High-Temperature Superconductivity

1. Objective

This experiment measures the superconducting phase transition in two types of ceramic materials known as **YBCO** and **BSCCO** ($YBa_2Cu_3O_7$ and $Bi_2Sr_2Ca_2Cu_3O_9$) at temperatures near 77 ° K. When cooled by liquid nitrogen, these normally electrically-insulating materials become **superconductors** at characteristic transition temperatures less than 77°K. As their electrical resistance and magnetic susceptibility are continuously measured through their transition temperatures, these materials demonstrate nearly perfect electrical conductivity and diamagnetism.

The electrical resistance of a BSCCO sample will be measured directly by sending a direct current through the sample and measuring the voltage difference across it. The magnetic susceptibility of YBCO will be measured by sending an alternating current through an ordinary wire inductor with a YBCO core and measuring the impedance in the circuit.

2. Theory

2.1 Superconductivity

While metals like copper conduct electricity better at low temperatures, some metals can remarkably carry electrical current with **zero resistance** when cooled below a critical temperature, typically a few kelvins above Absolute Zero. This phenomenon is known as **low-temperature superconductivity.** For instance, mercury and lead superconduct at temperatures of around 4°K and 7°K, respectively. In the 1980's, **high-temperature superconductors** that are not metals such as YBCO and BSCCO were discovered to superconduct at temperatures above the boiling point of liquid nitrogen (77°K) at atmospheric pressure. These materials are attractive from an engineering point of view because liquid nitrogen is relatively cheap and easy to handle compared to the liquid helium used in early superconductor experiments. Superconductivity has been observed at temperatures up to 138° K in materials related to YBCO and BSCCO.

The most widely accepted theory of low-temperature superconductivity is named **BCS Theory** after its authors Bardeen, Cooper, and Schrieffer, who shared the Nobel prize in 1972. BCS theory does not predict superconductivity at temperatures above 30 K, so the theory fails to explain why high-temperature superconductors exist! A universally accepted theory for high-temperature superconductivity theory is still being pursued.

In this experiment, we will use DC (direct current) and AC (alternating currents) circuits to observe the superconducting transition in high temperature superconductors. Here is

a quick review of relevant circuit theory needed for the experiment.

2.2 DC Resistance

Electrical resistance is a measure of a material's resistance to the passage of electrical current. For normal (non-superconducting) metals, this is governed by Ohm's Law:

$$V = I\,R$$

where I is the constant (DC) **current** passed through the sample and V is the **voltage drop** developed across it . Thus, a typical ohmmeter measures resistance by sending a DC current through the wires attached to both ends of the sample, and measuring the total voltage drop throughout the *wires (often called leads) and sample*. While we often assume that the resistance of the leads is small enough to be neglected, this is not the case in our experiment! Instead, our setup uses an ammeter and voltmeter together in an arrangement known as a **four-point measurement or probe,** as shown below. This process eliminates the lead resistances in the measurement.
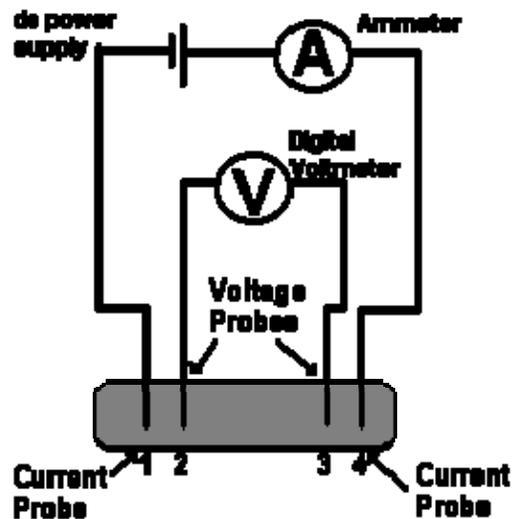

Figure 2 Schematic of Four-Point Probe

In this experiment, a sample of BSCCO has been pre-assembled with a four-point probe. The "current probe" wires are connected to a power supply which provides a constant current of **100 mA**. The "voltage probe" wires are connected to a high-precision digital voltmeter. From room temperature readings on the voltmeter, one can deduce that the resistance of the sample follows Ohm's Law $R = V\,/\,I$.

The sample is immersed in liquid nitrogen, which cools it to 77°K. The sample is then removed from the nitrogen and allowed to slowly warm up to room temperature. The voltage drop at various temperatures is recorded and the sample resistance is calculated and plotted as a function of temperature. The resulting graph should look like this:
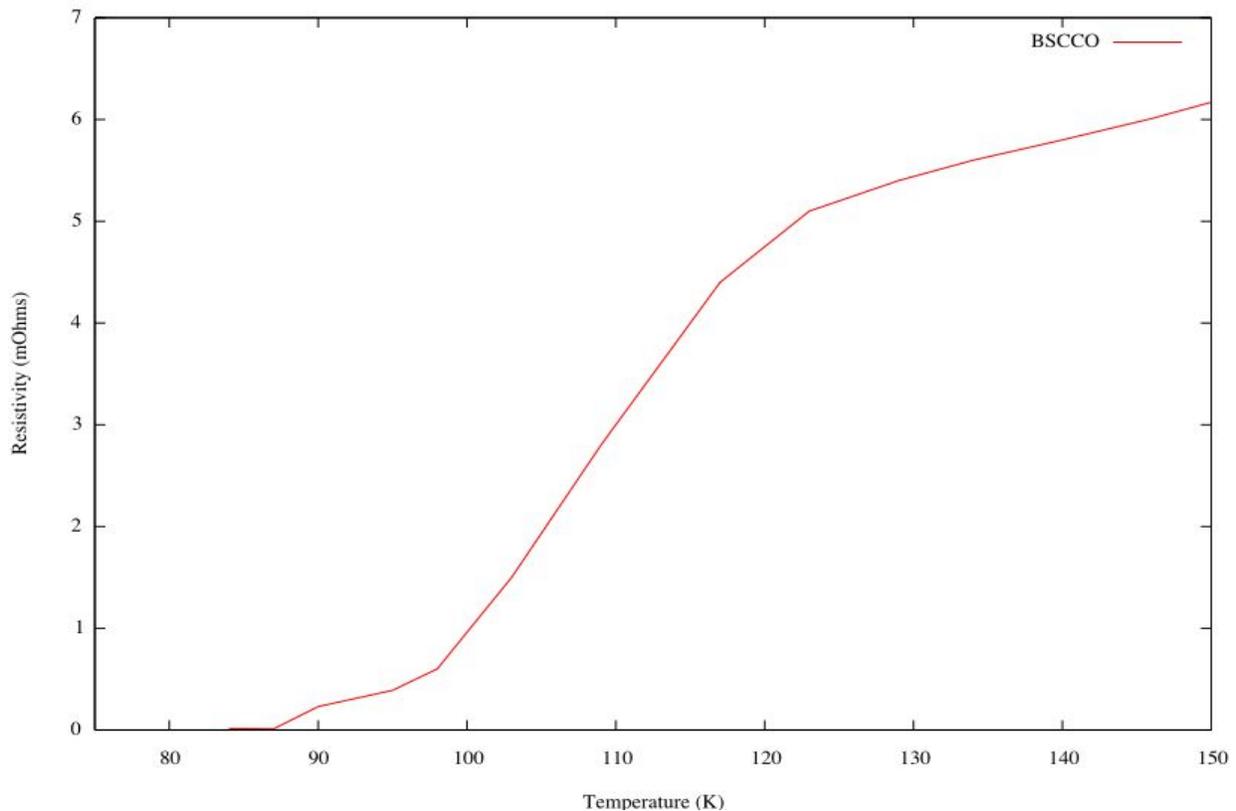
Like many materials, BSCCO's resistance decreases as it cools. Around 100º -120°K, it drops rapidly and under 90 °K, it is too low to measure accurately in this setup.

2.3 Using a Thermocouple to Measure Temperature

The temperatures involved in this experiment vary from 77°K to room temperature, and ordinary thermometers typically do not work well over such a range. Instead, we use a **thermocouple** connected to a DC voltmeter to determine temperature. A thermocouple is made from two different metal wires (typically copper and constantan) that naturally produce a small voltage difference when subjected to a temperature difference. The outermost ends of the wires will be kept at room temperature, while the other ends are immersed are connected to the sample. The voltage difference is measured and compared to a standard table of experimentally determined values such as the one on the next page. Use this table for converting thermocouple voltage readings to temperature (in °K).

Conversion from mV to Kelvin

°K	0	1	2	3	4	5	6	7	8	9	10	°K
60	7.60	7.53	7.46	7.40	7.33	7 26	7.19	7.12	7.05	6.99	6.92	60
70	6.92	6.85	6.78	6.71	6.64	6.56	6.49	6.42	6.37	6.33	6.29	70
80	6.29	6.25	6.21	6.17	6.13	6.09	6.05	6.01	5.97	5.93	5.90	80
90	5.90	5.86	5.83	5.79	5.75	5.72	5.68	5.64	5.60	5.56	5.52	90
100	5.52	5.48	5.44	5.41	5.37	5.34	5.30	5.27	5.23	5.20	5.16	100
110	5.16	5.13	5.09	5.06	5.02	4.99	4.95	4.91	4.88	4.84	4.81	110
120	4.81	4.77	4.74	4.70	4.67	4.63	4.60	4.56	4.53	4.49	4.46	120
130	4.46	4.42	4.39	4.35	4.32	4.28	4.25	4.21	4.18	4.14	4.11	130
140	4.11	4.07	4.04	4.00	3.97	3.93	3.90	3.86	3.83	3.79	3.76	140
150	3.76	3.73	3.69	3.66	3.63	3.60	3.56	3.53	3.50	3.47	3.43	150
160	3.43	3.40	3.37	3.34	3.30	3.27	3.24	3.21	3.18	3.15	3.12	160
170	3.12	3.09	3.06	3.03	3.00	2.97	2.94	2.91	2.88	2.85	2.82	170
180	2.82	2.79	2.76	2.73	2.70	2.67	2.64	2.61	2.58	2.53	2.52	180
190	2.52	2.49	2.46	2.43	2.40	2.37	2.34	2.31	2.29	2.26	2.23	190
200	2.23	2.20	2.17	2.14	2.11	2.08	2.05	2.02	1.99	1.96	1.93	200
210	1.93	1.90	1.87	1.84	1.81	1.78	1.75	1.72	1.69	1.66	1.64	210
220	1.64	1.61	1.59	1.56	1.54	1.51	1.49	1.46	1.44	1.41	1.39	220
230	1.39	1.36	1.34	1.31	1.29	1.26	1.24	1.21	1.19	1.16	1.14	230
240	1.14	1.11	1.09	1.07	1.04	1.02	0.99	0.97	0.94	0.92	0.89	240
250	0.89	0.87	0.84	0.82	0.79	0.77	0.74	0.72	0.69	0.67	0.65	250
260	0.65	0.62	0.60	0.58	0.55	0.53	0.50	0.48	0.45	0.42	0.40	260
270	0.40	0.38	0.36	0.34	0.32	0.30	0.28	0.26	0.24	0.22	0.20	270
280	0.20	0.18	0.16	0.14	0.12	0.10	0.08	0.06	0.04	0.02	0.00	280
290	0.00	-0.02	-0.04	-0.06	-0.08	-0.10	-0.12	-0.14	-0.16	-0.18	-0.20	290
300	-0.20	-0.22	-0.24	-0.26	-0.28	-0.30	-0.32	-0.34	-0.36	-0.38	-0.40	300

The superconductor itself is housed in a brass casing which has been pre-fitted with a thermocouple and wires for a four-point probe. The entire assembly looks like this:
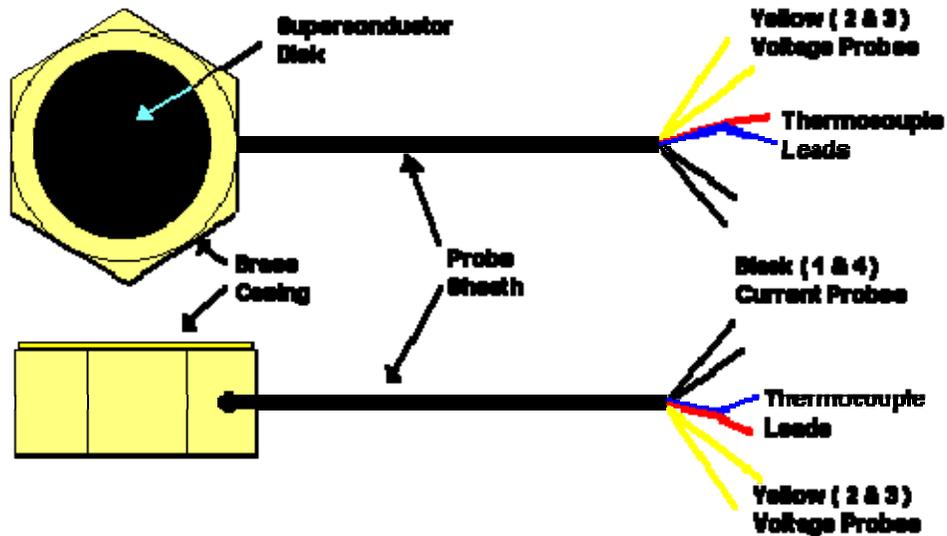

Figure 2 The Superconducting Four-Point Probe

2.4 AC Inductance, Reactance, and Impedance

When an alternating or sinusoidally oscillating (AC) current is passed through a closed electrical circuit, the laws of electromagnetism predicts that the circuit will develop induced voltages and currents that will oppose the AC current. The magntude of this effect is determined by the the geometry of the circuit, through its **inductance L.** The effect also increases with the **frequency f** of the driving AC current. These two factors can be summarized by the **inductive reactance X_L;** If f is the frequency of a power supply driving a circuit with an inductance of L, the reactance X_L is defined:

$$X_L = \omega L = 2\pi f L$$

The total measure of how much a circuit resists an AC current is called **impedance** and is usually denoted Z. The impedance lumps together the circuit's reactance and actual resistance. For a circuit with a known resistance R and reactance X,

$$Z = \sqrt{X^2 + R^2}$$

If a circuit includes one or more capacitors, there is an extra term in this formula called the **capacitive reactance**, but our circuit has no capacitors, so we ignore it for now.

If current in an AC circuit is constantly changing, what does an AC ammeter detect? An alternating current switches back and forth over time, so the *average* current through an AC circuit is zero! A more useful measure is **root-mean-square** current: I_{RMS}, the square root of the time-average of squared current. Electrical meters can typically also display root-mean-square voltages as V_{RMS}. These quantities are particularly useful because they obey an equation analogous to Ohm's Law for DC currents:

$$V_{RMS} = I_{RMS}\ Z$$

In this experiment, we are measuring the inductance of a coil of wire wrapped around a sample of YBCO. No current actually passes through the YBCO superconductor, but its diamagnetic (magnetic) properties can alter the inductance L of the coil of wire. By sending an alternating current through the coil and measuring the RMS current and voltage drop, we can find Z. If we know the frequency of the power supply and the resistance of the coil of wire, we can invert the equation for Z to find L. The circuit looks like this:
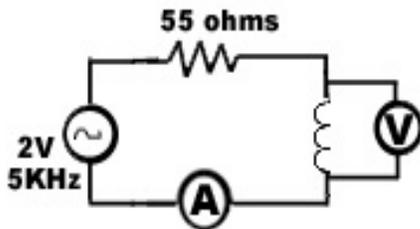
Notice that the AC voltmeter measures the voltage drop across the inductor, not across the entire circuit! Therefore the 55 ohm resistor does not affect our calculation of Z.

2.5 Magnetic Susceptibility

The inductance of a coil of wire can be increased or decreased by wrapping it around a

paramagnetic, ferromagnetic, or **diamagnetic** material. Both paramagnetic and ferromagnetic materials tend to reinforce the strength of an applied magnetic field while diamagnets weaken it. While paramagnetism and diamagnetism tend to be weak and difficult to observe in ordinary materials, superconductors, on the other hand, are very strong diamagnets.

If a coil of wire has inductance L_0, then inserting a material changes its inductance L :

$$L = (1 + \chi)L_0$$

The parameter χ ("chi," not the letter X) is the **susceptibility** of a material. χ is positive for paramagnets and ferromagnets, but negative for diamagnets. We **expect the susceptibility of YBCO to be nearly -1 when it is cooled below its critical temperature**.

The goal of the second experiment is to measure the susceptibility of the YBCO sample as a function of temperature. **Below the critical temperature of YBCO, we expect our sample to be a perfect diamagnet: the magnetic field induced by the coil is completely cancelled by the superconductor**.

3. Experimental Details

BEFORE YOU BEGIN: IMPORTANT PRECAUTIONS

- Pure nitrogen is chemically stable and is not corrosive, flammable, or poisonous. In liquid form, however, it is cold enough to cause serious injury on contact with skin, eyes, or clothing. Obey the safety precautions given below and as instructed by your instructor or TA. Handle the nitrogen with care and observe the following practical rules:

1. **Do not touch liquid nitrogen or any object cooled by liquid nitrogen with your skin. Do not splash or play with liquid nitrogen.** If a large amount of nitrogen spills on clothing, remove that piece of clothing quickly! Be aware that very cold objects may stick to skin, so do not touch the superconductor with your skin when it is cold!

2. Do not insert objects into liquid nitrogen that can cause it to unexpectedly boil and splash upwards. Keep your face away from boiling liquid nitrogen.

3.1 Experiment 1: DC Resistance of BSCCO

Equipment:
1. Constant-current power supply
2. 15-ohm resistor
3. Superconductor sample
4. High -precision digital DC voltmeter
5. Portable DC voltmeter (for thermocouple)
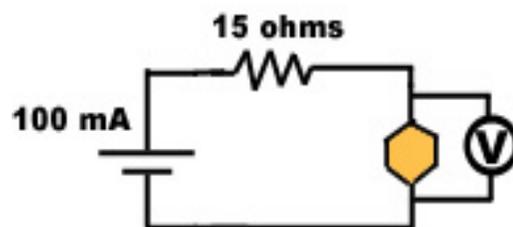
The equipment should be connected as shown: a DC power supply, 15-ohm resistor, and the **black wires** from the BSCCO sample are connected in series. (The hexagon in the diagram represents the BSCCO sample and the V is a high-precision voltmeter. The thermocouple leads are not shown because they are not part of the circuit.)

The **high-precision multimeter** should be connected to the **yellow** "voltage probe" wires coming from the BSCCO sample. The **multimeter should be set to read DC V**.

The **DC power supply** should be set to a voltage limit of **2V** and current limit of **100mA**. Two volts is slightly more than the voltage needed to provide a 100mA current at all times, so the power supply will automatically operate in "constant-current" mode.

The hand-held **portable multimeter** should be set to **DC mV**. Connect the multimeter leads with crocodile clips to the thermocouple leads coming from the BSCCO sample.

Check the readings on the power supply, portable meter, and high-precision meter:

- The power supply should display **100 mA** and between **1.5 V** and **2.0 V** .
- The portable multimeter should read **zero** to within **+/- 0.1 mV** .
- The high-precision voltmeter should display very roughly **1 mV** .

On your data sheet, write the voltage drop displayed on the high-precision meter and use Ohm's Law to calculate the resistance of the BSCCO sample at room temperature.

At this point, it is suggested that lab partners split up duties: one person to **handle the superconductor sample**, one person to **record data**, and one person to **watch the thermocouple readings** and call them out to the data recorder. A few seconds after the BSCCO sample is removed from its nitrogen bath, the thermocouple readings will change every few seconds as the sample heats up, so be prepared to write quickly!

When the BSCCO sample is immersed in liquid nitrogen, the portable multimeter will read about **6.4 mV**. If the voltages are negative, it means the thermocouple leads have been connected backwards. This is not a problem; simply disregard the minus sign.

In this experiment, the only variable being recorded is the **voltage drop** across the sample, as measured by the high-precision DC voltmeter. Thermocouple voltages and the corresponding kelvin temperatures are already written on the data sheet. For each thermocouple voltage on the data sheet, write down the voltage drop at that temperature. The resistance can be calculated later and plotted using the computer.

At this point, please tell the lab TA that you are ready to perform the experiment. Clear some space on the desk for two styrofoam cups and the TA will fill one with nitrogen.

Carefully pick up the superconductor sample by holding the rubber sheath covering the wires. Immerse the sample in the cup of liquid nitrogen. **Keep your face away from the nitrogen** at first, as it will bubble and boil and small droplets could splash upwards.

The thermocouple and voltage drop readings will change dramatically as the sample is cooled. Wait until they are reasonably stable before taking any data. The thermocouple should read near **6.4 mV,** while the voltage drop should be extremely low: typically near **1 or 2 microvolts**! This is direct evidence of superconductivity at 77 K.

Record the voltage drop in the 6.4 mV row of the data sheet. Now **carefully** remove the superconductor from its nitrogen bath and place it in the second (empty) foam cup.

DO NOT TOUCH THE BRASS HEXAGON. Handle the rubber insulating sheath only**.**

Each time the thermocouple voltage changes, record the high-precision voltmeter reading on the data sheet. When the thermocouple reaches **4.8 mV**, stop taking data.

As the sample warms, a layer of frost may form on the brass housing. **DO NOT TOUCH THE BRASS SAMPLE HOLDER WITH YOUR SKIN**. The sample will be extremely cold and unsafe to touch for at least 10-15 minutes. If you must handle the sample, use the rubber sheath, as it is a poor conductor of heat.

When you are done, **be aware that the first foam cup still contains liquid nitrogen.** Be careful not to knock over the cup as you are preparing for the next experiment!

3.2 Experiment 2: Magnetic Susceptibility of YBCO

Equipment:
1. AC power supply
2. 55-ohm resistor
3. Coiled-wire inductor with YBCO core
4. Oscilloscope (reads rms voltage)
5. Portable AC ammeter (reads rms current)
6. Portable DC voltmeter (for thermocouple)
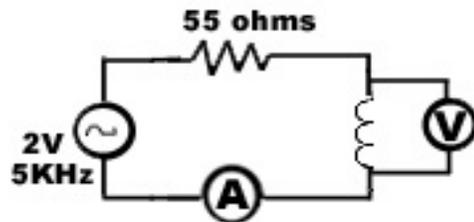
This experiment is very similar way to the first, except that the circuit now uses alternating current and the BSCCO sample has been replaced by an inductor with a YBCO core. The AC power supply, 55 ohm resistor, and another portable multimeter should be connected in series with the **black wires** from the inductor.

An **oscilloscope** will be used as a voltmeter and should be connected in parallel with the inductor as shown. Check that the oscilloscope is set to display **RMS voltage**.

Disconnect the portable multimeter from the BSCCO sample's thermocouple leads and connect the YBCO inductor's thermocouple leads instead. As in the first experiment, this portable multimeter will be used to determine the temperature of the YBCO sample.

Check that the power supply is set to **5000 Hz** and **2 V RMS**. Check that:

- The thermocouple multimeter is set to **DC mV** and reads **zero** to within **+/- 0.1 mV** .
- The other portable multimeter is set to **AC mA** and reads roughly **30 mA** .

- The oscilloscope shows a sine wave and reads approximately **1.9 V RMS** .

Again, it is suggested that lab partners split up duties: one to handle the sample, one to record data and one to call out the thermocouple readings for the data recorder. This time there are two variables to record: the **RMS voltage drop** displayed by the oscilloscope and the **RMS current** displayed by the second portable multimeter.

Record the RMS voltage drop and RMS current at room temperature as before. When you are ready, please inform your TA and, if necessary, ask for more liquid nitrogen.

Again, clear a space for two styrofoam cups and fill one with just enough liquid nitrogen to immerse the YBCO inductor. **Carefully** pick up the inductor by the rubber sheath and lower the inductor in the full cup. Be sure to **keep your face away from the cup** while the nitrogen boils and bubbles as before. Wait until the thermocouple voltage, current, and oscilloscope readings are reasonably stable before taking data.

Record the RMS voltage drop across the inductor and the RMS current in the circuit as before. When you are ready, carefully remove the inductor from its nitrogen bath and place it in the empty cup. As before, **DO NOT TOUCH THE INDUCTOR .** Handle only the insulating rubber sheath and be prepared to get out of the way if any nitrogen spills.

The inductor will heat up more rapidly than the brass assembly from the first experiment. Record both the RMS voltage drop and RMS current every time the thermocouple reading changes by 0.1 mV . Stop taking data at **4.8 mV** .

Be aware that the inductor will be unsafe to touch for at least 10-15 minutes. Also remember that **the first foam cup still contains liquid nitrogen,** so be careful not to spill it! If left undisturbed, the remaining nitrogen will evaporate harmlessly.

You are now done taking data, so log in to the lab computer and open Excel.

3.3 Analyzing BSCCO Resistance Data

Plot your BSCCO resistance versus temperature in °K and use this plot to estimate the critical temperature range of BSCCO. To do this, open a **new spreadsheet** using **Excel** with the first column for temperature and a second column for resistance in units of ohms (convert from mA) at the corresponding temperature. To convert your recorded voltage drop into resistance, use Ohm's Law.

Highlight both columns, plot them as an XY-scatter plot with lines and label the axes. Choose a temperature roughly in the middle of the transition range "by eyeball" and write it down on your data sheet as the estimated critical temperature of BSCCO. Include also an "eyeball estimate" of the transition range in °K. Print out your graph and hand in later with your completed data sheet.

3.4 Analyzing YBCO Susceptibility Data

Open another spreadsheet, copy and paste the recorded temperatures from the

previous experiment into column A, then enter the measured RMS voltages into column B, RMS currents into column C, and the resistance data from the data sheet into column D.

Remember that R is the resistance of the wire wrapped around the YBCO sample, so we do not expect it to drop to zero at low temperatures (the wire is not superconducting). We do expect to see the YBCO susceptibility become negative when it is superconducting. The susceptibility χ is defined by how the magnetic properties of the material within the coil affects the inductance L of the coil of wire:

$$L = (1 + \chi)L_0 \qquad \text{which can be rewritten as} \qquad \chi = \frac{L}{L_0} - 1$$

We can see that the graph of χ will have the same shape as the graph of L, except that χ will be rescaled by a constant and translated downward on the y-axis. With this in mind, it is useful to find L and plot it as a function of temperature. When the YBCO sample is below its superconducting critical temperature, we should see L drop sharply towards zero.

Finding inductance L from the RMS voltage and RMS current data is straightforward but tedious, so it's best to use a computer to do the actual calculations. Rewriting the AC version of Ohm's Law and using the definition of impedance Z above, we can solve for L

$$Z = \frac{V_{RMS}}{I_{RMS}} = \sqrt{\omega^2 L^2 + R^2}$$

L to find:

$$L = \frac{1}{\omega}\sqrt{\frac{V_{RMS}^2}{I_{RMS}^2} - R^2}$$

Type this formula into Excel. Click on a cell in the (blank) fifth column and press the = key. In Excel, the above formula looks something like this:

= (1 / (6.283*5000)) ((A1/B1)^2 - (C1)^2)^(1/2)

where "A1" means "the data in column A, row 1" and so forth. (Remember that the power supply frequency f is 5000 Hz, so the angular frequency ω is 2π * 5000 rad/s .)

Now click on this cell, find the square symbol in the corner, and drag it down over the entire fifth column, and Excel will apply the same formula to every cell in the fifth column. Plot column E versus column A obtain a graph of inductance vs. temperature. The SI unit for inductance is the **henry** H. As a quick check to see if everything has been entered correctly, the inductance should be about 10 mH at room temperature.

Print your group's graph, label the axes and turn it in with your completed lab report. Estimate "by eyeball" the critical temperature and temperature range of YBCO and write your estimates on the data sheet. (Don't worry if your plot of L never quite reaches zero - just turn it in and use your best eyeball-estimation to guess the range.)

If time permits, plot the susceptibility χ of YBCO as a function of temperature as well. (Hint: Use the data point taken at room temperature to estimate L_0. Assume that while χ may be unknown, it is probably very close close to 0 at room temperature.)

3.5 Just for fun: Magnetic Levitation

Look in your "superconductivity kit" for a disc-shaped sample of superconductor, some plastic tweezers, and one or more small, gold-colored cubes. Use the tweezers to place a superconductor sample in a shallow styrofoam dish and ask your TA to pour a small amount of liquid nitrogen around it. Once the boiling nitrogen has calmed down a bit, grab one of the cubes with the tweezers and gently place it over the superconductor.

The cubes are powerful "rare-earth" ferromagnets with a strong, persistent magnetic field. Diamagnets such as superconductors tend to be repelled by strong magnetic fields. As a result, superconductors will avoid magnetic fields even when there is no applied current through them. In this case, the superconducting sample and the rare-earth magnet strongly repel each other. This leads to magnetic levitation.

Once the nitrogen boils completely, the YBCO/BSCCO sample will begin to warm up. Eventually it will pass its critical temperature and lose its strong diamagnetism, and the magnet will no longer levitate.