# ON MAGNETIC FLUX TRAPPING IN SUPERCONDUCTORS

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*Abstract*

Magnetic flux trapping on cool-down has become an important factor in the performance of superconducting cavities. We have conducted systematic flux trapping experiments on samples to investigate the role of the orientation of an ambient magnetic field relative to the niobium's surface.

## INTRODUCTION

According to the perfect Meissner effect, a superconductor is expected to expel all magnetic flux when it becomes superconducting. However, it is well known that superconducting cavities made from Niobium trap some of the magnetic flux during the transitions to its superconducting state while being exposed to an external magnetic field. The trapped flux will result in normal conducting vortices, which add significantly to the total surface resistance. As a result, shielding of an SRF cavity against the earth's magnetic field is essential, and usually magnetic flux strengths below 0.5 µT are required for high Q cavity performance.

Recently, flux trapping has gained an increasing interest: it was found that the amount of flux being trapped depends on the cool-down speed and also on the surface preparation details.

Our research now indicates a third factor: the orientation of the magnetic field with respect to the superconductor surface.

## EXPERIMENTAL SET-UP

To investigate the role of field orientation in flux trapping we designed a simple and flexible set-up. It consisted of a sample, clamped into position by a copper frame, two solenoids that could either be oriented parallel or orthogonal to the sample, 4 flux gate sensors to measure magnetic field components (axial with respect to the sensor) and two cernox sensors to measure the temperature of the sample during the thermal cycle. Details of the set-up are shown in Fig. 1.

The solenoids consisted of wire coiled 25 times around cylinders of stainless steel. Each solenoid had a diameter of 3.8 cm and was mounted to the insert via stainless steel screws. During our tests we operated the solenoids at 0.05 A when mounted orthogonal (Fig. 1 (a)) and at 0.4 A when mounted parallel (Fig. 1 (b)). During the experiment the whole ensemble was placed inside a helium dewar which was well shielded against external magnetic fields. In every trial, we cooled the sample down to 4.2 K with various magnetic field configurations, and recorded the fluxgate readings and how they

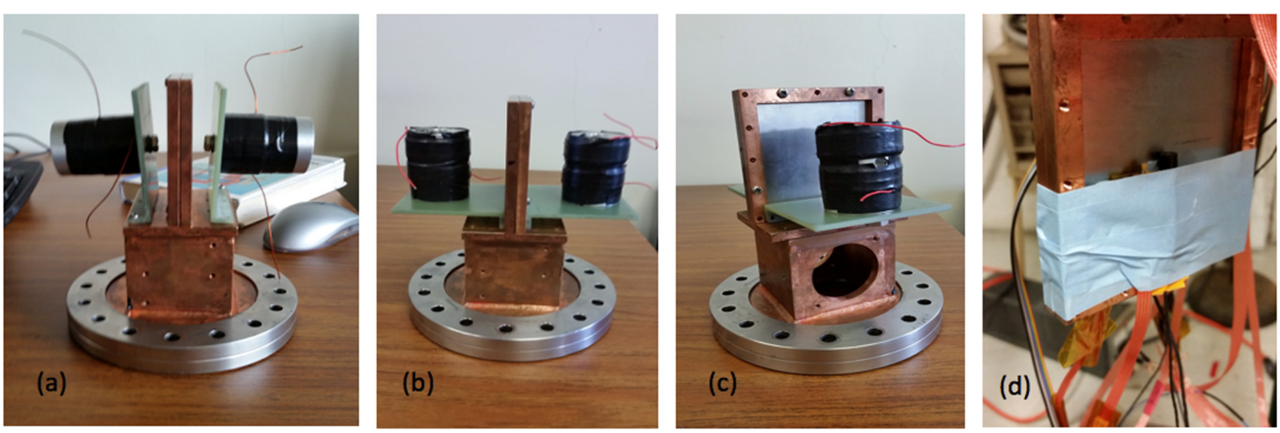


Figure 1: Experimental set-up: (a) solenoids placed orthogonal to the sample (enclosed in a copper clamp), (b) solenoids parallel to the sample, (c) more detailed view of the set-up showing the sample, (d) location of the transversal flux gate heads and the temperature sensor.

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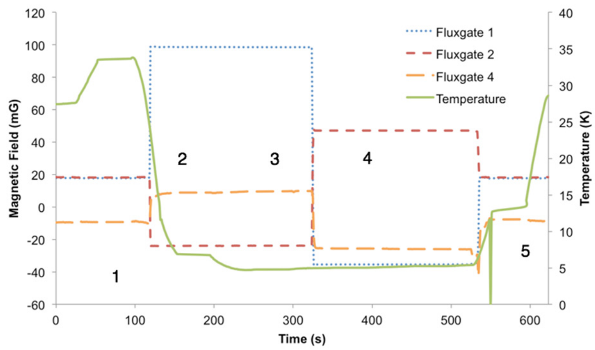


Figure 2: Typical experimental data set. The solenoid axes in this trial where parallel to the sample, producing fields in opposite directions.

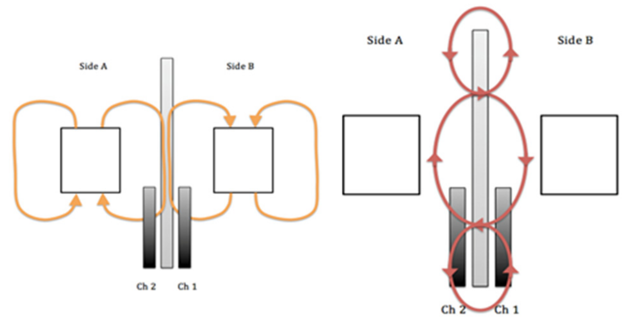


Figure 3: Visualization of the field configuration in phase 2 (left) and phase 4 (right) for the data shown in Fig. 2.

changed as flux was trapped. We then switched off the solenoids to allow the fluxgates to observe the sample's trapped flux. Finally, we warmed the sample above $T_c$ to observe the flux being released. Our experiment involved two major variables: the orientation of the solenoids (horizontal or vertical) and the direction of the current through each solenoid, which could be set for each individually.

As a naming convention we refer to solenoid 1 (S1) as being to the left of the sample and S2 to the right. The field orientation as given in tab. 1 should be interpreted in that sense—central solenoid field pointing up (U), down (D), left (L) or right (R).

Figure 2 shows a typical data set and the 5 phases of each experiment:

1. $T>T_c$, solenoids off
2. $T>T_c$, solenoids on
3. $T<T_c$, solenoids on
4. $T<T_c$, solenoids off
5. $T>T_c$, solenoids off

Magnetic field readings where named accordingly ($B_1 \ldots B_5$). Accounting for the residual magnetic flux, the solenoid field was identified as

$$B_{Solenoid} = B_2 - B_5$$

and the trapped flux as

$$B_{Trapped} = B_4 - B_5.$$

A compilation of the measured data is given in Tab. 1.

## ANALYSIS

We ran a total of 16 configurations including redundant trials to ensure consistency of the data. To better understand the data, we found it helpful to depict each field configuration in a sketched diagram. In composing these diagrams, we first discerned the locations on the sample at which much of the solenoids' field should pass through and approximated each of these points as a magnetic dipole for the sake of drawing the field lines.

Depending on the field configuration we were able to measure parallel or orthogonal magnetization of the sample. For example, tests with the solenoids oriented horizontally in opposite directions involved a dominant parallel field due to the cancelation of the perpendicular field from either side of the niobium sample; whereas the trials involving horizontal fields pointing in one direction involved primarily dominant perpendicular external fields due to a lack of cancelation.

This allowed us to distinguish parallel from orthogonal fields trapped on cool-down. Using the field map as sketched in fig. 3 (right) we were then able to determine if the fluxgates picked up the field from a magnetization parallel or perpendicular to the sample's surface. It should be mentioned that every flux gate sensor only measures the field component aligned with its geometrical axis.

All data together with the analysis is given in Table 1. The amount of flux trapped was defined as

$$\left|B_{Trapped}/B_{Solenoid}\right|.$$




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Table 1: Summary of Magnetic Field Readings for Different Field Configurations. For details see text.

| S1 | S2 | Fluxgate Channel | $B_1$ [mG] | $B_2$ [mG] | $B_3$ [mG] | $B_4$ [mG] | $B_5$ [mG] | $B_{Trapped}$ [mG] | $B_{Solenoid}$ [mG] | Trapping |
|---|---|---|---|---|---|---|---|---|---|---|
| R | L | 1 | -12.6 | -68.2 | -67.6 | -8.81 | -13.6 | 4.75 | -54.6 | 8.7% |
| R | L | 2 | -14.6 | -68.5 | -69.5 | -9.80 | -14.1 | 4.33 | -54.4 | 8.0% |
| L | R | 1 | -15.6 | 41.4 | 42.5 | -18.9 | -16.0 | -2.91 | 57.3 | 5.1% |
| L | R | 2 | -19.1 | 36.0 | 35.2 | -23.8 | -19.1 | -4.72 | 55.1 | 8.5% |
| R | - | 1 | -15.8 | -53.7 | -52.0 | 11.0 | -16.4 | 27.4 | -37.3 | 73.5% |
| R | - | 2 | -19.4 | -36.9 | -39.2 | -40.3 | -19.2 | -21.1 | -17.7 | 119% |
| U | U | 1 | 17.0 | -173 | -173 | 30.9 | 18.6 | 12.3 | -192 | 6.4% |
| U | U | 2 | 17.5 | -152 | -152 | 15.7 | 19.2 | -3.50 | -171 | 2.1% |
| D | D | 1 | 17.7 | 208 | 208 | 5.16 | 16.9 | -11.8 | -191 | 6.2% |
| D | D | 2 | 18.7 | 188 | 188 | 20.9 | 17.5 | 3.40 | -171 | 2.0% |
| D | U | 1 | 18.0 | -62.1 | -62.1 | 71.9 | 18.1 | 53.8 | -80.2 | 67.1% |
| D | U | 2 | 18.4 | 61.4 | 61.2 | -9.77 | 18.1 | -27.9 | -43.3 | 64.4% |
| U | D | 1 | 17.8 | 98.8 | 98.5 | -35.3 | 17.8 | -53.1 | 81.0 | 65.6% |
| U | D | 2 | 18.4 | -24.0 | -23.9 | 46.8 | 18.3 | 28.5 | -42.3 | 67.4% |

Analyzing the data one finds that all results fall into two classes: those with flux trapping in the order of 5-10 % and those with flux trapping of 65 % or higher.

Our analysis shows that low flux trapping values correspond to field configurations producing mostly parallel fields at the sample close to the fluxgate sensors. These situations occurred when the solenoids were oriented either horizontally in opposite directions or vertically in the same direction. Therefore, one can conclude that parallel fields are less likely to be trapped. Vice versa the flux trapping probability is rather high for perpendicular fields.

As an example, the solenoid configuration of Fig. 3 is annotated as S1: U, S2: D, which resulted in a magnetization perpendicular to the sample at the location of the fluxgate probes. According to the sketch in Fig. 3 (right) this field is picked up by the fluxgates even though they only measure fields parallel to the surface. Consequently, we concluded that the magnetization measured as ~66% of the field is the flux trapping of the orthogonal field.

Even though we give quantitative figures our conclusions are limited to a rather qualitative statement. The reason for this comes from the field interpretation according to Fig. 3. A complete analysis would probably require numerical field simulations for all scenarios and a full mapping to the experimental data—which we so far did not do.

## SUMMARY AND CONCLUSION

We measured the flux trapped by a niobium sample after cooling it below the critical temperature in the presence of a magnetic field with the field being either mostly parallel or mostly perpendicular to the sample. It was found that the orientation of the magnetic field with respect to the surface affects the amount of magnetic flux trapped by the superconductor.

The data showed that a dominantly perpendicular external field consistently resulted in more trapped flux than a dominantly parallel field. Our measurements suggest that approximately 65% or more of the perpendicular flux was trapped and that 10% (or less) of the parallel flux was trapped. From both findings we can estimate a limit on how much parallel or perpendicular flux can be trapped. However, we do not have sufficient evidence to claim parallel flux is never trapped while perpendicular flux is fully trapped—even though this would conform to our data.