancement of about 7 µT is measured.

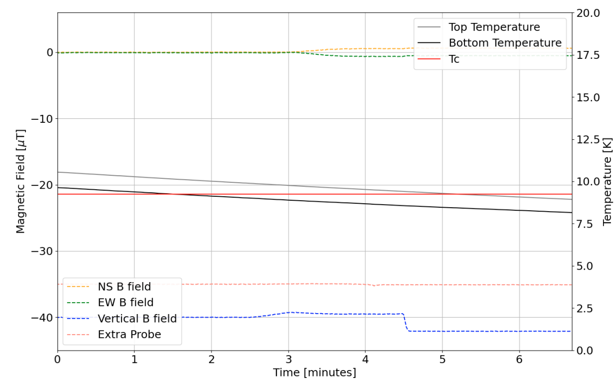

Figure 9: Fluxgate probe readings and cavity temperature plotted over time for a slow cool-down with a vertical applied magnetic field of 40 µT. A field enhancement of about 2 µT is measured.

the horizontal magnetic field. The horizontal field starts out at 40 µT before the superconducting transition, and then decreases to about 5 µT after the bottom and top of the cavity drop below the critical temperature. In contrast, the slow horizontal cool down shown in Fig. 11 reveals far less flux expulsion, and the horizontal magnetic field is only reduced to about 35 µT. The COMSOL simulation on the other hand showed no flux trapping for the horizontal cool-down. It is hypothesized that flux reaching the inner conductor is removed as the outer conductor transitions into the Meissner state. This removal of flux is thought to be more effective for the fast cool-down because larger temperature gradients help overcome the pinning force and reduce flux trapping [2].

The flux expulsion or trapping that occurs during a cavity cool-down will affect the cavity's performance. This can be seen by measuring the cavity surface resistance after different cool-downs. The surface resistance of the QWR after fast and slow cool-downs with a vertical applied field is plotted as a function of peak rf field in Fig. 12. The surface resistances for the vertical field cooled data sets are com-

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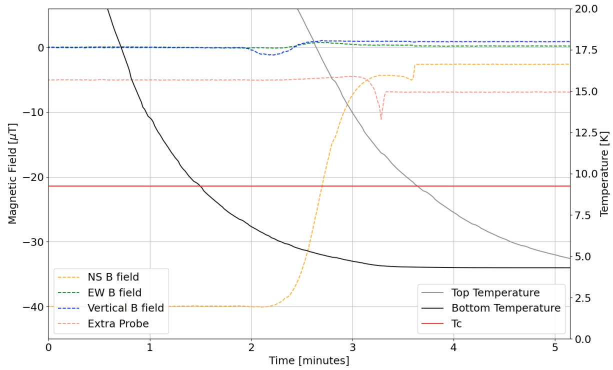

Figure 10: Fluxgate probe readings and cavity temperature plotted over time for a fast cool-down with a horizontal applied magnetic field of 40 µT. Very strong flux expulsion is observed during the superconducting transition as the vertical field goes from about 40 to 5 µT.

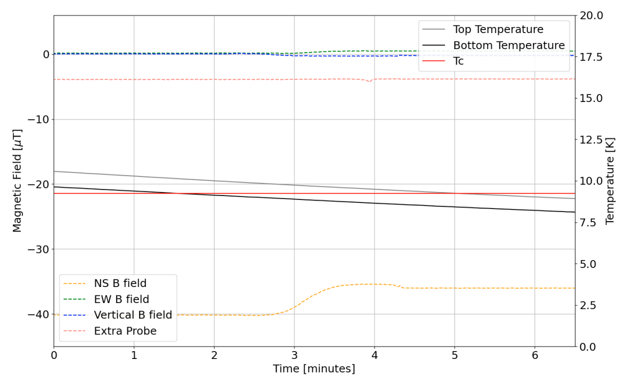

Figure 11: Fluxgate probe readings and cavity temperature plotted over time for a slow cool-down with a horizontal applied magnetic field of 40 µT. Much less flux expulsion is observed compared to the fast cool-down.

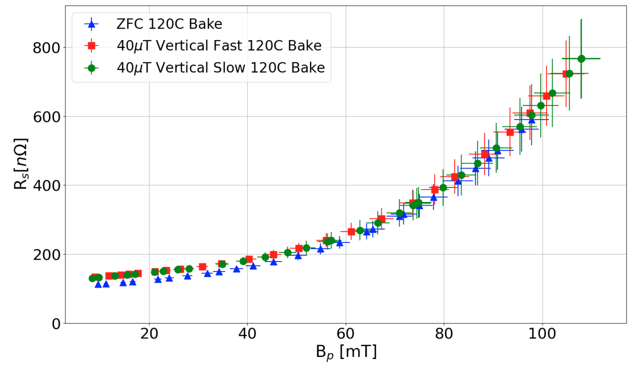

Figure 12: Surface resistance as a function of peak rf field for the 644 MHz mode at 4.2 K. There is no significant difference in surface resistance between the fast and slow cool-downs for the vertical applied field.

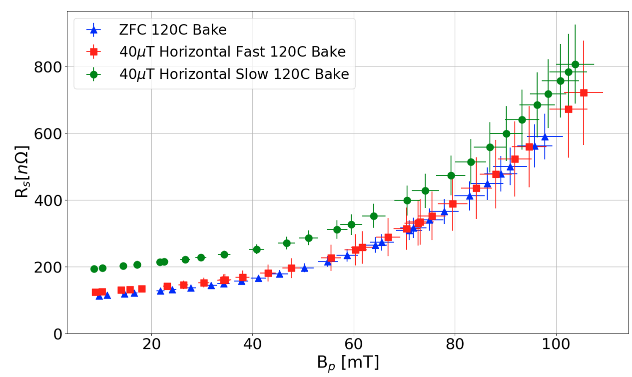

Figure 13: Surface resistance as a function of peak rf field for the 644 MHz mode at 4.2 K. The slow cool-down leads to higher surface resistance than the fast cool-down due to increased trapped flux.

pared to the ZFC measurements, which are described in the Methodology section. There is no significant difference in surface resistance between the fast and slow cool-downs with a vertical applied field, which is to be expected since neither cool-down showed strong flux expulsion in the magnetic field measurements.

For the horizontal field cooled case, the fast cool-down leads to lower surface resistance than the slow cool-down, which is shown in Fig. 13. This is due to the increased flux expulsion during the fast cool-down.

CONCLUSION

The TRIUMF QWR test cavity was used to explore the effects of cool-down speeds, temperature gradients, and magnetic field orientations on flux expulsion and cavity performance. Studies of this kind had not been previously done on TEM mode coaxial SRF cavities. Cool-down speed and temperature gradient did not have a strong influence on flux trapping when a vertical magnetic field was applied to the QWR. However with a horizontal magnetic field, the fast cool-down resulted in much more flux expulsion compared to the slow cool-down. Future experiments will likely include repeating these tests on the TRIUMF half wave resonator test cavity.

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