Contents

1 Physical Background

1.1 Superconductivity

Materials in which superconductivity can be observed are called superconductors. The best known property of superconductors is that the resistance of the conductor drops to almost zero for a temperature T below the critical temperature T_{crit}. Superconductors are also perfect diamagnets, meaning that when an external, changing magnetic field is applied to the conductor, it will induce an electric current in the conductor which leads to a magnetic field that exactly cancels the external field. This effect is known as the Meissner-Ochsenfeld effect and also leads to superconductors levitating above magnets.

In its superconductive state a material has a temperature dependent energy gap with

$$E_{\text{gap}} = E_{\text{fermi}} \pm \Delta E \tag{1}$$

with the fermi-energy E_{fermi} and the temperature dependent energy ΔE. Furthermore for $T < T_{\text{krit}}$ the electrons change into a macroscopic quantum state and form cooper pairs.

Apart from a temperature higher than the critical temperature there are different reasons superconductivity breaks or cannot be achieved. A strong magnetic field, as well as a high electric current can have this effect. Also an electromagnetic alternating field with an approximate frequency of $\Delta E/\hbar$ has this effect.

There are two different types of superconductors that are distinguished by the magnetic field inside the conductor.

Superconductors Type I For an external magnetic field below the critical magnetic field strength, the magnetic field inside the conductor abruptly drops to 0. Only a thin layer is penetrated by the magnetic field.

Superconductors Type II (high-temperature superconductors) There are two critical field strengths, H_1 where the magnetic field is partially displaced and H_2 where it is completely displaced. Between these two field strengths isolated points, so-called vortices are formed.

1.2 London Equations

The London equations are used to calculate the penetration depth of a magnetic field. First of all it is assumed that the electrons are only accelerated by an electric field $\vec{E}$ so that $m\dot{\vec{v}} = -e\vec{E}$ applies. This assumption together with $\vec{j} = n_e e \vec{v_e}$ and the Maxwell equations leads to

$$\frac{\partial}{\partial t}\left(\vec{\nabla} \times \vec{j} + \frac{n_e e^2}{mc^2}\vec{B}\right) = 0. \tag{2}$$

As we have said in the previous section a superconductivity does not hold a magnetic field inside so the expression in brackets has to be time independent and zero which leads to the London equation

$$\vec{\nabla} \times \vec{j} = -\frac{n_e e^2}{mc^2}\vec{B}. \tag{3}$$

Additionally the two equations

$$\nabla^2 \vec{B} = \frac{4\pi n_e e^2}{mc^2} \vec{B} \tag{4}$$

$$\nabla^2 \vec{j} = \frac{4\pi n_e e^2}{mc^2} \vec{j} \tag{5}$$

can be found. These equations are solved by exponential functions with range $\Lambda = \sqrt{\frac{mc^2}{4\pi n_e e^2}}$. So a magnetic field can penetrate a superconductor to a certain range and will also create a shielding current orthogonal to the magnetic field.

1.3 BCS-Theory

In a conductor usually free electrons cause conductivity. In a superconductor conductivity is caused by cooper pairs. Cooper pairs are electron pairs that are formed because of interactions between electrons and the crystal lattice. When an electron moves through a material positive charges of the lattice, so the protons, are attracted. Attraction of protons causes the deformation of the lattice which makes another electron move into the area of higher positive charge density. The second electron hat opposite spin and the two electrons correlate. In a superconductor many electron pairs will form and create a condensed state. In this condensed state one cannot break a single pair, but to break one pair all connections have to be killed. So the energy barrier to break a connection has increased and all the coupled electrons move as a whole which is essential for superconductivity.

Mostly same but said in other words electrons are fermions and for a tempearture close to 0 K most of the electrons are in the same state and it is likier to find another electron to pair with as it would be at higher temperatures. The bond of two electrons makes them one boson system and because of the bose-statistics cooper pairs can go to a lower energetically state. Furthermore for the created cooper pairs there is only one wave function and the conductor becomes superconductive.

1.4 Flux Quantization

The SQUID is a circular superconductivity so we know

$$\oint \vec{j} \, \mathrm{d}\vec{l} = 0. \tag{6}$$

As the phase is an unambigous parameter it is only allowed to change in multiples of 2π. Moreover we know Stokes theorem so

$$\oint \vec{A} \, \mathrm{d}\vec{l} = \Phi_B \text{ and } \oint \vec{\nabla}\Theta \, \mathrm{d}\vec{l} = 2\pi n \tag{7}$$

can be written down. Using these equations and Londons equation (eq. (3)) we find a relation for the magnetic flux through the ring which is quantized in multiples of $\hbar/2e$:

$$\begin{gathered} |\Phi_B| = n\frac{\hbar}{2e} = n\Phi_0 \\ \text{with } \Phi_0 = (2.067\,833\,667 \pm 0.000\,000\,052) \cdot 10^{-15}\,\mathrm{Wb}. \end{gathered} \tag{8}$$

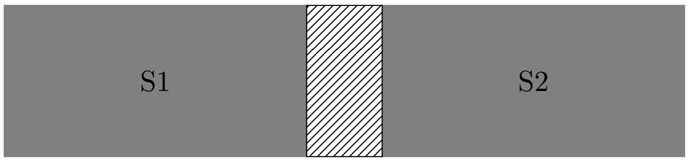


Figure 1: Josephson contact (black hatched) between two equal superconductors

1.5 Josephson Effect

The Josephson effect describes the tunneling of cooper pairs through a thin isolating layer between two superconductors fig. 1.

Comparably to the tunneling of electrons through potential barriers copper pairs can tunnel through isolating layers. Even if the layer is not superconductive the pair does not loose energy. As the layer is not superconductive it can be interfused by a magnetic field which changes the phase shift. This concludes in the Josephson direct current

$$I = I_0 \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}. \tag{9}$$

1.6 The SQUID

The SQUID is used to measure small changes of magnetic fields. It does so by using superconductivity and flux quantisation. There are different implementations of SQUIDs an easy one is used here, the RF-SQUID.

A RF-SQUID fig. 2 consists of a superconductive ring which can be put into liquid nitrogen. At one point the ring has a weak link that functions as a Josephson contact. The second component of the RF-SQUID is a oscillating circuit which can generate a magnetic field. Also with help of the oscillating circuit the voltage can be measured.

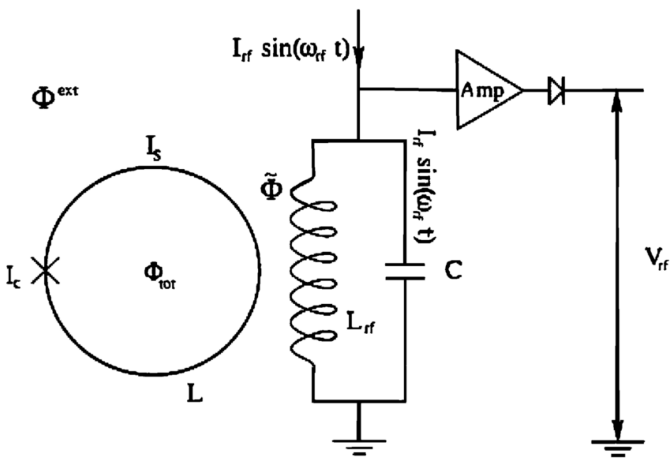


Figure 2: Setup of a RF-SQUID consisting of a superconductive ring and an oscillating circuit, [Source 1]

1.7 Lock-In Method

The SQUID that is used in the FP is amplified by a Lock-In-Amplifier. It detects weak signals even if there is a strong background. The signal that is measured is combined with a reference signal and integrated. The orthogonality of sine and cosine is used to filter all parts of the signal that do not match the reference signal and eliminate the background.

1.8 Calculating the Magnetic Field of a Conductor Loop

As the measured magnetic field of the conductor loop can be compared to a theoretical value it is calculated. To do so the formula

$$\begin{aligned} B_z = \frac{\mu_0 p}{2\pi z^3} \text{ with } p = AI = A\frac{U}{I} \\ \text{where } p :\ & \text{dipole moment,} \\ z :\ & \text{z distance between probe and SQUID} \end{aligned} \tag{10}$$

can be used.

With the SQUID there is another possibility to calculate the magnetic field. With use of the feedback-resistor $s_i[\mathrm{V}/\Phi_0]$ a voltage ΔV can be converted to a magnetic flux. To calculate the magnetic field one would need the area that is penetrated by the flux. As in the superconductive state just a part of the area actually is penetrated an effective area should be used. Instead of this we use the field-flux-coefficient $9.3\,\mathrm{nT}/\Phi_0$ that is given in the manual. With the coefficient the magnetic field can be calculated with

$$B_z = F\frac{\Delta V}{s_i}. \tag{11}$$

2 Task Definition

1. Calibrate the SQUID with help of the control-panel and find the best values to optimize and maximize the SQUID-pattern.
2. Determine the dipole moment and the field intensity of the conductor loop for the five different resistances and compare it the calculated values.
3. Determine the dipole moment and the field intensity of various other probes.
4. Make a polar plot of the intensity of the magnetic field depending on the angle.

3 Setup and Implementation

3.1 Setup

The SQUID that is used in the FP is a RF-SQUID.

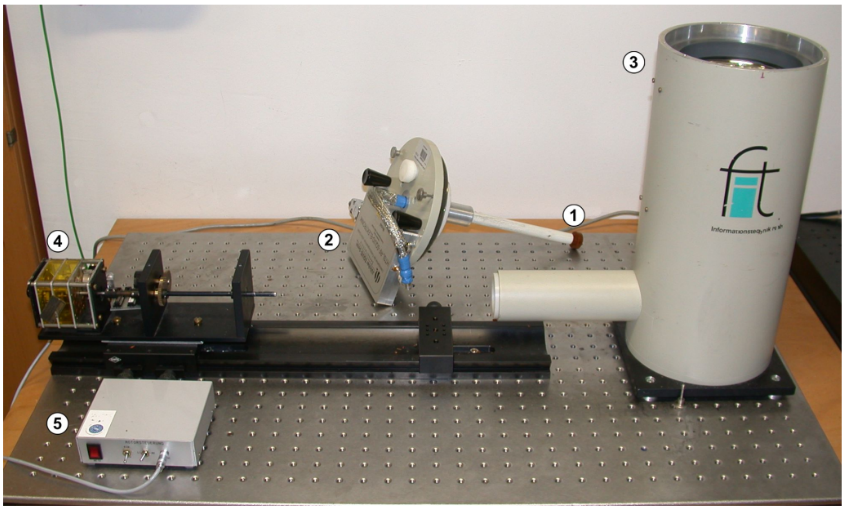


Figure 3: Photo of the setup, 1)SQUID-RING, 2)electric parts of the SQUID, 3)vessel with liquid nitrogen, 4)sleigh and engine with mounting, 5)switch for the engine, [Source 1]

The main part (fig. 1) that can be submerged into liquid nitrogen where it reaches the critical temperature. The superconductive ring is intermitted by a thin weak link at one point. The weak link works as the Josephson contact. The second part of the experiment is the oscillating circuit that can generate a magnetic field and is used to measure voltage. These two components form the measuring device.

For measuring the magnetic field it is indispensable that the probe is turning directly under the SQUID. To do so there is an engine that can be set to different angular velocities. A mounting for the probe can be attached to the engine and the whole part is located on a sleigh so the probe can be moved under the SQUID.

To analyse the measurements the experiment is connected with an oscilloscope that can be read out with a computer. On the computer the are two different programs tu use while calibrating and measuring.

In order to achieve a large variety of measurements different samples are available and can be put into the mounting. Besides a mounting with a conductor loop with different resistances exists.

3.2 Implementation

As the experiment has already been built up by people that tried to make it work the implementation started right away with the measurements. First of all the distance between probe and the SQUID was measured. After that the SQUID was inserted in the vessel and cooled down.

3.3 Implementations in the Test-Mode

To calibrate the experiment the test-mode is used. The probe is taken out of the vessel and in the computer program JSQ Duo Sensor Control is set into test-mode. The test-mode couples a triangle voltage in the oscillating circuit to realise a controllable change in the magnetic flux. On the oscilloscope the triangle signal and the SQUID signal were displayed and the SQUID signal was triggered on the triangle signal.

To calibrate the SQUID the parameters VCA (amplitude of current) was set to about 1000 and the second parameter VCO (frequency of current) was changed until the maximum amplitude could be observed. Now both parameters were slowly variated until the pattern looked like the characteristic SQUID-pattern that was given in the manual. The third parameter was used to set the offset around zero. These three parameters as well as the chosen values for the integration capacity and the resistance were noted. With the second program the data was exported as a .csv-file and saved.

In the following measurements the chosen parameters were not changed.

3.4 Implementations in the Measure-Mode

In the JSQ Duo Sensor Control the measure-mode was selected. In this mode the parameters from the test-mode are saved and the triangle voltage is switched off.

To measure a probe it is attached to the mounting, moved into the vessel and turned with help of the engine. Done so a sine-like signal should be observed on the oscilloscope.

The first day of the experiment this was not possible. As we have not built up the experiment we can not say if there was a problem with loose contacts or a strong external magnetic field. The experiment has been moved to another room that was expected to have less external magnetic fields but this did not help.

The second day the implementations in the test-mode were repeated and the parameters noted and saved. The control was changed to measure-mode and a fist probe was inserted. Nothing was done differently to the day before nevertheless we were able to get analysable signals so a complete series of measurements was done.

First of all a small iron stick was put into the mounting and measured on angular velocity 10. As it did not give a good sine the iron stick was not measured with other velocities.

Secondly the conductor loop was measured with five different resistances and as long as it made sense (as long as we got a good looking signal) with three different angular velocities (10, 6, and 2). The stronger the resistance got the worse the sine was visible, so for the stronger resistances only the fastest velocity was chosen.

The third probe was a small piece of magnetic material, a magnetic flake that was measured at velocities 10 and 5.

An iron flake was the last probe to be measured and it was only done at velocity 10.

For all of the measurements mentioned above the voltage-range of the oscilloscope was noted and the data was saved as a .csv-file.

Furthermore the angular velocity of the modes 10, 5 and 2 was measured with a phone but only to compare if the measured one is on the right scale.

With these measurements done the experiment was finished, the experimental setup was cleaned, sorted and the SQUID was taken out of the vessel and blow-dried.

4 Analysis

4.1 Theoretical Calculation of the Magnetic Field

To test the Quality of the measurement later on some theoretical calculation was made. For the calculation of the magnetic field of the conductor loop the following equation was used:

$$B(z) = \frac{\mu_0}{2}\frac{Ur^2}{Rz^3}$$

In this equation z represents the distance between sample and the SQUID-Sensor and U the voltage applied on the resistor with resistance R and r the radius of the conductor loop. The error of the magnetic field is calculated with gaussian error propagation.

$$s_B = \frac{\mu_0}{2}\sqrt{\left(\frac{r^2}{Rz^3}s_U\right)^2 + \left(\frac{2Ur}{Rz^3}s_r\right)^2 + \left(\frac{Ur^2}{R^2z^3}s_R\right)^2 + \left(\frac{3Ur^2}{Rz^4}s_z\right)^2}$$

The measured radius is $r = (1.8 \pm 0.3)$ mm with estimated error. The measurement of the voltage was repeated after several times because we noticed that the voltage seemed to be quite unstable. For the calculation of the magnetic field we calculated the mean value for the voltage and the unbiased standard deviation because it was higher then the given error for the used voltmeter. We measured the voltages $U_i = 2.66, 2.73, 2.69, 2.81$ and 2.81 V. Therefore the used value for the voltage is $U = (2.74 \pm 0.07)$ V. So the expected values of the magnetic field for the given resistors are shown in table 1.

Resistor	Resistance [Ω]	Magnetic Field [nT]
R1	51.47 ± 0.05	1.3 ± 0.5
R2	100.8 ± 0.1	0.7 ± 0.3
R3	300.8 ± 0.3	0.22 ± 0.08
R4	501.6 ± 0.5	0.13 ± 0.05
R5	1000 ± 1	0.07 ± 0.02

Table 1: In this table the theoretical magnetic fields for the different resistors are listed. The calculation of the errors was done as described earlier.

It should be mentioned that the relative errors of the so calculated magnetic fields are quite high. But the measurement of the distance z was not as accurate as it probably should have been. And as the magnetic field is dependent to the inversed cubic of z the error of that measurement has a strong impact on the overall error.

4.2 Theoretical Calculation of the Magnetic Dipole Moment

The dipole moment of a conductor loop is given by

$$p_{\text{mag.}} = A \cdot \frac{U}{R},$$

where A represents the area which is limited by the conductor loop. The used voltage and resistances where the same as in the previous section. Using gaussian error propagation the error was calculated with the following formula:

$$s_{p_{\text{mag.}}} = \sqrt{\left(\frac{U}{R}s_A\right)^2 + \left(\frac{A}{R}s_U\right)^2 + \left(\frac{AU}{R^2}s_R\right)^2}. \tag{12}$$

A is calculated with $A = \pi r^2$ so the error of the area is given as $s_A = 2\pi r s_r$. The calculated errors are displayed in table 2.

Resistor	Resistance [Ω]	Magnetic Dipole Moment [μA m^2]
R1	51.47 ± 0.05	0.5 ± 0.2
R2	100.8 ± 0.1	0.26 ± 0.09
R3	300.8 ± 0.3	0.09 ± 0.03
R4	501.6 ± 0.5	0.05 ± 0.02
R5	1000 ± 1	0.026 ± 0.009

Table 2: In this table the theoretical magnetic dipole moments are displayed. The calculation of the values and their errors was done as mentioned before.

4.3 Analysis of the Measured Data

To analyse the measured data a sine fit of the following form was made:

$$f(x) = a + b \cdot \sin(cx + d),$$

where a represents the offset of the measurement, b the amplitude, ΔU c the rotation speed of the probe and d the phase of the sine wave when the measurement was started. For the calculation of the magnetic field we use the fit parameter b so the amplitude of the sine wave. So we get the magnetic field in z direction which we calculated before on a theoretical basis. The data and the sine fit are displayed in the appendix. The formula for the calculation is

$$B_z = F \cdot \frac{b}{s_i}.$$

$F = 9.3\,\text{nT}/\Phi_0$ is the field flux coefficient and $s_i = 1.9\,\text{V}/\Phi_0$ which is a parameter caused by the experimental settings. Thus the error is calculated by

$$s_{B_z} = F \cdot \frac{s_b}{s_i}.$$

For the conductor loop we repeated the measurement for different resistances and different rotation speeds the final results of this measurements are displayed in table 3. For a later discussion we also calculated the magnetic dipole moments. The calcu-

Resistor	Rotation Setting	Magnetic Field [nT]	Magnetic Dipole Moment [µA m^2]
R1	$\omega 10$	1.263 ± 0.009	0.50 ± 0.07
R1	$\omega 5$	1.217 ± 0.009	0.48 ± 0.07
R1	$\omega 5$	1.21 ± 0.01	0.48 ± 0.07
R1	$\omega 2$	1.21 ± 0.01	0.48 ± 0.07
R2	$\omega 10$	0.662 ± 0.006	0.26 ± 0.04
R2	$\omega 5$	0.610 ± 0.007	0.24 ± 0.03
R2	$\omega 2$	0.612 ± 0.006	0.24 ± 0.03
R3	$\omega 10$	0.221 ± 0.004	0.09 ± 0.01
R3	$\omega 5$	0.186 ± 0.004	0.07 ± 0.01
R3	$\omega 2$	-	-
R4	$\omega 10$	0.100 ± 0.004	0.040 ± 0.006
R5	$\omega 10$	-	-

Table 3: In this table the measured values of the magnetic field and the magnetic dipole moment for a conductor loop with different settings are displayed. The calculation of the listed values where executed as described before. The measurements of the empty spots gave data where no sinus fit was possible the data is shown in the appendix.

lation was done as shown in the following equations:

$$\begin{aligned} p_{\text{mag.}} &= 2\pi \cdot \frac{z^3 B_z}{\mu_0} \\ s_{\text{mag.}} &= \frac{2\pi}{\mu_0}\sqrt{(z^3 \cdot s_{B_z})^2 + (3B_z z^2 \cdot s_z)^2}. \end{aligned}$$

The so calculated values for the magnetic dipole moment are displayed in table 3. For comparing purposes the mean of the measured values for both the magnetic field and the magnetic dipole moment where calculated and are shown in table 4. There

Resistor	Magnetic Field [nT]	Magnetic Dipole Moment [µA m^2]
R1	1.225 ± 0.005	0.49 ± 0.04
R2	0.628 ± 0.004	0.25 ± 0.02
R3	0.204 ± 0.003	0.08 ± 0.01
R4	0.100 ± 0.004	0.040 ± 0.006
R5	-	-

Table 4: This table displays the mean values of the magnetic field and the dipole moment for each resistor. Since for R5 no sine fit was possible there were no values calculated.

where also different given samples to measure. The calculation for their magnetic field and their magnetic dipole moment where the same as for the conductor loop. The results to these measurements are displayed in table 5

Sample	Magnetic Field [nT]	Magnetic Dipole Moment [µA^2 m]
Iron Stick	52.27 ± 0.05	21 ± 3
Iron Flake	0.032 ± 0.006	0.013 ± 0.003
Magnet Flake (ω10)	47.5 ± 0.2	19 ± 3
Magnet Flake (ω5)	47.8 ± 0.2	19 ± 3

Table 5: In this table the magnetic fields and the dipole moments for different samples are listed.

4.4 Polar Plot of the Magnetic Field

For the polar plot the angle and the absolute value of the magnetic field was calculated. The function `pyplot.polar` from the `matplotlib` package was used. The angle was calculated with the fit parameters c and d in the following way

$$\alpha = c \cdot t + d,$$

where t is the time when the voltage was measured. The polar plots are shown in the appendix.

5 Discussion

To discuss the quality of the measurement the theoretical values can be compared to the measured values of the magnetic field and the magnetic dipole moments of the conductor loop. For comparison these results are displayed in table 6. Looking

Resistor	$B_{\text{theo.}}$ [nT]	$p_{\text{mag.,theo.}}$ [µA m^2]	$B_{\text{meas.}}$ [nT]	$p_{\text{mag.,meas.}}$ [µA m^2]
R1	1.3 ± 0.5	0.5 ± 0.2	1.225 ± 0.005	0.49 ± 0.04
R2	0.7 ± 0.3	0.26 ± 0.09	0.628 ± 0.004	0.25 ± 0.02
R3	0.22 ± 0.08	0.09 ± 0.03	0.204 ± 0.003	0.08 ± 0.01
R4	0.13 ± 0.05	0.05 ± 0.02	0.100 ± 0.004	0.040 ± 0.006
R5	0.07 ± 0.02	0.026 ± 0.009	-	-

Table 6: In this table all results for the conductor loop are displayed for comparison

at the table one can see that the theoretical values for the magnetic field have a much bigger uncertainty than the measured ones. The reason for this lies as we already said in the analysis in the big error on the measured distance z. With the given setup and the measuring methods it was not possible to measure the distance properly and we tried to make it more accurate by measuring three distances and adding them up. As we determined the error with gaussian error propagation it got even bigger because of this, even if the measured value probably got better. For the measured values the distance z was irrelevant so the error got a lot smaller here.

Nevertheless we can say that all measured values are surprisingly close to the calculated ones if you remember that the experiment did not work at all the days before. This also makes it hard to decide whether a magnetic field in the background was the reason for the experiment not working or a loose contact.

Furthermore we can see that the magnetic field decreases with stronger resistance. This has been expected as a higher resistance means a lower current and in consequence a lower magnetic field.

For the measurement with the other samples we got the values displayed in table 7.

Sample	Magnetic Field [nT]	Magnetic Dipole Moment [µA^2 m]
Iron Stick	52.27 ± 0.05	21 ± 3
Iron Flake	0.032 ± 0.006	0.013 ± 0.003
Magnet Flake ($\omega 10$)	47.5 ± 0.2	19 ± 3
Magnet Flake ($\omega 5$)	47.8 ± 0.2	19 ± 3

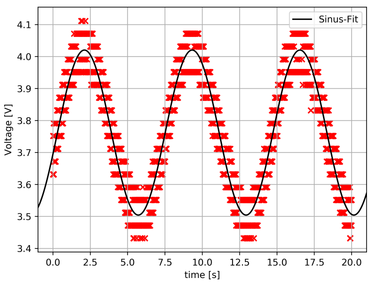
Table 7: In this table the magnetic fields and the dipole moments for different samples are listed.

These values are on a reasonable scale even though the signal we measured with the SQUID seemed quite suspicious. The smalles measured field was for the iron flake with $B_{\text{iron flake}} = (0.032 \pm 0.006)\,\text{nT}$ the strongest field was measured with the iron stick $B_{\text{iron stick}} = (52.27 \pm 0.05)\,\text{nT}$. Though one has to look on the plots and decide if the signal for the iron stick still can be interpreted as a sine.

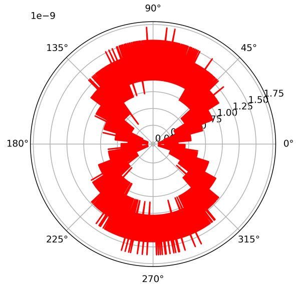
The polar plots shown in the appendix looked just like we expected. For a perfect dipole the polar plot should show two circles with their crossing point on the origin. The plots we got show this pattern for the measurements were we acually measured a sine signal. For the remaining plots one can only say that the polar plots show the expecting, a measurement that does not give results.

6 Appendix

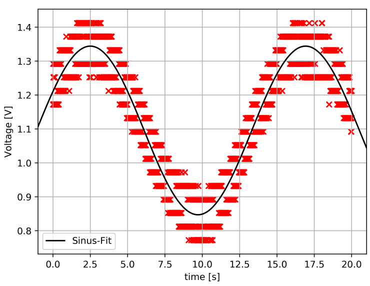
Figure 4: Sine Fits and polar plots



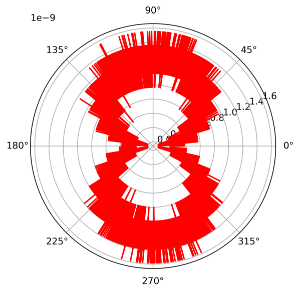
(1) Sine fit for current loop 1



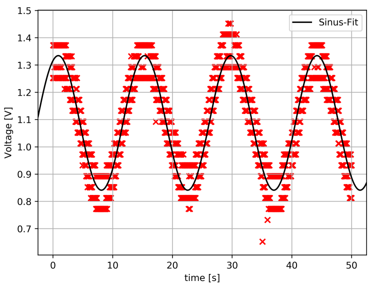
(2) Polar plot for current loop 1



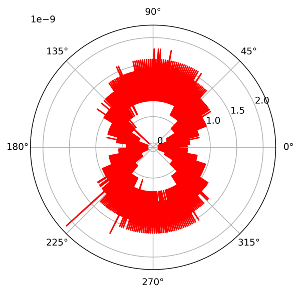
(3) Sine fit for current loop 2



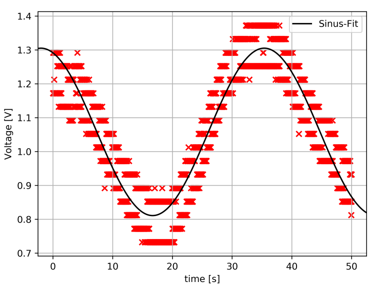
(4) Polar plot for current loop 2



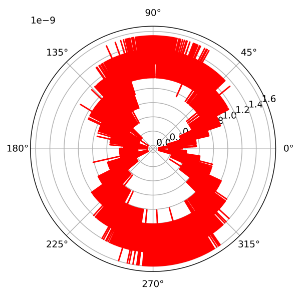
(5) Sine fit for current loop 3



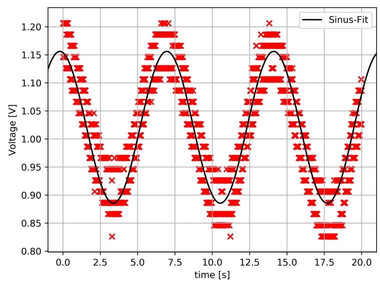
(6) Polar plot for current loop 3



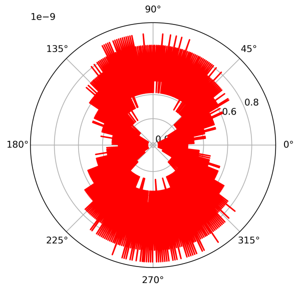
(7) Sine fit for current loop 4



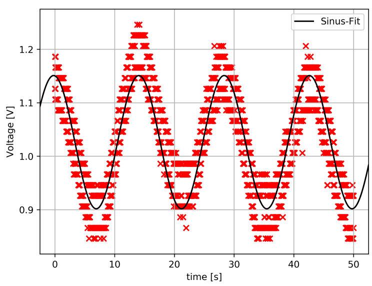
(8) Polar plot for current loop 4



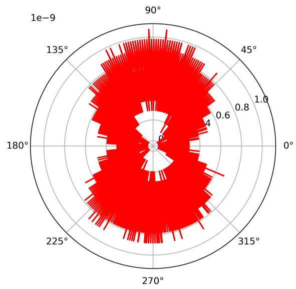
(9) Sine fit for current loop 5



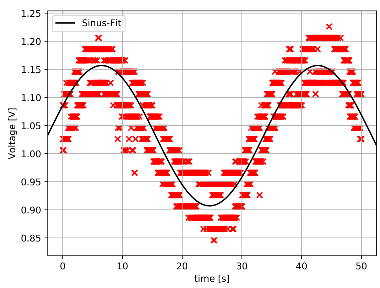
(10) Polar plot for current loop 5



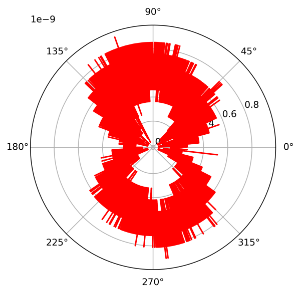
(11) Sine fit for current loop 6



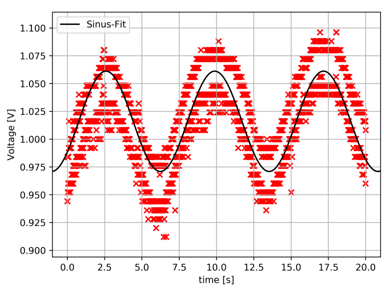
(12) Polar plot for current loop 6



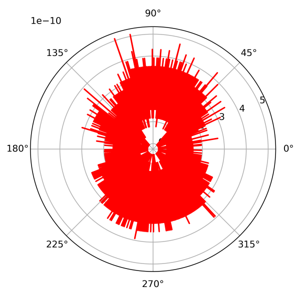
(13) Sine fit for current loop 7



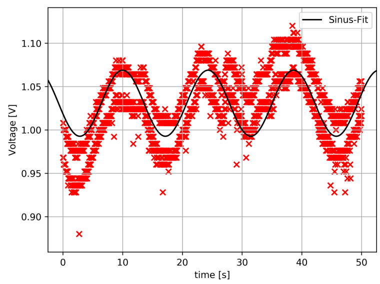
(14) Polar plot for current loop 7



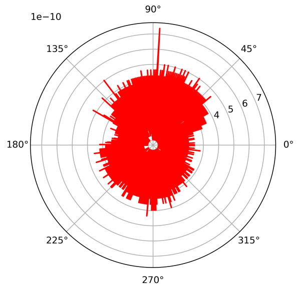
(15) Sine fit for current loop 8



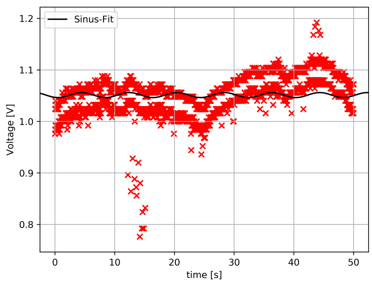
(16) Polar plot for current loop 8



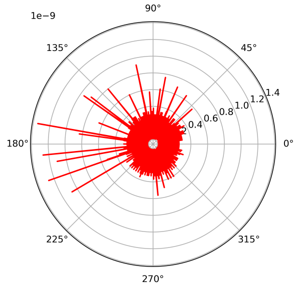
(17) Sine fit for current loop 9



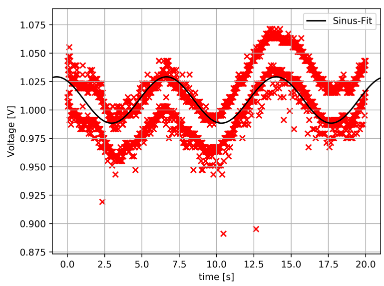
(18) Polar plot for current loop 9



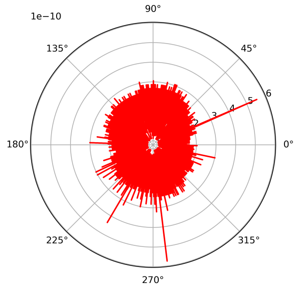
(19) Sine fit for current loop 10



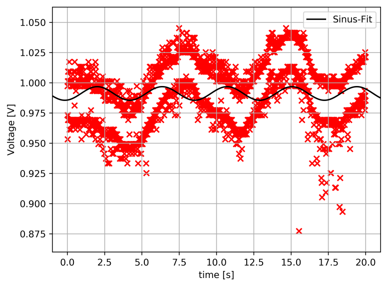
(20) Polar plot for current loop 10



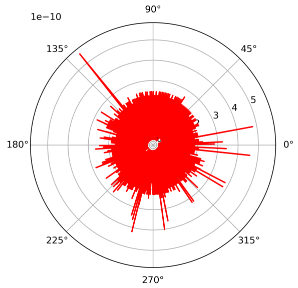
(21) Sine fit for current loop 11



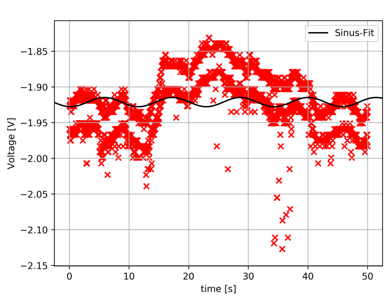
(22) Polar plot for current loop 11



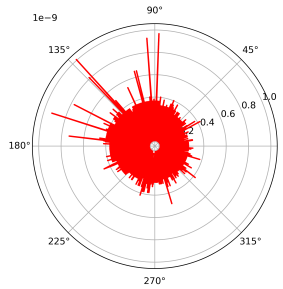
(23) Sine fit for current loop 12



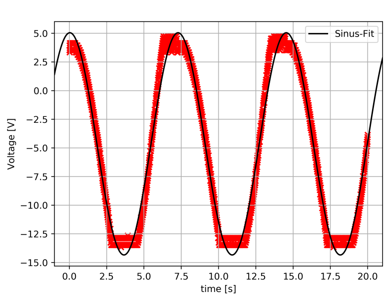
(24) Polar plot for current loop 12



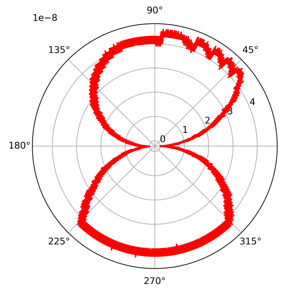
(25) Sine fit for iron Flake



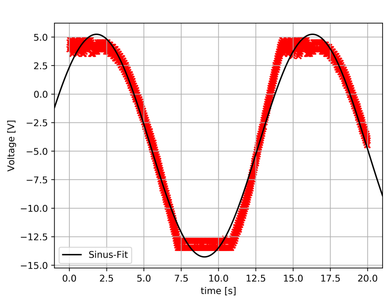
(26) Polar plot for iron Flake



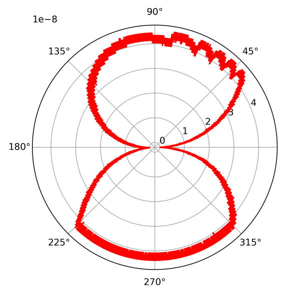
(27) Sine fit for magnet flake 1



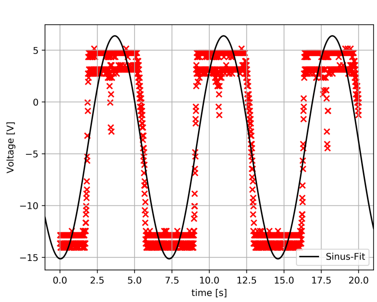
(28) Polar plot for magnet flake 1



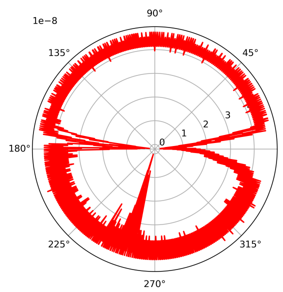
(29) Sine fit for magnet flake 2



(30) Polar plot for magnet flake 2



(31) Sine fit for iron stick



(32) Polar plot for iron stick

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References

[Source 1] *"Versuchsanleitung Fortgeschrittenenpraktikum Teil 1, Super Conductive Interference Device, M. Köhli Stand 09/2019."*

```
import numpy as np
from matplotlib import pyplot as plt
from scipy.optimize import curve_fit
from module import *

# SET Variables ================================================================
name = "spule11"

F = 9.3e-9 # [T/Phi_0]
mu_0 = 1.25664e-6 # N/A^2

k = 1.9 # [V/Phi_0]          <---  depends on feedback resistor

R = 510.6# Ohm              <---  with conductor loop used resistor
s_R = 0.5

r = 0.00175 # m              <---  radius of conductor loop
s_r = 0.0003

a = np.pi*r**2 # m^2
s_a = np.pi*2*r*s_r

z = 0.043 # m                <---  distance SQUID/sample
s_z = 0.002

ul = [2.66,2.73,2.69,2.81,2.83]
U = mean(ul) # V                  <---  voltage applied on resistor
s_U = sigma(ul)

print(U)
print(s_U)
# READ File ====================================================================
with open(name+".csv","r") as f:
    doc = f.read()

lines = doc.split("\n")
del lines[0]
del lines[-1]
xx = list() # [s]
yy = list() # [V]
for i in range(0,len(lines)):
    entrys = lines[i].split(",")
    xx.append(float(entrys[0]))
    yy.append(float(entrys[2]))

# SET Plotrange ================================================================
left = min(xx)
right = max(xx)
span = abs(left-right)
space = 0.05*span

# EXECUTE Programm =============================================================
popt, pcov = sin_fit(xx,yy,None,left,right,space,name)
A = popt[0]
B = popt[1]
C = popt[2]
D = popt[3]
s_A = np.sqrt(pcov[0][0])
s_B = np.sqrt(pcov[1][1])
s_C = np.sqrt(pcov[2][2])
s_D = np.sqrt(pcov[3][3])
# print("A:",A," +- ",s_A)
# print("B:",B," +- ",s_B)
# print("C:",C," +- ",s_C)
# print("D:",D," +- ",s_D)

string = name+"_ANALYSE \nFitparameter zu f(t) = A + B*sin(C*t + D) \n"+\
"A: "+str(A)+" +- "+str(s_A)+"\nB: "+str(B)+" +- "+str(s_B)+\
```

```
"\nC: "+str(C)+" +- "+str(s_C)+"\nD: "+str(D)+" +- "+str(s_D)

aa = list(map(lambda x: C*x +D, xx))
BB = list()
for i in range(0,len(yy)):
    BB.append(abs(F*(yy[i] - A)/k))

# B-Feld/p-Moment ===============================================================
Bmag = F*B/k                                # MEASURED
Bmag2 = mu_0*0.5*U*(r**2)/(R*(z**3))        # THEORETICAL
pmag = 2*np.pi*Bmag*(z**3)/mu_0             # MEASURED
pmag2 = a*U/R                               # THEORETICAL

s_Bmag = F*s_B/k
s_Bmag2 = mu_0*0.5*np.sqrt(((r**2)/(R*(z**3))*s_U)**2 +
        (2*U*r/(R*(z**3))*s_r)**2 +
        (U*(r**2)*s_R/((R**2)*(z**3)))**2 + (3*U*(r**2)*s_z/(R*(z**4)))**2)
s_pmag = (2*np.pi/mu_0)*np.sqrt((s_Bmag*z**3)**2 + (s_z*Bmag*3*z**2)**2)
s_pmag2 = np.sqrt((U*s_a/R)**2 + (a*s_U/R)**2 + (a*U/(R**2))**2)

string2 = "B_Feld:\nTheoretisch: "+str(Bmag2)+" +- "+str(s_Bmag2)+\
        "\nGemessen: "+str(Bmag)+" +- "+str(s_Bmag)+\
        "\np_mag:\nTheoretisch: "+str(pmag2)+" +- "+str(s_pmag2)+\
        "\nGemessen: "+str(pmag)+" +- "+str(s_pmag)

# SAVE Files ====================================================================
with open(name+"_ANA.txt","w") as f:
    f.write(80*"="+"\n"+string+"\n"+80*"="+"\n"+string2+"\n"+80*"=")

plt.polar(aa,BB,'-r')
plt.savefig(name+"_POLAR.png",dpi = 500)
# plt.show()
```

```
import numpy as np
from matplotlib import pyplot as plt
from scipy.optimize import curve_fit

#DEF Functions ================================================================
def sinus(x,a,b,c,d):
    return a + b*np.sin(c*x + d)

def mean(x):
    return sum(x)/len(x)

def sigma(x):
    summe = 0
    for k in x:
        summe += (k - mean(x))**2
    return np.sqrt((1/(len(x)-1))*summe)

def sin_fit(x_data,y_data,s_data,left,right,space,name):
    plt.scatter(x_data,y_data,marker = 'x',color = "red")

    dists = list()
    dummylist = [(x, y) for x, y in sorted(list(zip(x_data,
        list(map(lambda y: abs(y - mean(y_data)),
        y_data)))), key=lambda t: t[1])[:int(len(x_data) / 15)]]

    mdist = 0
    p1 = (0, 0)
    p2 = (0, 0)

    dummylist2 = sorted(dummylist, key=lambda t: t[0])
    for i in range(len(dummylist2) - 1):
        dist = dummylist2[i + 1][0] - dummylist2[i][0]
        dists.append(dist)
        if dist > mdist:
            mdist = dist
            p1 = dummylist2[i]
            p2 = dummylist2[i + 1]


    guess_freq = np.pi / mdist

    popt, pcov = curve_fit(sinus, x_data, y_data,p0 = [mean(y_data),
        (3/np.sqrt(2))*sigma(y_data),guess_freq,0])

    xx = np.linspace(left-space,right+space,400)

    plt.plot(xx,sinus(xx, *popt),color = "black", label = "Sinus-Fit")
    plt.xlim(left-space,right+space)
    plt.grid()
    plt.legend()
    plt.xlabel("time [s]")
    plt.ylabel("Voltage [V]")
    plt.savefig(name+"_PLOT.png",dpi = 500)
    # plt.show()
    return popt, pcov
```

SQID - Superconducting Quantum Interference Device

l_1 : 22,0 cm $s_{l_{1,2,3}} = 0,1$ cm
l_2 : 1,4 cm
l_3 : + 1,3 cm

$l_{ges} = 25,7$ cm

CH1 : 2V
CH2 : 50 mV
CH1 Zeit 120 ms

h : 29 cm $s_h = 0,1$ cm

$d = |l_{ges} - h|$ (Abstand SQUID - Probe)

Kalibrierungsmessung (Tag 1)

Oszi : CH1 (Ein) : 2V

CH2 (Aus) : 200 mV

Time : 120 ms

JSQ Duo Sensor Control :

CH1	VCA :	1461	IntegrC :	2200 pF
	VCO :	1570		
	OFF	2120	FB-R :	100 kΩ
CH2	VCA	0	IntegrC :	1000 pF
	VCO :	1333		
	OFF	0	FB-R :	100 kΩ

Messung: Leiterschleife

R1 : Braun Gold Braun Braun Grün

$V_{ab} = 2,73$ V Messbereich 20V (Voltmeter)

Motoreneinstellung $\boxed{10}$ → 5 Umd. in 36,00 s

Kalibrierungsmessung (Tag 2)

JSQ Duo Sensor Control:

CH1	VCA	1147	IntegrC	2200 pF
	VCO	1389	FB-R	100 kΩ
	OFF	1804		
CH2	VCA	0	IntegrC	1000 pF
	VCO	1333	FB-R	100 kΩ
	OFF	0		

Messung	Kommentar	CH 2: 1V
Stab 1	w -> 10 hoch	
Spule 1	w -> 10, R_1	
Stab 2	(ist eine Spule ∇) w -> 5, R_1	
Spule 3	w -> 5, R?, lange Aufnahme	
Spule 4	w -> 2, R_1	
Spule 5	w -> 10, R_2	CH 2: 500 mV
Spule 6	w -> 5, R_2	-"-
Spule 7	w -> 2, R_2	-"-
Spule 8	w -> 10, R_3	CH2: 200 mV
Spule 9	w -> 5, R_3	CH2: 200 mV
Spule 10	w -> 2, R_3	-"-
Spule 11	w -> 10, R_4	CH2: 100 mV
Spule 12	w -> 10, R_5	CH2: 100 mV

R_1: U_{ab} = 2,66 V (20 V Bereich)
R_2: U_{ab} = 2,73 V
R_3: U_{ab} = 2,69 V
R_4: U_{ab} = 2,81 V
R_5: U_{ab} = 2,83 V

Widerstandswerte Foto

Leiterschleife : d = 3,5 mm

Span 1 ω -> 10 , CH2 = 5V
Span 2 ω -> 5 , CH2 = 5V } Magnetspan
Eisenspan 1 ω -> 10 , CH2 = 200 mV

Rotationsgeschwindigkeiten

5 : 43,43 s , 3 Umdrehungen
2 : 70,72 s , 2 -"-