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INVESTIGATION OF TRAPPED FLUX DYNAMICS VIA DC-MAGNETIC QUENCHING

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Abstract

Trapped magnetic flux increases the surface resistance in superconducting radio-frequency cavities. A better understanding of its behaviour could help to develop a method of expelling trapped flux from the superconducting surface.

Using a superconducting coil with ferrite core attached to a 3 GHz TESLA-type 3-cell Niobium cavity fully immersed in liquid Helium, we were able to subject the cavity walls to unusually large magnetic fields (estimated >150 mT $/\mu_0$) and create magnetic quenches. With Fluxgate sensors attached in three spatial directions inside the cavity, we were able to monitor the quench dynamics and extract parameters of the flux dynamics from the hysteretic behaviour of the measured fields resulting from the applied coil current. First results of manipulation of the trapped flux with high magnetic fields are presented.

INTRODUCTION

Superconducting cavitys are limited in their performance by various factors. One of them is trapped magnetic flux, the contribution of which depends on the cooldown dynamics and the ambient field during superconducting transition [1]. In this work not the mechanisms of trapping [2,3], but rather the dynamics of already trapped magnetic flux are investigated under the influence of a locally strong external magnetic field. A better understanding could lead to a method of expelling trapped flux from the superconducting surface even after the superconducting transition, and therefore a better performance of the cavity. The first experiment should show that trapped magnetic flux can be manipulated by a superconducting coil with ferrite core in higher regimes than usual [4]. Additional analysis provides insights into the dynamics and helps to define further investigations and the configuration of ongoing measurements.

After describing the experimental setup, results and interpretations are presented. To the end, a short summary with an outlook for further investigations is given.

EXPERIMENTAL SETUP

To investigate the behaviour of trapped magnetic flux in a superconducting cavity under an external magnetic field, a superconducting coil with a horseshoe-shaped ferrite yoke is used to generate the external field, as seen in Fig. 1. The two ends of the yoke are placed underneath the superconducting cavity, such that two regions of increased induction are created in the cavity wall, which can be made large enough to exceed the critical field. To measure the magnetic field

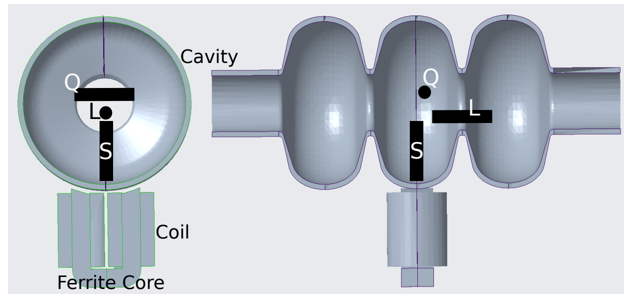

Figure 1: Experimental setup. In grey the cavity, which is a 3 GHz 3-cell Cavity. Inside of it three fluxgate sensors in black labelled with the initials S,Q and L. Below a coil with an U-shaped ferrite yoke. Left a cross view along the beam axis, right a cross view from the side.

inside the cavity, three fluxgate magnetometers are installed. A customized 3d-printed holding frame matched to the cavity shape provides fixtures for one sensor in each Cartesian direction. The Cavity also works as a magnetic shield for the sensors from the direct field of the Coil. Since the cavity is operated fully immersed in lHe with open beampipe, magnetic stray fields could in principle leak to the sensors. However, simulations and measurements showed that the magnetic field from the coil is small and not registered by the sensors when the cavity is superconducting without trapped flux. Therefore all measured field-changes had to result from a magnetic quench or trapped flux.

The Cavity was placed in a bath cryostat with liquid helium. At 2 K in the superconducting phase the coil was turned on to generate different patterns of magnetic field.

The measurements have the following format: A number of (different) current pulses are applied to the coil, which result in a magnetic field. The field then interferes with the trapped flux or, when strong enough, produces a magnetic quench, which should result in more trapped flux after the cavity is superconducting again. The signals of the magnetometers are then analysed. The magnetometers measure the magnetic field inside the cavity and are expected to represent the trapped flux in the cavity surface.

RESULTS & ANALYSIS

The effect of the applied field on the trapped flux was visible. The sensors reacted to the coil, depending on the strength of the current. As in the case of the cavity with the least possible trapped flux (directly after a cooldown) a certain threshold field was necessary to change the field inside the cavity. It has to be noted, that the two sensors nearest to the coil (S+Q) were not used as frequently as

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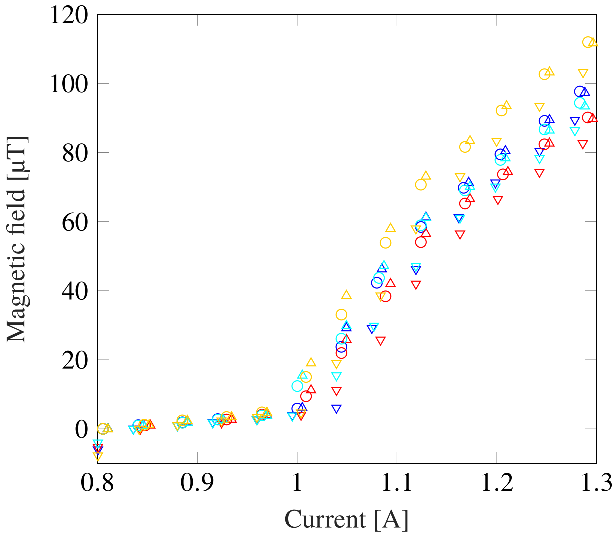

Figure 2: Measured magnetic field before(▽), during (◯) and after(△) a pulse of current I. The magnetic field is given as difference to the initial magnetic field. pos(blue and light blue) means pulses of current I, neg(red and yellow) of the current $-I$. In red o and blue o are the data from the measurements at 16 mbar, in light blue o and yellow o the measurements at 30 mbar. Interesting is the indication, that the yellow curve has a different slope than the red, where the same effect can only be guessed for the blue curves.

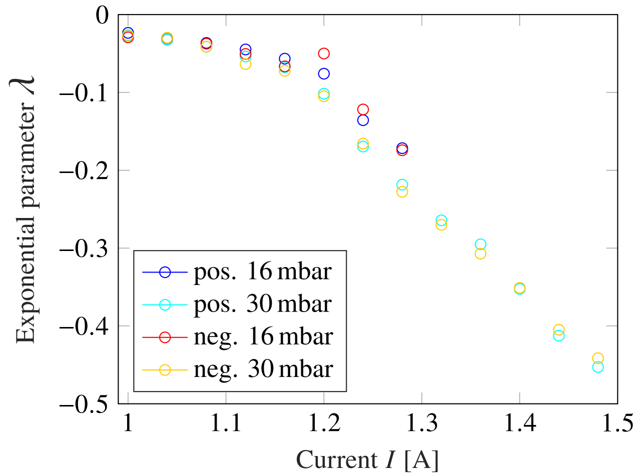

Figure 3: The progress of the magnetic field in dependence of time was fitted with an exponential function $e^{-\lambda t}$. The parameter λ is then displayed for the different currents of amperage I (pos) and $-I$ (neg), at a Helium-pressure of 16 mbar (red o and blue o) and 30 mbar (light blue o and yellow o). Higher currents have a faster time constant, meaning the magnetic field changes quicker and reaches the end value earlier. Also a difference in the pressure is probably leading to a different time constant, as the gap in the curves suggests.

the third sensor (L) for analysis, due to the fact that they were in "overrange" after high fields penetrated the cavity. The Fluxgate magnetometers only can measure fields up to 600 µT, which were exceeded most of the time. Nonetheless, the third sensors revealed encouraging data.

At smaller currents $I \leq 1$ A only a small reaction is observed when the current rises. For currents 1.1 A $\leq I \leq$ 1.2 A a slower reaction can be seen: the measured field changes during the whole time the current is applied. For $I \geq 1.3$ A faster and stronger changes in the measured field are observed.

To study the current dependency, pulses with increasing current from 0.8 A to 1.3 A in 0.04 A steps were applied. The sensors S and L were over their range most of the time. Hence, the sensor L was analysed. The pulses were each 100 s long, with 50 s pause in between. The biggest change in the magnetic field observed by the sensor was during the current pulses, not at the rise. To visualize the change in the magnetic field, the magnetic field measured by the sensor L is displayed in Fig. 2 by comparing the magnetic field before (▽), during (◯) and after (△) the pulse. To eliminate the offset at the beginning, the values of the first circle were set to zero. A difference between during and after the pulse not always means a change when turning off the coil, because the average value is taken. As seen below, the magnetic field changes during the constant current, so the average is lower than the endvalue. The same value for after a pulse and before the next pulse should be the same, because no external force is applied during that timespan. For Currents smaller than 1 A there only is a small increase when flux is trapped before. The Cavity then is in a mixed state, but still superconducting. Nonetheless, the change in the external field is measured, meaning macroscopic field can overcome the expulsion. A definite increase in the measured magnetic field is seen from 1 A. After that, a non-linear behaviour is observed. The meaning of the latter effect is not clear yet.

For increasing currents, the change over time in the measured magnetic field differs non-trivial. Every curve (progress of magnetic field during current pulse) is fitted with an exponential function $e^{-\lambda t}$. The exponential function is not the best function to describe the progress, but a first approach for investigating the time constant of the progress. The time constants of the fits are displayed in Fig. 3. Additionally, the halftime changes with increasing currents and during each progress. This is shown in Fig. 4. There the times after which the difference to the endvalue decreases to $1/2^n$ of the initial difference. An exponential function would generate a linear curve in this graph, because the halftime would stay constant. Starting from low amperages, the curves are convex, going to nearly linear (1.12 A) and concave functions for high currents. Convex means, that the change starts slow and is getting faster, concave functions indicate a fast start and a slow down over time.

We assume two physical effects with different time constants, where one dominates in the beginning or at high external fields and one at the end where already a lot of flux is induced in the cavity. One effect has to be the pushing in of trapped flux. This should have a saturation whith a

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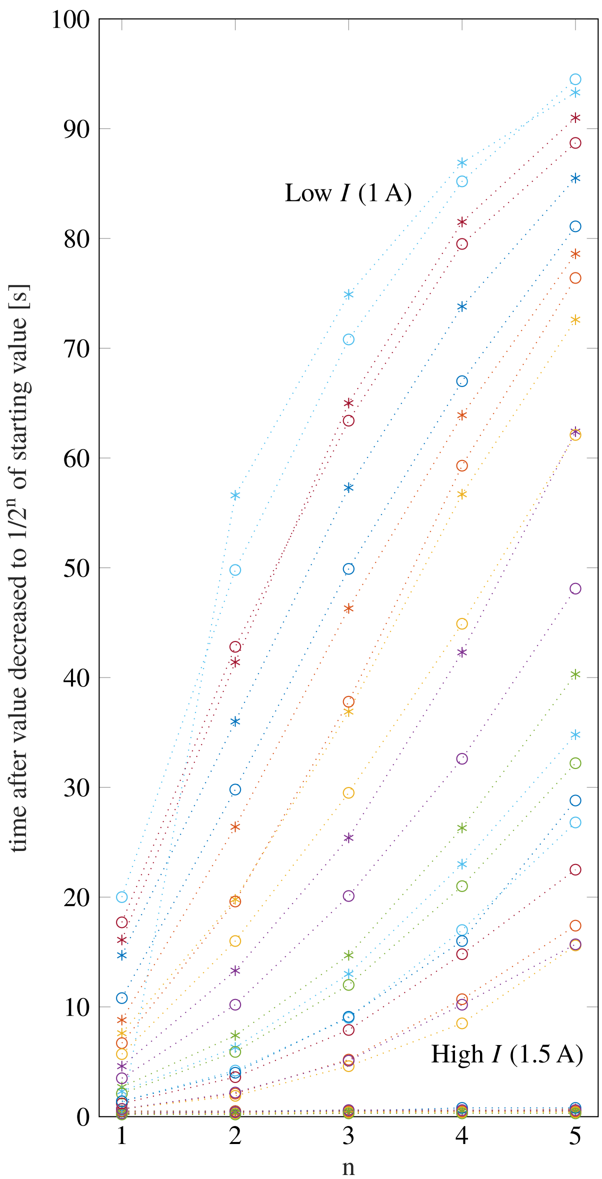

Figure 4: Displayed here is the time over which the difference to the end value decreased to $\frac{1}{2^n}$ from the difference at the beginning. Therefore, an estimation for the time constant can be made and how it changes over time. For an exponential function a linear behaviour would be seen in this graph. Displayed for different currents (0.8–1.5 A) at a Helium-pressure of 16 mbar(*) and 30 mbar(o). The graphs that showed no progress were for currents $I \leq 1$ A. The other graphs correspond to Currents from 1 A (top, light blue) to 1.5 A (bottom, purple) in 0.04 A steps. As can be seen the behaviour in this graph changes for different currents.

corresponding time constant. The other effect could be the expanse of the normal conducting region, which depends on the interaction of flux movement and the superconducting region.

SUMMARY & OUTLOOK

With a superconducting coil with ferrite core we were able to manipulate trapped magnetic flux inside the cavity walls. First measurements showed results with a clear current dependency of the mobility of trapped flux. The process of the movement during pulses reveals the existence of at least one time constant with which the progress can be described. The data also indicate the existence of two processes in the mechanism of moving trapped flux. The movement could not yet be described by [5]. But still further measurements are necessary to test the hypothesis. For better analysis in the next experiment hall sensors with a greater range will be installed.

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