Integration of Magnetization and Penetration Depth Measurements for Superconducting Samples

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We present penetration depth and magnetization measurements using the Cantilever and Tunnel Diode Oscillator techniques on the heavy fermion superconductor $CeCoIn_5$. My goal is to attempt to combine both the Cantilever and TDO techniques by constructing coils that have different inner diameter, number of turns, and wire thickness. . The penetration depth measurements for the coils are made with a TDO circuit board that has a tunnel diode. I investigated the different properties of the coils to determine the best combination for the Cantilever and TDO technique.

$CeCoIn_5$ is a newly discovered material first reported in 2001. It was discovered by C. Petrovic et al.[i]. This heavy fermion superconductor (T_c = 2.3 K) has a structure composed of alternating layers of $CoIn_2$ and $CeIn_3$. When both of these layers are combined, they form the tetragonal unit cell of $CeCoIn_5$. In order to learn more about the properties of this single crystal layered material, two techniques were used to analyze its properties at low temperatures.

The cantilever magnetometry technique measures the magnetization of a material. It does this by reading the capacitance between two parallel plates, which act as a capacitor. It has a bottom fixed plate made of copper, which is glued with epoxy to the platform. The top plate, also referred to as cantilever, is made of beryllium-copper. The cantilever is placed over a G-10 piece to keep it from coming in contact with the bottom plate and to act as a fulcrum. The cantilever and G-10 piece are held in place with two screws that connect it to the platform (see **Figure 1** and **Figure 2**). The $CeCoIn_5$ sample is then glued to the cantilever with GE varnish to keep it from falling off while the probe is in the magnet. When the dilution refrigerator has reached base temperature, approximately 20 mK, the magnetic field is increased and the cantilever begins to experience a torque due to the misalignment of the magnetic moment of the sample with the applied field. Since the torque is directly proportional to the change in capacitance, a capacitance bridge is used to measure the change in capacitance to find the magnetization of the $CeCoIn_5$ sample (see **Figure 3**).

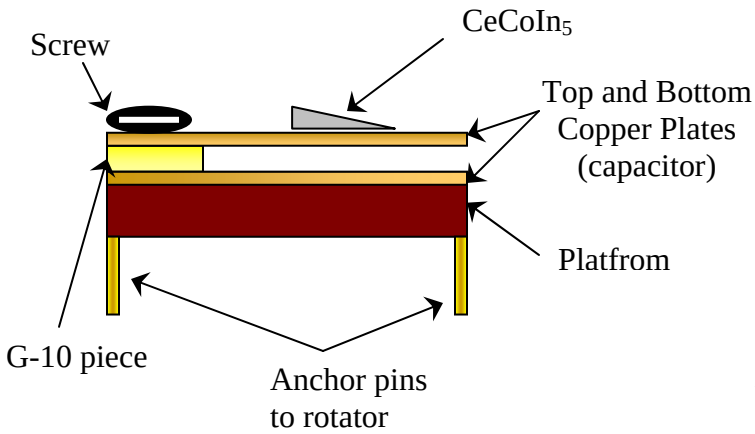


Figure 1
Cantilever platform side view.

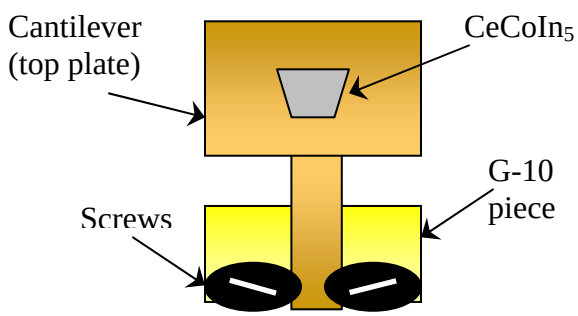


Figure 2
Cantilever on platform, top view. The cantilever is 12 micrometers thick.

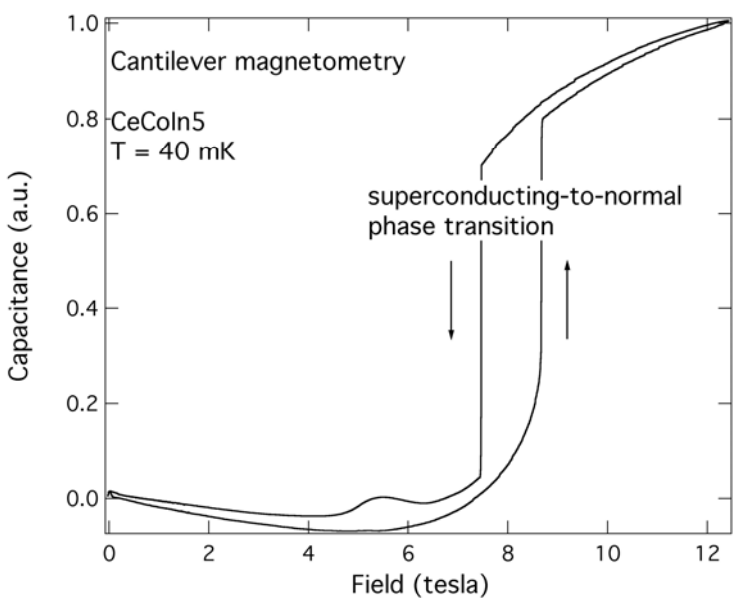


Figure 3
Cantilever Magnetometry graph with an up and down sweep, as shown by the arrows. The down sweep is slightly shifted lower in field due to hysteresis in the sample.

The Tunnel Diode Oscillator (TDO) technique measures the penetration depth (surface conductivity) of a $CeCoIn_5$ sample. In order to prepare a TDO platform, a coil needs to be mounted on a G-10 piece with a sample of $CeCoIn_5$ that is small enough to fit in the middle of the coil. GE varnish is placed over the coil and sample to keep them in place on the G-10 piece. The G-10 piece is securely glued on the platform with epoxy (see **Figure 4**). The next step is to solder the coil that is on the platform to the coaxial wire that is coming form one end of the TDO circuit board. The other end of the TDO board has a coaxial wire that runs to the top of the probe. From the top, it is connected to the TDO rack and the computer for penetration depth readings. Since the penetration depth is proportional to the resonance frequency, measurements are made on the frequency counter (see **Figure 5**).

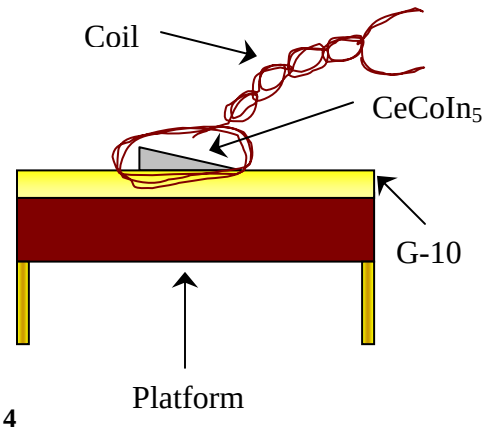


Figure 4
TDO platform side view.

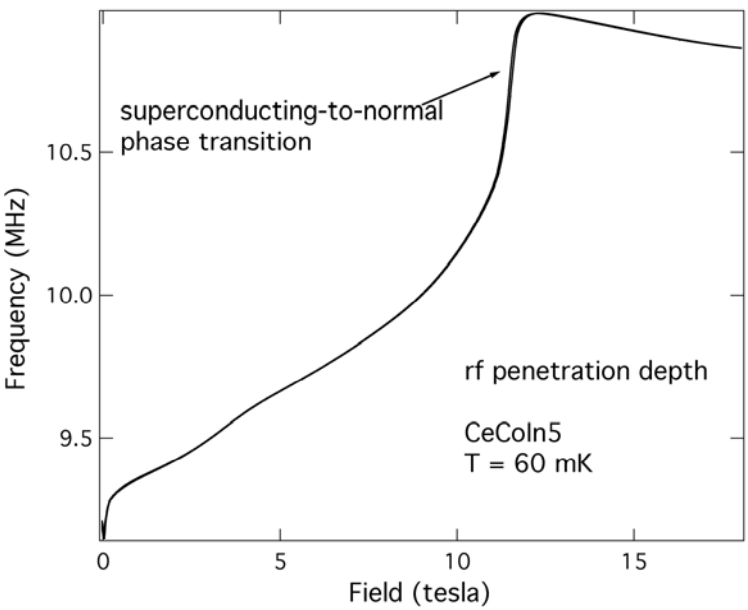


Figure 5
Penetration depth graph using TDO at 60 mK.

The main goal of the experiment is to observe and measure the penetration depth of an ac field on a superconductor at a fixed temperature as a function of the magnetic field. In an attempt to combine both the cantilever and TDO technique, coils were constructed that have different inner diameters, different number of turns, and different wire thickness to help determine the best coil for the cantilever and TDO measurements.

Two types of wire were used for the experiment, #38 American Wire Gauge (.0045 inches or .1143 mm thick) and #44 American Wire Gauge (.0022 inches or .05588 mm thick). Each wire was fabricated into two different size coils, one with an inner diameter of 2.5 mm and the other with an inner diameter of 3 mm. The inner diameter was made by using a #100 mandril (2.5 mm) and a #125 mandril (3 mm). The number of turns on the coil was determined by how many times the wire went around the mandril. For each mandril 3 and 6 turn coils were produced; therefore each type of wire had a total of four coils.

Once the coil was made and the insulation was removed from the ends of the coil, it was soldered to one coaxial wire that led to the TDO circuit board. The TDO board is composed of three resistors, three capacitors and one tunnel diode. When the coaxial wire was soldered to the TDO board, the TDO board was exposed to 600° F for the time the soldering iron was touching the TDO board. This rapid change in temperature can cause the TDO components to malfunction. It is important to only make contact with the TDO board for one or two seconds at a time when soldering any object.

In order to check whether a coil was soldered on correctly, a resistance check needs to be made to verify whether the circuit is ready for testing. If a coil is attached to the TDO board then the ohmmeter should read 460Ω and 477Ω when the polarity is changed (these specific values are due to the TDO board used for the experiment). However if there is no coil attached or if the coil was soldered incorrectly resulting in an open circuit, the ohmmeter should read 602Ω with the used set of components.

Once the circuit is ready and it is connected to the TDO rack, it can be dipped into liquid nitrogen. The coil is too small to resonate at room temperature with out the tunnel diode, therefore it is necessary to go from 300 K (room temperature) to 77 K (liquid nitrogen) to see the circuit resonate. Once the TDO board is properly biased, then it is a self resonant circuit with frequencies typically in the range of 50 to 500 MHz depending on capacitance and inductance. When taking data from the oscilloscope, there are four main things to look for in each coil: the fundamental frequency (MHz), the amplitude (dB), the bias range (mV), and the number of harmonics.

The same procedures are followed for each coil until all the measurements have been gathered for both the #38 AWG and the #44 AWG coil measurements. The data is as followed in **Figure 6** and **Table 1**.

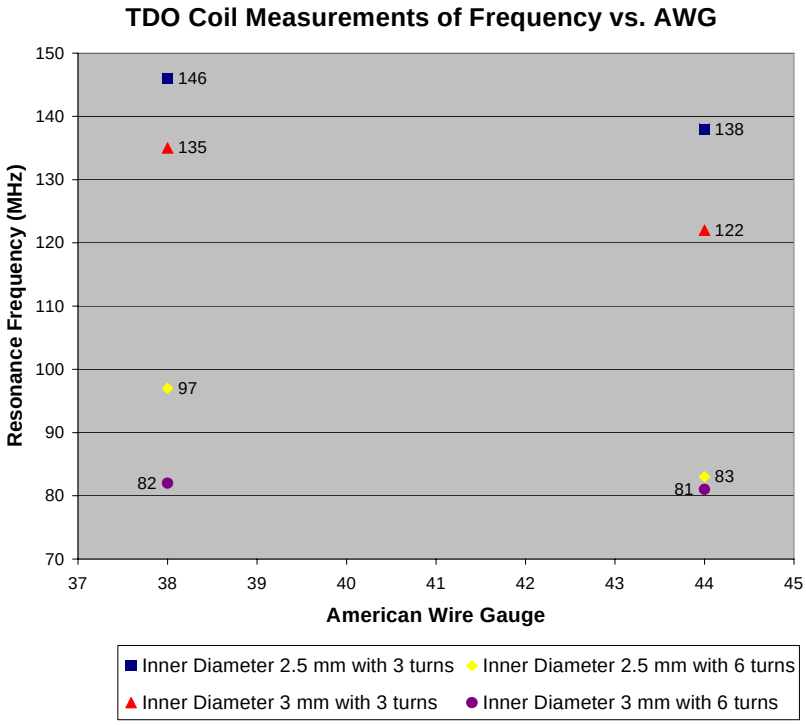


Figure 6
Tunnel Diode Oscillator Coil Measurements of Frequency vs. American Wire Gauge.

Table 1
Coil test data using Tunnle Diode Oscillator. Data was taken at a bias value of 45 mV.

The next step is to place the coils on

 # 38 Wire
mandrill 100 w/3 turns

Bias Range :	39 mV 67 mV
F_0 :	146 MHz
amplitude :	(-) 6 dB
F_1 :	295 MHz
F_2 :	440 MHz
F_3 :	587 MHz
F_4 :	733 MHz
F_5 :	880 MHz

 # 38 Wire
mandrill 100 w/6 turns

Bias Range :	38 mV 80 mV
F_0 :	97 MHz
amplitude :	(-) 33 dB
F_1 :	194 MHz
F_2 :	291 MHz
F_3 :	388 MHz
F_4 :	484 MHz
F_5 :	581 MHz
F_6 :	775 MHz

 # 38 Wire
Mandrill 125 w/3 turns

Bias Range :	39 mV 71 mV
F_0 :	135 MHz
amplitude :	(-) 21 dB
F_1 :	271 MHz
F_2 :	407 MHz
F_3 :	542 MHz
F_4 :	678 MHz
F_5 :	813 MHz
F_6 :	949 MHz

 # 38 Wire
mandrill 125 w/6 turns

Bias Range :	38 mV 83 mV
F_0 :	82 MHz
amplitude :	(-) 31 dB
F_1 :	164 MHz
F_2 :	246 MHz
F_3 :	328 MHz
F_4 :	410 MHz
F_5 :	492 MHz
F_6 :	574 MHz
F_7 :	656 MHz

 # 44 Wire
mandrill 100 w/3 turns

Bias Range :	39 mV 70 mV
F_0 :	138 MHz
amplitude :	(-) 27 dB
F_1 :	275 MHz
F_2 :	412 MHz
F_3 :	549 MHz
F_4 :	686 MHz
F_5 :	824 MHz
F_6 :	961 MHz

 # 44 Wire
mandrill 100 w/6 turns

Bias Range :	38 mV 80 mV
F_0 :	83 MHz
amplitude :	(-) 21 dB
F_1 :	166 MHz
F_2 :	249 MHz
F_3 :	333 MHz
F_4 :	416 MHz
F_5 :	499 MHz
F_6 :	582 MHz
F_7 :	665 MHz
F_8 :	748 MHz

 # 44 Wire
Mandrill 125 w/3 turns

Bias Range :	39 mV 72 mV
F_0 :	122 MHz
amplitude :	(-) 27 dB
F_1 :	244 MHz
F_2 :	366 MHz
F_3 :	488 MHz
F_4 :	610 MHz
F_5 :	732 MHz

 # 44 Wire
mandrill 125 w/6 turns

Bias Range :	38 mV 81 mV
F_0 :	81 MHz
amplitude :	(-) 40 dB
F_1 :	161 MHz
F_2 :	242 MHz
F_3 :	323 MHz
F_4 :	403 MHz
F_5 :	483 MHz
F_6 :	570 MHz
F_7 :	651 MHz
F_8 :	732 MHz

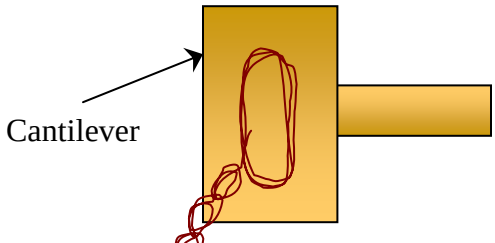
cantilevers to see how its' properties change. The same eight coils from the first part of the experiment are used with the cantilevers on the second part of the experiment. The coil is placed on the cantilever and it is glued together with GE varnish (see **Figure 7**). The same procedures that apply to the coil also apply to the combined cantilever and TDO setup. Once the measurements were taken, the coil and cantilever are dipped into a 1:1 ratio solution of ethanol and toluene. This solution removes the GE varnish from the cantilever and coil to allow the cantilever to be reused for all other coils.

Once the procedures have been repeated for all cantilever and coil measurements on both the #38 AWG and the #44 AWG, the data can be compiled as shown as follows in **Figure 8** and **Table 2**.

Based on the data collected from the experiment, it is possible to combine both the cantilever and TDO technique (see **Figure 9**). However there are positive and negative effects that arise from the combination of both techniques. The cantilever damps the circuit and decreases the number of harmonics, which is a positive effect. At the same time, the cantilever creates interference on the circuit causing two signals with #44 AWG to completely disappear due to eddy currents, which is a negative effect. Another observation is the shift in frequency to higher values when attaching the TDO coil to the cantilever. Furthermore, it turns out that the bias range decreases resulting in a smaller range of surface conductivity that can be measured. Therefore the parameters for the coil need to be selected carefully as a result of the two counter acting effects.

Figure 7
Cantilever and coil top view. Coil not drawn to scale. The top should have a rounder look and the turns should be right below it (not slanted to the left side as shown in the picture above).

Figure 8
TDO Coil on Cantilever Measurements of Frequency vs. American Wire Gauge.



# 38 Wire mandrill 100 w/3 turns	**# 38 Wire** mandrill 100 w/6 turns	**# 38 Wire** mandrill 125 w/3 turns	**# 38 Wire** mandrill 125 w/6 turns
Bias Range : 43 mV 52 mV	Bias Range : 42 mV 58 mV	Bias Range : 42 mV 53 mV	Bias Range : 41 mV 59 mV
F_0 : 179 MHz amplitude : (-) 8 dB	F_0 : 138 MHz Amplitude : (-) 30 dB	F_0 : 180 MHz amplitude : (-) 27 dB	F_0 : 118 MHz amplitude : (-) 27 dB
F_1 : 357 MHz F_2 : 536 MHz	No Visible Harmonics	No Visible Harmonics	No Visible Harmonics
# 44 Wire mandrill 100 w/3 turns	**# 44 Wire** mandrill 100 w/6 turns	**# 44 Wire** mandrill 125 w/3 turns	**# 44 Wire** mandrill 125 w/6 turns
Bias Range : 44 mV 49 mV	No Oscillations	Bias Range : 42 mV 48 mV	No Oscillations
F_0 : 118 MHz amplitude : (-) 36 dB		F_0 : 172 MHz amplitude : (-) 33 dB	
No Visible Harmonics		No Visible Harmonics	

Table 2
Testing Coil on Cantilever using Tunnel Diode Oscillator. Data was taken at a bias value of 45 mV.

The results show that 3 turns yield larger amplitudes than 6 turns, therefore the fewer number of turns the coil has the larger the amplitude will be. However the data shows that all the amplitude values are negative, which means the closest amplitude to zero would be the best in this case.

The next step in this project would be to place a sample inside the coil to see how the cantilever affects it and if the data changes with the sample in the coil.

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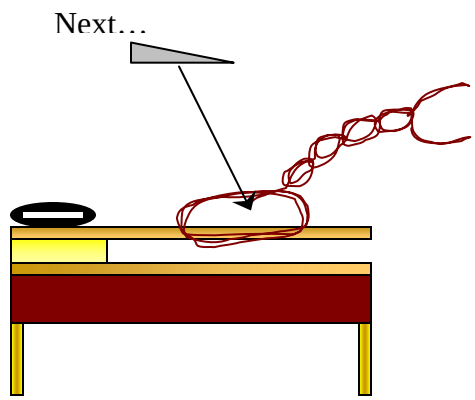

Figure 9
Cantilever and TDO platform side view.

References

[i] C. Petrovic et al., J. Phys.: Condens. Matter **13**, 337 (2001).