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I am submitting herewith a thesis written by Samuel Masaki Travaglini entitled "Transport Critical Currents in YBaCuO-based Coated Conductors: Angular, Magnetic Field, and Temperature Dependencies". I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Condensed Matter Physics.

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Transport Critical Currents
in YBaCuO-based Coated Conductors:
Angular, Magnetic Field
and Temperature Dependencies

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Samuel Masaki Travaglini

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Dedication

I would like to dedicate this thesis first and foremost to the Lord God, for without Him, none of this would be possible. I would also like to give dedication to my family for all of their support and encouragement throughout this process, and throughout everything that I have done in my life. These include my Grandparents, Arthur and Christine Travaglini, as well as my parents, Michael and Eiko Travaglini, and my brother Dustin Travaglini. I want to give dedication to all my friends who have expressed concern, interest, and support over the past years. These include my girlfriend, Amanda Pratt, whose encouragement was always highly valued, and my good friends Josh and Paul Murphy who have known me since I started down this path of study. Finally, I would like to dedicate this to all of my teachers throughout all of my schooling who have given me the ability, knowledge, and support to accomplish what I have to this point.

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Abstract

High-temperature superconductivity has been a focus of much study over the past 20 years, particularly within the cuprate class of superconductors. The effectiveness of these cuprate superconductors is limited by factors including the formation of vortices within the superconductor, orientation within external magnetic fields, the strength of these magnetic fields, temperature, and whether any doping agents have been used. Any of these factors individually can affect the transport critical current levels. In this research, YBaCuO and NdBaCuO-based coated conductors were studied in a liquid-nitrogen-cooled environment at either 77 K or 65 K. Field levels were varied between 0 T and 8 T while orientation was held constant, as well as orientation varying through 140 degrees of rotation while the field was held constant. From the data, n -values (in the voltage-current power-law relation $V \propto I^n$) and α values (a power-law relation $J_c \propto H^\alpha$) were calculated, and plots of angular and field dependencies were made. The results showed parallels between doping and improved pinning ability of vortices in addition to an unsuspected weak variation of n -values in relation to orientation within constant magnetic fields.

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1 Introduction

1.1 General Introduction

Ever since superconductivity was first discovered in 1911 by Heike Kamerlingh Onnes, the aim has been to improve the feasibility of making a superconductor more than a physics lab curiosity and tool. Initial superconductors needed to be cooled with liquid helium, which has a boiling temperature of 4.2 K at atmospheric pressure. Clearly this will not be feasible as a way to make superconductors widely useful in a real-world setting. As new materials have been discovered and the methods for constructing superconductors have evolved, the temperature at which superconductivity is observed has steadily risen. This has been influenced by the desire of scientists and the public to make the power of superconductors more universal in use. As such, high temperature superconductors have been the focus of much research and study during the past 20 years. The cuprate superconductors of greatest technological interest at present have a critical temperature, T_c , near 90 K on average. This critical temperature is the temperature below which a conductor becomes a superconductor and loses its electrical resistivity. There have not been many superconductors with a T_c higher than 100 K, although a mercury cuprate has a T_c as high as 138 K, and T_c can be even higher when tested under pressure.[1]

1.2 The Meissner Effect

One of the earliest discoveries about superconductors was that of the now-termed Meissner effect, which was discovered in 1933 without any theoretical expectation.[2, 3] The Meissner effect is the property that causes superconducting elements to expel magnetic fields when they are cooled below T_c . As a superconducting element cools through T_c , the magnetic field lines within the sample are expelled as superconductivity is achieved.[3] Figure 1 shows what happens during the phase transition from the normal state to superconducting state.

The fact that the magnetic field is expelled allows for the superconducting properties to take over, as the interference from the field would degrade the superconducting effect eventually to the point of returning the conductor to the normal state. The figure shows effectively what happens, although these general statements are valid only under low magnetic fields.

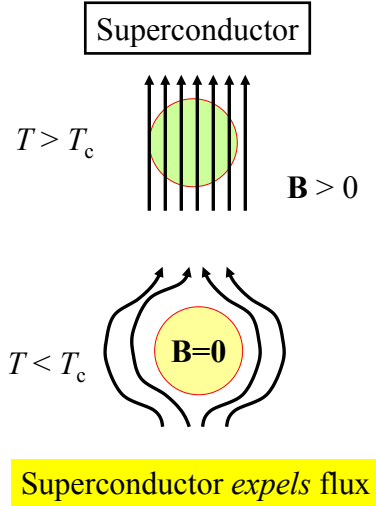


Figure 1: A basic illustration of the Meissner Effect. Image courtesy J.R. Thompson[4]

1.3 Type I and Type II Superconductors

In the discussion of superconductors, two different categories of materials are found. These are labeled as Type I and Type II superconductors, and they are defined by the magnetic properties that they exhibit. In general terms, Type I superconductors include all pure and “clean” superconducting elements except niobium, while Type II superconductors include niobium as well as most alloys and chemical compounds.[2] In terms of the magnetic properties, completely pure and clean Type I superconductors exhibit perfect diamagnetism. In other words, as long as the external magnetic field does not exceed a critical field, H_c , the superconducting element is able to expel the magnetic field from its interior. However, once $|H|$ surpasses H_c , the magnetic field effects overcome the superconductive pairing, and superconducting capabilities are lost.[3] For Type II superconductors, this critical field effect is less prominent. There is a lower critical field, H_{c1} where the magnetic field begins to penetrate the material as quantized flux lines. The packing density of these flux lines increases until an upper critical field, H_{c2} , is reached resulting in the return to the normal, electrically resistive state of the material.[3]

1.4 Vortices and Flux Lines

Unfortunately, defining a superconductor’s state is not nearly as simple as making a sample cold and it turning into a superconductor indefinitely. For Type II superconductors, there is a mixed, or vortex, state that is entered once H_{c1} is exceeded. Figure 2 shows a schematic phase diagram detailing where

each of these states occurs.

In the mixed state, microscopic currents generate multiple vortices within the superconducting film. These vortices can be visualized as a very small tornado, with the “eye” of the tornado acting as the vortex core and the winds acting as the microscopic currents circulating the core. A visualization of this is provided in Fig. 3 below.

The radius of the vortex line’s core (the “eye”) is known as the coherence length.[6] In addition, there is a length of magnetic field decay from the vortex center, which is known as the penetration depth λ . The above diagram, Fig. 1, showing $B = 0$ inside the superconductor holds true for areas deep inside the material, but for areas close to the edges, there is some magnetic field penetration. How far this penetration propagates is also defined as λ .

Another term that is frequently interchanged with “vortices” is “flux lines”. Although it falls outside the scope of this discussion, there are instances in the most extreme cases that the interchangeability is

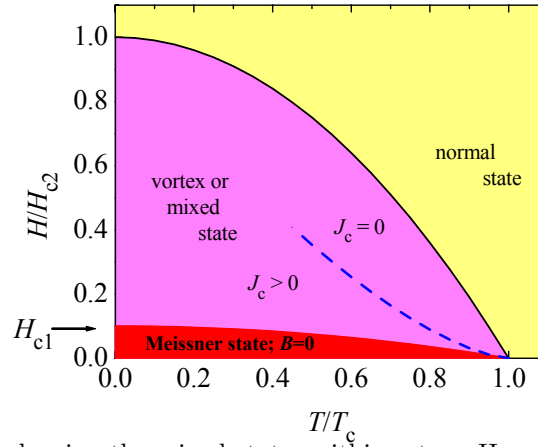


Figure 2: A phase diagram showing the mixed states within a type II superconductor. Image courtesy J.R. Thompson[4]

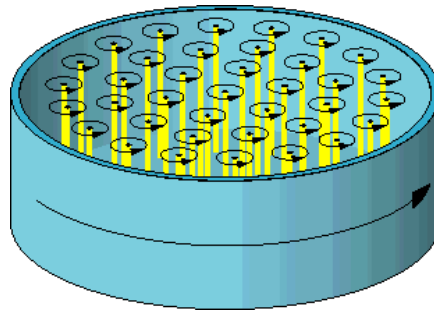


Figure 3: Diagram of the vortices that appear within a superconductor. Image courtesy Qiang Du [5]

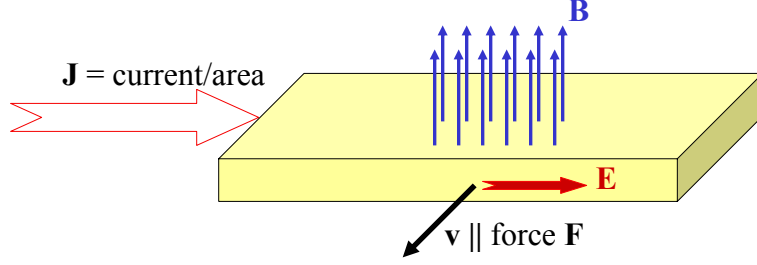


Figure 4: Schematic of the forces that are in effect inside a superconducting sample. Image courtesy J.R. Thompson[4]

not valid. However, for most common Type II superconductors under normal circumstances, the use of either term, vortices or flux lines, is acceptable. In order to give a strict definition, flux lines are tubes of confined magnetic flux with a radius given by λ , the distance with which a weak magnetic field can penetrate into a bulk superconductor.[6]

In addition to the vortex state, the dotted line in Fig. 2 running through the mixed state is important. This line delineates the irreversibility field, or H_{irr} . Also in Fig. 2, below H_{irr} , there is a critical current density $J_c > 0$. Above this line, however, $J_c = 0$, and any current flow is resistive. At low temperature, both H_{c2} and H_{irr} are very large and cannot be measured directly because of the inability of current machines to operate at high enough fields.

1.5 Basics of Flux Pinning

In the absence of flux-pinning by material inhomogeneities, the magnetic flux lines in a type II superconductor interact repulsively and form a regular array, known as the Abrikosov lattice.[7]

The vortex array is of practical importance since it experiences a Lorentz-like force, exerted when a current is passed through the sample, as seen in Fig. 4. This is described in mathematical terms by

$$\vec{\mathbf{F}} = \frac{1}{c} \vec{\mathbf{J}} \times \vec{\mathbf{B}} \quad (1)$$

Here $\vec{\mathbf{J}}$ is the electric current per unit area and $\vec{\mathbf{B}}$ is the flux density.

Under the influence of this force, the motion of these vortices at velocity $\vec{v}$ creates an electric field

$$\vec{\mathbf{E}} = \frac{1}{c} \vec{\mathbf{B}} \times \vec{v} \quad (2)$$

where $\vec{v}$ is perpendicular to both $\vec{\mathbf{B}}$ and the applied current. The resulting parallel coincidence of

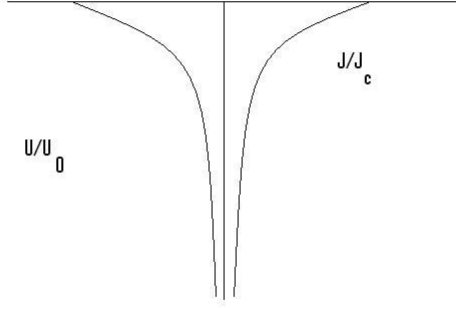


Figure 5: This figure is a rough sketch of a potential well that a vortex must overcome in order to move within a superconductor

current and an electric field produces power dissipation as heat. Consequently, the vortices must be kept stationary (“pinned”) to prevent dissipative motion and energy loss.[4]

1.5.1 A Brief Feasibility Derivation of the Current-Voltage Index n

Through experimental means, a relationship between current density J and electric field E has been shown to be very non-linear in superconductors. Frequently, these two variables can be related by a power law dependence that follows the form of $E \propto J^n$. While an in-depth analysis of flux pinning is beyond the scope of this thesis, a brief explanation is necessary in order to show how this n -value relationship is obtained. For some additional information on flux pinning methods, see section 1.7.6 on doping. As a basic example, consider a vortex pinning energy $U(J)$ that has a near-logarithmic dependence on J given by the equation

$$U = U_0 \ln \left(\frac{J}{J_c} \right) \quad (3)$$

At finite J , flux lines can be excited from the pinning potential by thermal activation as shown in Fig. 5. Another possibility is that the energy well size decreases, allowing for easier movement. This possibility, however, is not necessary in terms of deriving n .

Now, we can define an electric field $E = v \frac{B}{c}$ as the field generated by the combined effects of Lorentz force and thermal activation. This thermal activation causes the vortex average jump velocity, v , which is related to an attempt frequency, f , and a jump distance x by the equation

$$v = f x e^{\frac{-U_p}{kT}} \quad (4)$$

where U_p is the pinning barrier that needs to be overcome by thermal activation. We can therefore see that the electric field can be set equal to a critical field E_c by the equation

$$E = E_c e^{\left(\frac{-U_p}{kT}\right)} \quad (5)$$

Based on the fact that $U_p = -U$, we can exchange $-U_p$ in our last equation and instead write

$$E = E_c e^{\left[\ln\left(\frac{J}{J_c}\right) \frac{U_0}{kT}\right]} \quad (6)$$

By dividing by E_c and then taking the natural logarithm of both sides of the equation, we have

$$\ln\left(\frac{E}{E_c}\right) = \ln\left(\frac{J}{J_c}\right)^{\frac{U_0}{kT}} \quad (7)$$

which then reduces to a simple relationship between the electric field and critical current given by

$$\frac{E}{E_c} = \left(\frac{J}{J_c}\right)^{\frac{U_0}{kT}} \quad (8)$$

From this equation, the n -value of a superconductor is determined by setting n equal to the quantity of $\left(\frac{U_0}{kT}\right)$. Figure 6 shows some predicted $E(J)$ curves for various values of n .

Essentially what this diagram shows is the full range of cases for a superconductor when n is varied from 1 to ∞ . At the lower end of the spectrum, there is an ohmic relationship that is $\rho = \frac{E_0}{J_0}$, up to the ideal critical state superconductor with a well-defined current density $J_c = J_0$. [6] For the limit $n = \infty$, this represents the static critical state where the vortex density gradient is balanced by the pinning force. In other words, the vortices within the sample will be completely pinned. For all n less than ∞ , there is always the possibility of moving vortices due to thermal activation. [6]

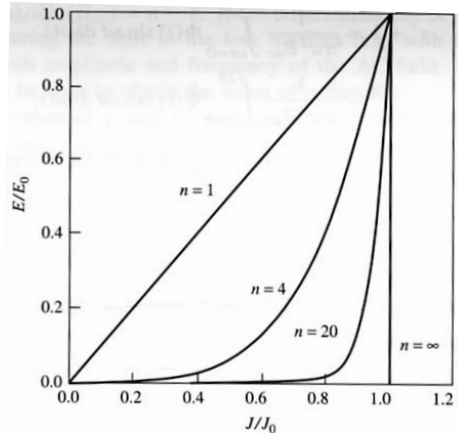


Figure 6: $E(J)$ curves for various values of n . Image courtesy Fossheim [6]

1.5.2 Expected Isotropic Pinning Model

Another important factor in superconductivity relates to the angular dependence of J_c . For each class of High- T_c superconductor compounds, there is an intrinsic electronic anisotropy. Therefore the current conduction is very dependent on the direction of current travel in relation to the crystal structure. As will be shown later in the Yttrium Barium Copper Oxide crystal structure, there are CuO_2 layers separated by layers of other atoms. The superconductivity resides mostly in the CuO_2 layers, and as such, the sample conducts most efficiently when the current flows in the planes of the CuO_2 . The same cannot be said if the current is traveling in the c -direction, as it will have to travel through the less conductive portions of the crystal structure. This is anisotropic behavior.

In order to effectively pin the flux lines that appear within these samples, isotropic pinning sites may be introduced into the sample. These are random points that offer no directionality in pinning, and can essentially be viewed as spherical inhomogeneities within the sample. For more detailed information regarding the theory of isotropic pinning, see Blatter et al.[8]

Since current superconductors exhibit electronic properties that are anisotropic with relation to the magnetic field orientation, it is often found that pinning is stronger when the field is parallel to the ab planes.[9] Therefore, we should discuss the predicted dependence of J_c on field orientation. The basic theory is based on a parameter γ that is defined as

$$\gamma = \sqrt{\frac{m_c}{m_{ab}}} \quad (9)$$

Here, m_c and m_{ab} are the respective effective electronic masses along the c -axis and in ab planes. This value, while not constant for different HTS material classes, generally is between 5 and 7 in YBCO. Since we are working with $J_c(\theta, B)$, we assume that this parameter is affected only by a scaled, effective field defined as $H_{eff} = \frac{H}{\gamma(\theta)}$. [9] This effective field depends on the electronic anisotropy parameter

$$\gamma(\theta) = [\sin^2(\theta) + \frac{1}{\gamma^2} \cos^2(\theta)]^{-\frac{1}{2}} \quad (10)$$

where θ is the angle between the field and the ab planes. One can see that at $\theta = 0$, $\gamma(\theta) = \gamma$. By way of several steps, this leads to the relation that, for isotropic pinning sites,

$$J(\theta)_c \propto H^{-\alpha} = H_{eff}^{-\alpha} = \left(\frac{H}{\gamma(\theta)} \right)^{-\alpha} \quad (11)$$

Using this theory, it would be expected that a J_c versus θ plot would have the appearance of Fig. 7 seen below. More discussion on α will be given in the following section.

What this figure shows is a strong J_c peak for $B \parallel ab$, or $\theta = 0$. As the sample rotates through $\theta = 90$ or $B \parallel c$, the pinning effect is diminished, and the flux lines begin to move. This causes the current conduction to be dissipative, reducing J_c , and therefore the superconductive ability of the sample.

1.6 Importance of the Flux-Pinning α Parameter

Another variable that will be continually mentioned in the results portion of this paper is known as α . This variable characterizes a power-law relation between J_c and the field (H) that a superconductor is interacting with. Figure 8 shows what a generic J_c versus H curve looks like on a log-log scale.

The line of the graph between the field independent portion and the irreversibility field (H_{irr}) is where a logarithmic slope is measured, giving the α value. While full mathematical derivations predict some values of α for specific pinning regimes, as in Blatter et al., the experimentally observed values often have no theoretical basis to date.[8] A clearer description of the importance of α and its use in this

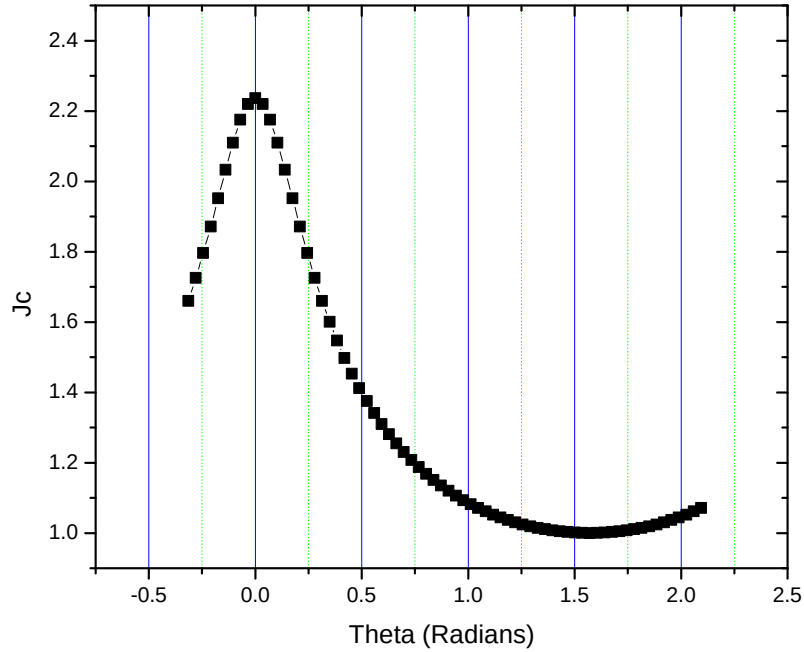


Figure 7: Schematic of J_c vs. θ for a isotropically pinned superconductor based on Eqs. 10 and 11

study will be given in the results section.

1.7 Fabrication Methods for Superconductors

Early superconductors were simply basic elements that were cooled to extremely low temperature by liquid helium. As the study of superconductivity has progressed, compounds have been fabricated and studied that have improved superconducting properties, raised T_c substantially, and allowed for greater critical currents in higher magnetic fields. The following discusses some of the compounds and substrates, although the specifics of the methods used to create them fall outside the realm of this thesis. Since the growth process used in the present study for coated conductors is a bottom-up approach, the discussion will start with the substrates that are used to support the superconductor, and continue up through the buffer layers and finally the superconductor itself. As a visual reference, use Fig. 9 to see where each of the layers is grown in relation to each other.

1.7.1 IBAD Substrate

A substrate backing is needed to grow the superconductor on, and a popular choice is known as the ion-beam-assisted deposition (IBAD) substrate. This method is one of two main approaches to advanced superconductor wire growth processes, and has been shown to be highly useful in the deposition of aligned films on crystalline, polycrystalline and amorphous substrates.[10] The material for the substrate

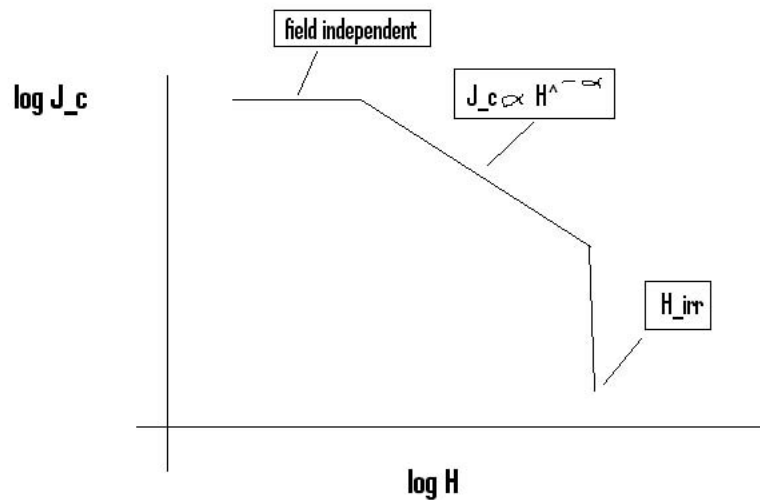


Figure 8: Generic J_c vs. H graph showing where α values are derived from

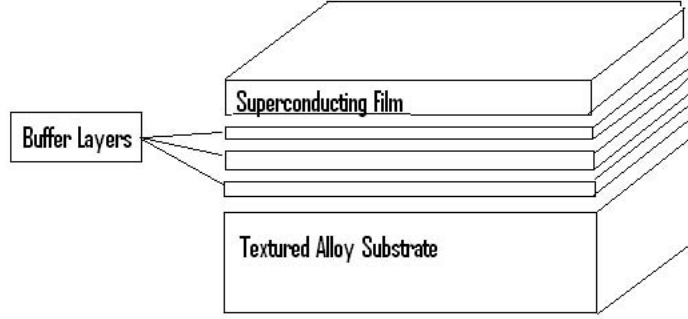


Figure 9: Schematic diagram showing where the layers of a superconducting sample are in relation to each other

is generally a metal alloy, usually consisting of non-magnetic elements.

1.7.2 RABiTS

Another type of growth technique that has been developed places the superconductor on rolling-assisted-biaxially-textured-substrates, or RABiTS.[11] Initial results with this approach gave J_c measurements above 10^6 A/cm² at 77 K with no magnetic field.[11] The popular choice of material is a nickel-tungsten (Ni-W) alloy which is used almost exclusively when the substrate is formed using the RABiTS technique.[12] Both of these substrates provide strength and flexibility for the superconductor film that is to be grown on them later.

1.7.3 Buffer Layers

Once the substrate has been prepared, various buffer layers must be made before a superconductor is grown on top of it. These layers are necessary to provide a crystalline template for epitaxial growth and for chemical isolation from interaction with the metal substrate.[13] This interaction comes on the molecular level, since materials in direct contact tend to diffuse into each other. Therefore, if the substrate was in direct contact with the superconductor, the metal atoms of the substrate would interact and diffuse into the superconductor.[6] The buffer layers should be non-reactive with the superconductor, be chemically stable, nonporous, strongly bonding, and ideally electrically conductive.[6] The buffer layers are grown bi-axially, which means that the c -axis is normal to the plane of the conductor and

substrate.[6]

1.7.4 YBCO Compound

One of the main compounds currently used in the study of superconductivity is known as YBCO (Yttrium Barium Copper Oxide) with the chemical formula $\text{YBa}_2\text{Cu}_3\text{O}_7$. Figure 10 shows the chemical structure for this compound.

There were a number of early growth methods for films of the YBCO compound on single crystal substrates, but they were fairly limiting in that the substrates used were not flexible and unavailable in the sizes and shapes of many applications.[13] A specific growth method known as pulsed laser deposition (PLD) was used early on to grow YBCO on an IBAD substrate that exhibited strong potential for high critical current densities.[14]

1.7.5 NdBCO Compound

Another similar compound frequently used is NdBCO (Neodymium Barium Copper Oxide), with a chemical formula of $\text{NdBa}_2\text{Cu}_3\text{O}_7$. The chemical structure of NdBCO takes on the same form as that of YBCO, with the obvious exception of substituting Nd for Y. For both YBCO and NdBCO, the

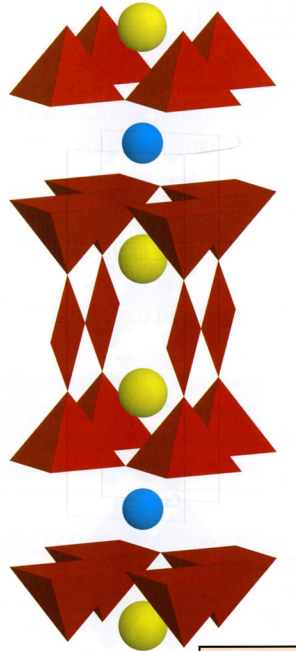


Figure 10: Chemical structure diagram of YBCO. Image courtesy of H. Shaked[16]

superconductor itself is grown directly on the previously formed substrate and buffer layers in the form of a thin film. In addition, both of these superconductor materials are grown bi-axially in order to align the c -axis normal to the ab planes, just as in the buffer layers. The superconductors are grown epitaxially, meaning that the square lattices from the bi-axial growth process align the ab plane squares as closely as possible between the buffer layers and the superconductor.[6]

1.7.6 Doping

As a way to off-set the problems caused by moving flux lines, some superconducting samples are doped with another compound or substance to create microscopic regions of non-superconducting material, or inclusions. One example of this that will be seen specifically in the results sections is a sample containing BZO (BaZrO_3) compound that is incorporated inside the superconducting film. The purpose of these lines of BZO nanoparticles (see Fig. 11) is to help pin the flux lines by creating areas where they have more difficulty moving. Currently, some other doping compounds include gadolinium zirconium oxide ($\text{Gd}_2\text{Zr}_2\text{O}_7$, or GZO) and magnesium oxide (MgO).[15]

The doping process consists of creating linear defects of BZO by a chemical process. This forms stacks of self-aligning nanoparticles that are approximately parallel with the c -axis. As evident in Fig. 11, these stacks of BZO are clearly visible using transmission electron microscopy (TEM).

Doping of superconducting films has proved successful in terms of allowing for an increase in J_c , as well as added ability to pin vortices that form within the superconductor. It also has helped weaken the field dependence observed in superconductors that are doped.

2 Experimental Procedure

2.1 Precautions

The experimental samples that are used in the testing of superconductors are inherently fragile. Therefore, great care must be taken in the handling of these samples. The first problem to be encountered is the difficult problem related to the size of these samples. The handling is difficult due to the small sample size of current superconductors, generally with overall dimensions of 12 mm x 4 mm with a

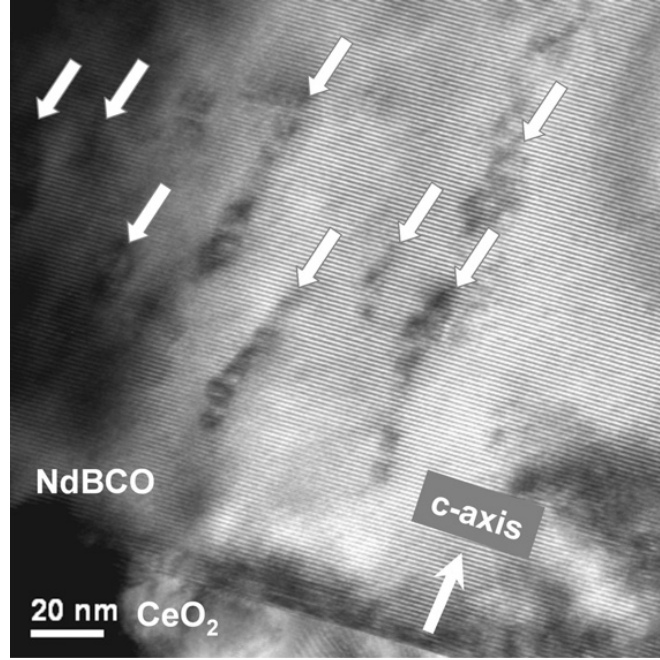


Figure 11: A TEM image of Nd61121B with the BZO stacks visible. Figure courtesy S.H. Wee[18]

narrow patterned measurement bridge. Keeping the samples dry and not allowing water to condense on them is important, especially when the sample is warming up after being tested. Contact from the skin, especially on the contact leads, should be avoided as this can cause an increase in contact resistance which will in turn lead to additional heating. Finally, the amount of current that will be sent through a sample, while dependent upon each individual sample, must be chosen carefully in order not to overload the sample and cause the superconducting bridge to be destroyed.

2.2 Sample Specifications

The samples studied in this work were YBCO superconductors deposited on RABiTS substrate by AMSC and NdBCO doped with BZO on IBAD substrate made by ORNL.[17, 18] Table 1 summarizes vital information for each individual sample. As clarification, the column of dimensions refers to the dimensions only of the superconducting bridge, and not the entire sample.

2.3 Procedure

The following gives the detailed account of the sample preparation in addition to the LabView setup within the computer being discussed.

2.3.1 Sample Preparation

For reference, a schematic has been provided in Fig. 12 that shows the main parts of the sample.

First, a narrowed region known as the “bridge” is defined by laser scribing, with the widths given in Table 1. Next, the samples must have indium placed upon the silver squares to ensure good contact between the current leads and the sample. The silver squares, as well as the silver dots on the sample, are placed on top of the sample after the growth process by a sputtering technique. After the indium is attached, the samples are placed on a support backing that is dabbed with vacuum grease to help the sample stay in place through the course of the experiment. The current leads and spring-loaded contacts (pogos) which measure the voltage drop across the bridge are placed in a 4-point measurement arrangement. The two current leads on the outside are to come in contact with the indium, and the two pogos are to be in contact with the silver points on the sample. In order to ensure this, the pogos must be aligned precisely on the silver points. For a sample completely coated in silver, the placement upon the sample of the pogos is not position dependent assuming that the pogos are on either sides of the bridge. With the pogos aligned, a final check is given to the resistance of the sample to ensure good contact between the sample and the contact leads.

Once the sample resistance is confirmed to be good, the sample is placed inside a cryostat to begin the cooling process. Figure 13 shows the basic parts of the cryostat.

Table 1: The specifications for each sample that was studied

Sample Name	Dimensions	Substrate	SC Compound
ORNL281	2 mm x 1000 μm x 0.8 μm	RABiTS	YBCO
ORNL282	2 mm x 1000 μm x 0.8 μm	RABiTS	YBCO
Nd61121B	4 mm x 170 μm x 0.7 μm	IBAD	NdBCO

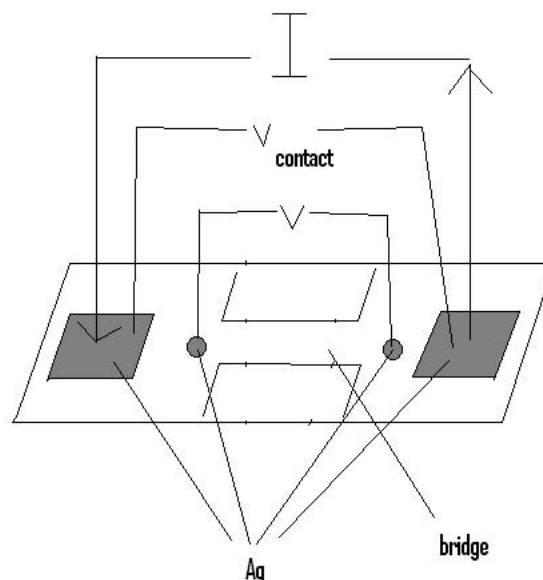


Figure 12: This figure shows the basic set-up of a sample, along with the 4 points through which the measurements are made

First, flowing helium gas is used to ensure that as little air as possible enters the sample space. The probe is then placed down inside the cryostat before being sealed. The probe is attached to an independent motor which allows for the sample stage to be rotated under computer control while inside the sample space. This sample space is then evacuated in order to remove the air and any moisture that were introduced along with the probe. An outer chamber of liquid nitrogen shields the sample space from room temperature thermal radiation. In order to cool the sample, a vaporizer connected to the inner liquid nitrogen bath by means of a capillary is used. A needle valve regulates the flow of the liquid nitrogen through the capillary. The needle valve can be opened and closed by means of the stepper motor attached to it. Throughout the process, the vaporizer is pumped on. This is done in order to facilitate the cooling process. Since the temperature is defined by how quickly the molecules within a system are moving, it follows that faster moving molecules correspond to a higher overall temperature of a system. Therefore, by pulling out the faster moving nitrogen molecules by means of the pump, the total thermal energy of the nitrogen is lowered, and therefore the sample is able to cool more rapidly. There is a vacuum space surrounding the two nitrogen chambers in order to ensure that the inner and outer nitrogen chambers are not in thermal contact with the outside room temperature environment. Using this method, temperatures as low as 65 K can be easily achieved. If lower temperatures are required,

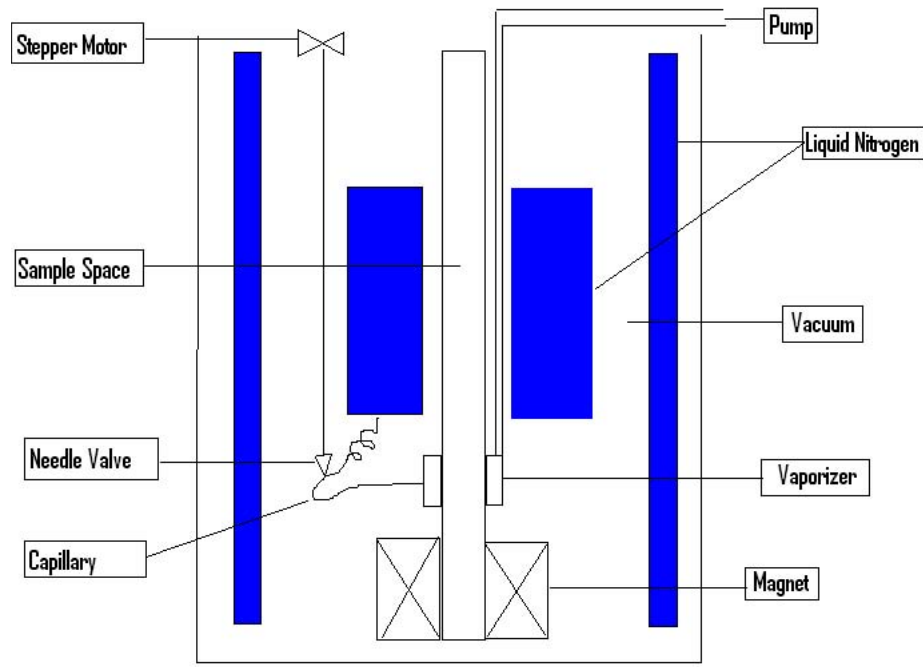


Figure 13: A schematic drawing of the main points of the cryostat. This is a cutaway drawing, as the actual apparatus is circular

liquid helium is used in the same process, allowing for sample measurements as low as 2.5 K.

2.3.2 Computer and Instrumentation

The rest of the process is controlled by computer. The schematic shown in Fig. 14 gives the basic connections that comprise the system.

The Keithley 2440 SourceMeter and Valhalla 2555A Current Calibrator provide the current that flows through the sample. The Keithley instrument is used for currents that are less than 5 amps, while the Valhalla instrument is used for currents above 5 amps. The relay box switches between the two current sources as the situation calls for. As a check on the Valhalla instrument, the current is run through a resistor, with one of the analog inputs on the DAQ board measuring the voltage drop across the resistor. This is done since the Valhalla instrument has some off-set, and allows for a check to make sure of the exact amount of current being put through the sample. The current that is sent out from the instruments is controlled by the DAQ board on the computer. It is in an alternating square wave pattern, with each pulse lasting 30 ms. The reason for the 30 ms pulses is that it ensures the heating due to the current in the leads and contacts is minimal, while allowing sufficient signal-to-noise ratio.

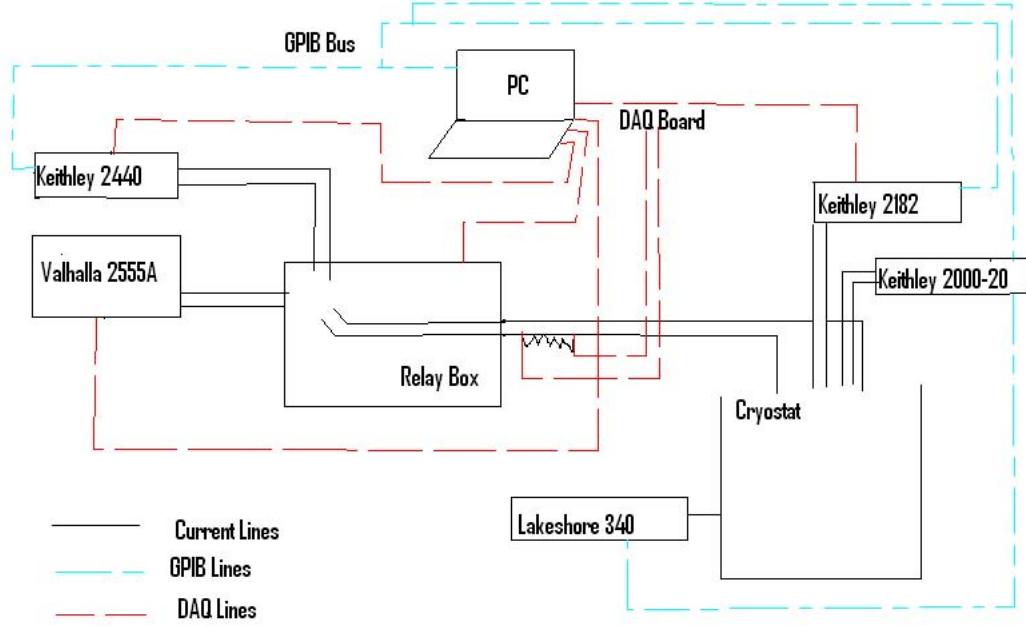


Figure 14: Diagram showing all the necessary instruments used to make measurements of current and voltage

In addition, the alternating current allows for any voltage due to a thermal gradient to be canceled out. By taking the positive and negative voltage and subtracting them from each other, any thermal emf, V_{therm} , is eliminated. A Keithley 2182 Voltmeter measures the voltage across the sample, and is controlled by the GPIB Bus on the computer. It takes the voltage reading for one power line cycle ($\frac{1}{60}$ Hz) in the middle of each current pulse to average over any line frequency pickup within the pulse. A Lakeshore 340 Temperature Controller controls and measures the temperatures of both the sample and the cryostat. This is controlled by a GPIB Bus connection, and consists of feedback loops that allow for accurate temperature readings of both the sample space and cryostat.

As the sample cools, the automated LabView program runs everything after the dimensions of the sample, temperature set-point, field, orientation, current, temperature tolerance, and several other factors have been given. Once the sample is superconducting, a contact resistance measurement is taken. Since a superconductor is defined by not having any resistance, the only place where resistive heating can take place is through the contacts. This heat must be limited, as excessive amounts will warm and possibly destroy the sample. The computer calculates the maximum current I_{max} by the equation

$$P_{limit} = IV = I_{max}^2 R_{contact} \quad (12)$$

which can be re-written as

$$I_{max} = \left(\frac{P_{limit}}{R_{contact}} \right)^{\frac{1}{2}} \quad (13)$$

2.3.3 Experimental Criteria

For these experiments, the measurements focused on the critical current (I_c) versus field (H) and I_c versus angle (θ). There were five specific types of runs that were required from these two basic types of data sets. For I_c versus θ , measurements at 65 K in fields of 3 T and 5 T, as well as 77 K in a 1 T field were studied. I_c versus H was studied at 65 and 77 K with the sample in an orientation that placed the ab planes perpendicular to the magnetic field. As clarification for the orientation of the sample within the cryostat, Fig. 15 shows the magnetic field, and the ab planes of the sample perpendicular to the field, as it was in the actual testing. The sample stage can be rotated by a stepper motor.

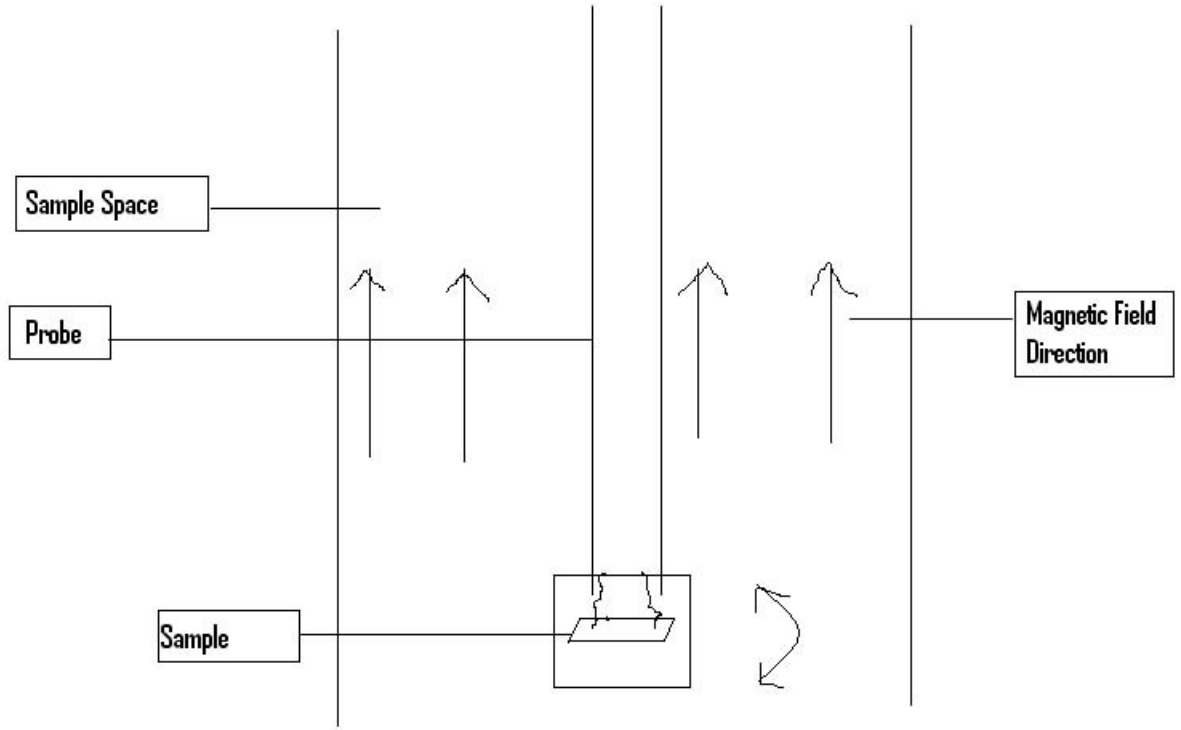


Figure 15: Diagram showing the orientation of the sample within the sample space as well as the direction of the applied magnetic field

3 Results

These experiments were designed to study the α and n values that could be obtained from samples that are oriented within an external magnetic field. The first two samples are $\text{YBa}_2\text{Cu}_3\text{O}_7$ coatings deposited on RABiTS templates by the solution technique metallo-organic deposition (MOD).[17] The third sample was prepared by the vapor deposition technique, pulsed laser deposition (PLD), on a commercial IBAD substrate. This sample is $\text{NdBa}_2\text{Cu}_3\text{O}_7$ with the additional chemical dopant BaZrO_3 and is labeled as Nd61121B.[18] The results will be presented according to the type of measurement being taken, with a general discussion in section 4 of the overall scope of the data collected.

3.1 Resistance vs. Temperature Data

The first piece of information that is gathered for each sample is the Resistance (R) versus Temperature (T) measurement. These are taken as the sample cools down in order to determine when the sample reached the superconducting transition at a specific temperature T_c . Figure 16 is the R vs. T data collected for ORNL 281, which shows that T_c was reached at 87.2 K. The variations in the measured R once the superconducting state was reached can be attributed to voltage noise. Next is sample ORNL 282, with its corresponding R vs. T graph shown in Fig. 17. This measurement shows T_c to be 90.6 K. Finally, sample Nd61121B with the R vs. T graph given in Fig. 18. This sample had a T_c of 93.9 K.

For all three samples, the R vs. T table of values is supplied in the appendix beginning on page 65. While data are taken during the entire cooling process, only the data relevant to the charts is supplied. They show resistances at temperatures just before T_c is reached, through the transition phase, and shortly after superconductivity has been achieved.

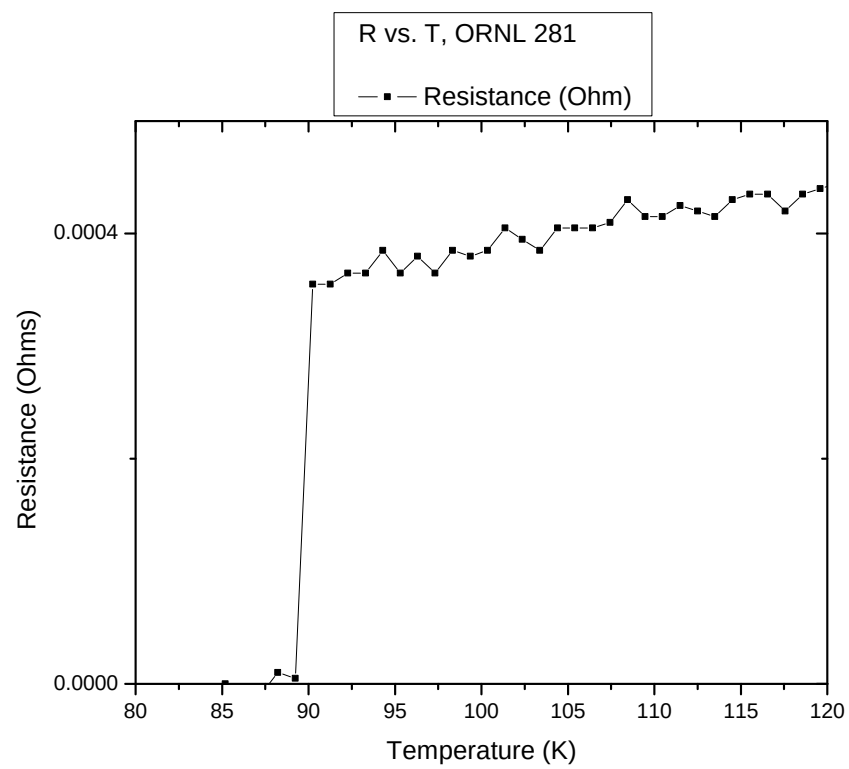


Figure 16: R vs. T for sample ORNL 281

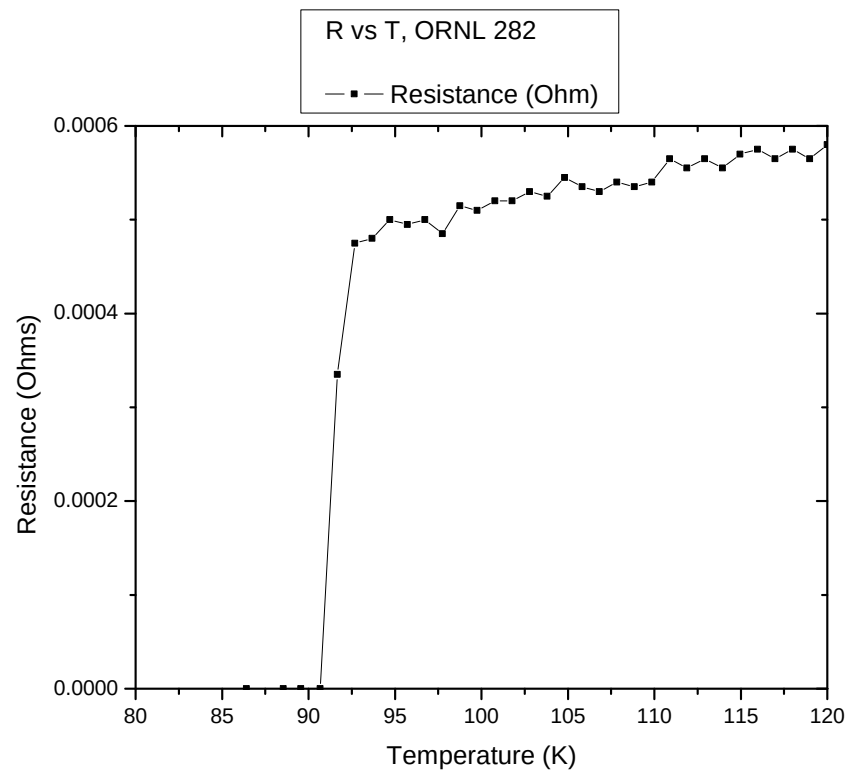


Figure 17: R vs. T for sample ORNL 282

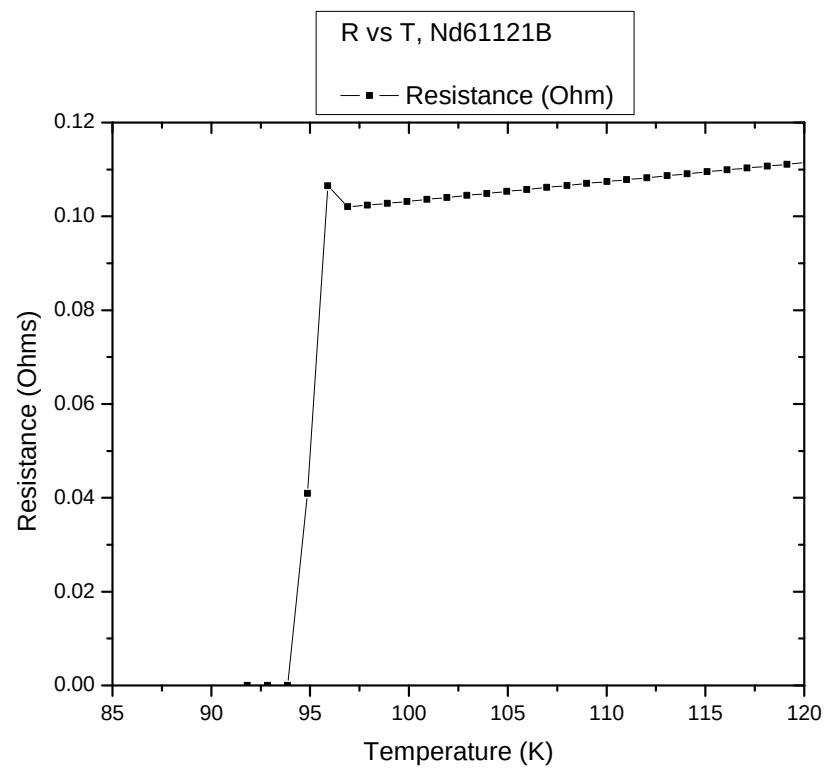


Figure 18: R vs. T for sample Nd61121B

3.2 IV Curves and n -value Data

The next measurements consist of taking Voltage versus Current (IV). They are taken at both 77 K and 65 K with the magnetic field oriented perpendicular to the sample plane and the strength decreasing from 8 T to 0 T over the course of the measurement. The first set of IV curves come from sample ORNL 281, and are shown in Figs. 19 and 20. It should be noted that the fields were varied from 8 T to 0 T, and follow the same order and magnitude as those given in the tables in the appendix. An important piece of information that can be drawn from these graphs is the n -value of a superconductor. As noted, the n -value describes the power-law relationship of the voltage to the current in the dissipative state of flux motion for currents both above and below the defined I_c . A brief mathematical description was given in the section on flux pinning. Figure 21 shows the n -values, which were extracted from fits to the voltage-current curves, plotted against H at both 77 and 65 K, allowing for comparison between the two temperature measurements. The IV curves of ORNL 282 follow in Figs. 22 and 23, with the n -value graph for this sample in Fig. 24. The final set of IV curves from Nd61121B are in Figs. 25 and 26, with n vs. H in Fig. 27.

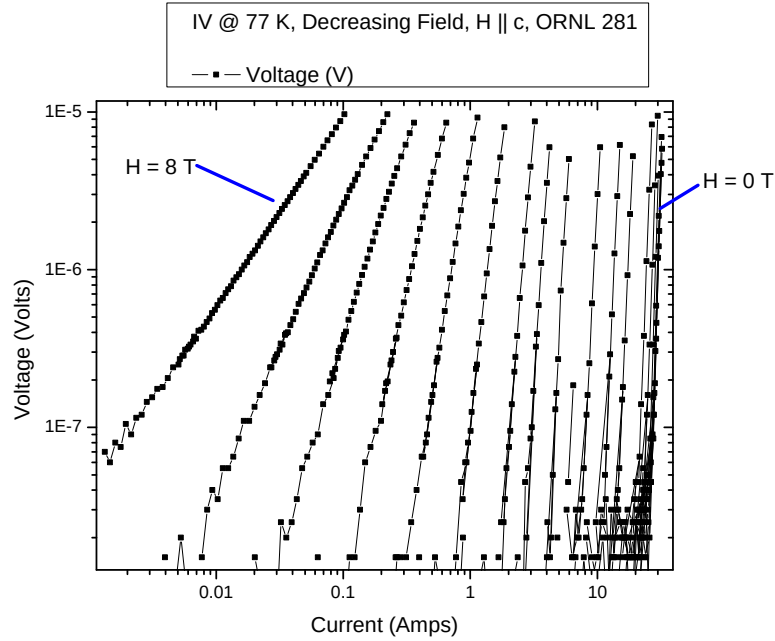


Figure 19: IV Curve for sample ORNL 281 taken at 77 K in a magnetic field of decreasing strength.

The order and values of the magnetic fields are the same as those listed in Table 3

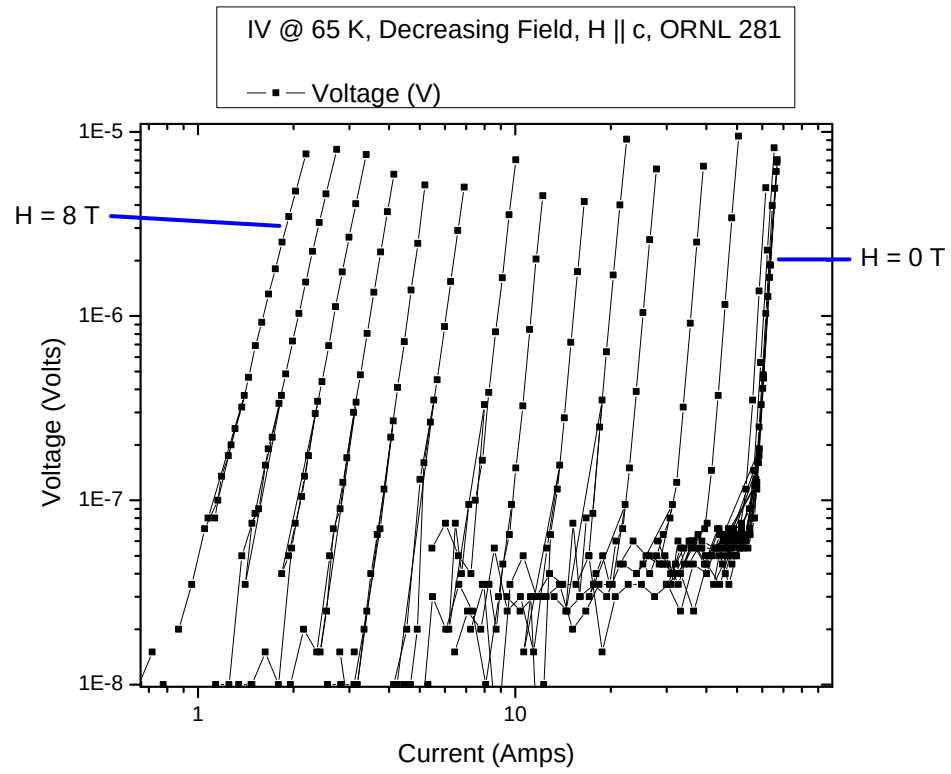


Figure 20: IV Curve for sample ORNL 281 taken at 65 K in a magnetic field of decreasing strength.

The order and values of the magnetic fields are the same as those listed in Table 3

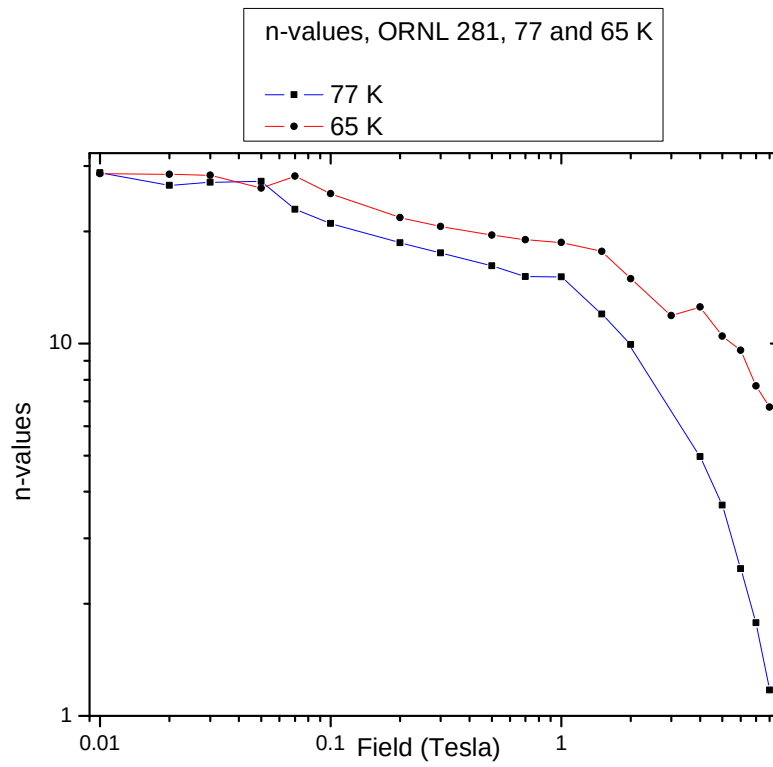


Figure 21: The n -values for ORNL 281 shown at both 77 K and 65 K in relation to field

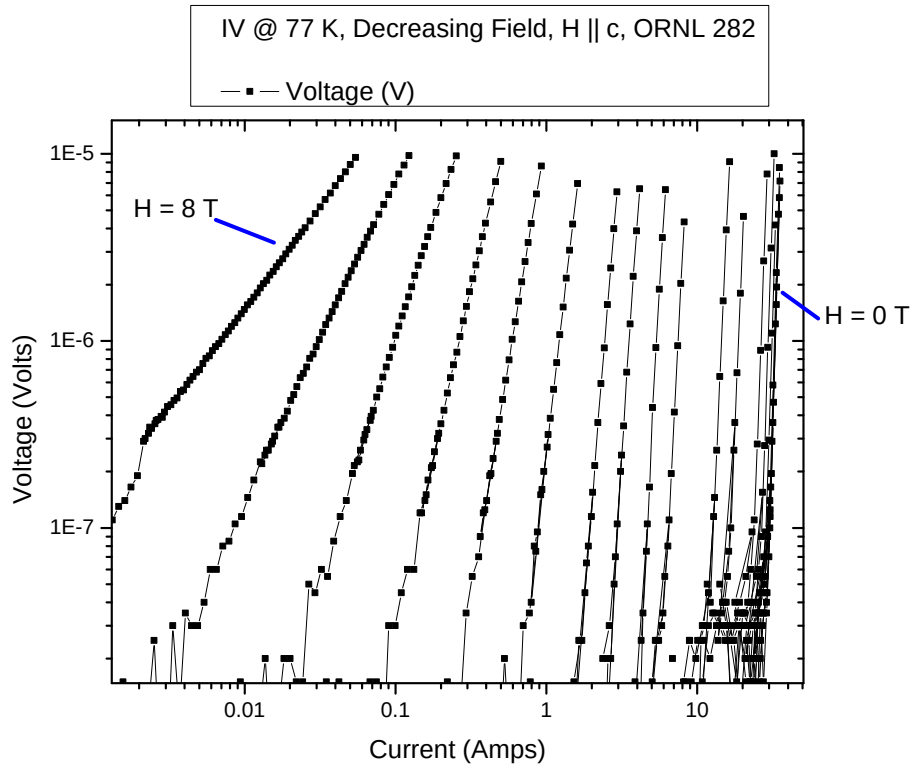


Figure 22: IV Curve for sample ORNL 282 taken at 77 K in a magnetic field of decreasing strength.

The order and values of the magnetic fields are the same as those listed in Table 4

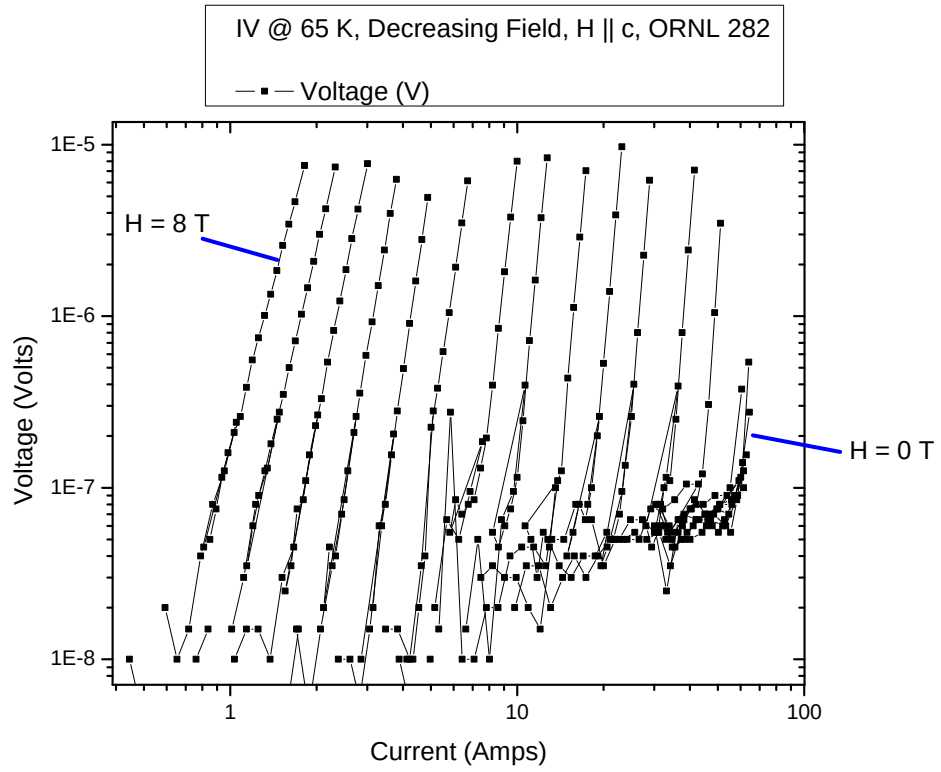


Figure 23: IV Curve for sample ORNL 282 taken at 65 K in a magnetic field of decreasing strength.

The order and values of the magnetic fields are the same as those listed in Table 4

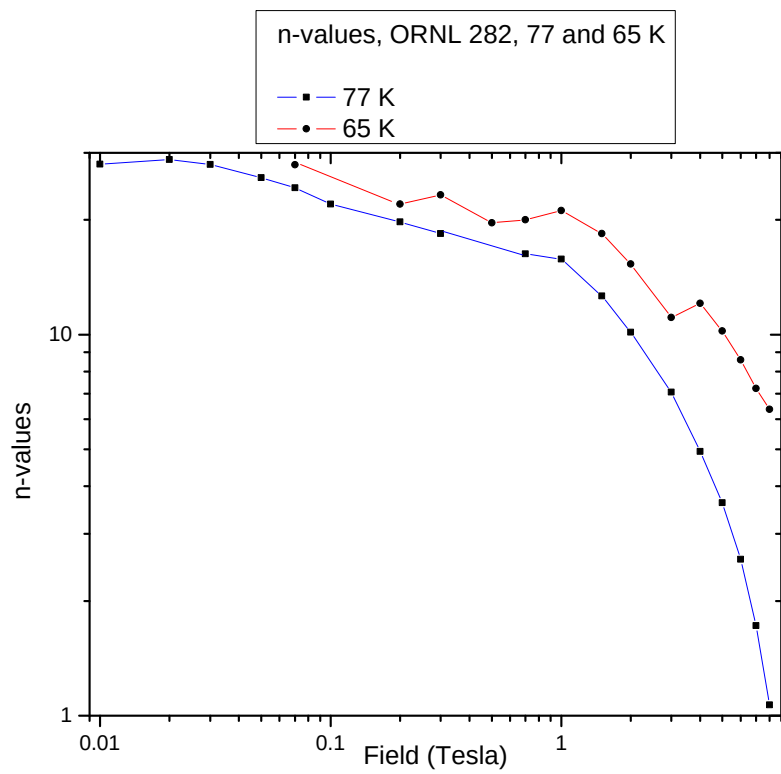


Figure 24: The n -values for ORNL 282 shown at both 77 K and 65 K in relation to field

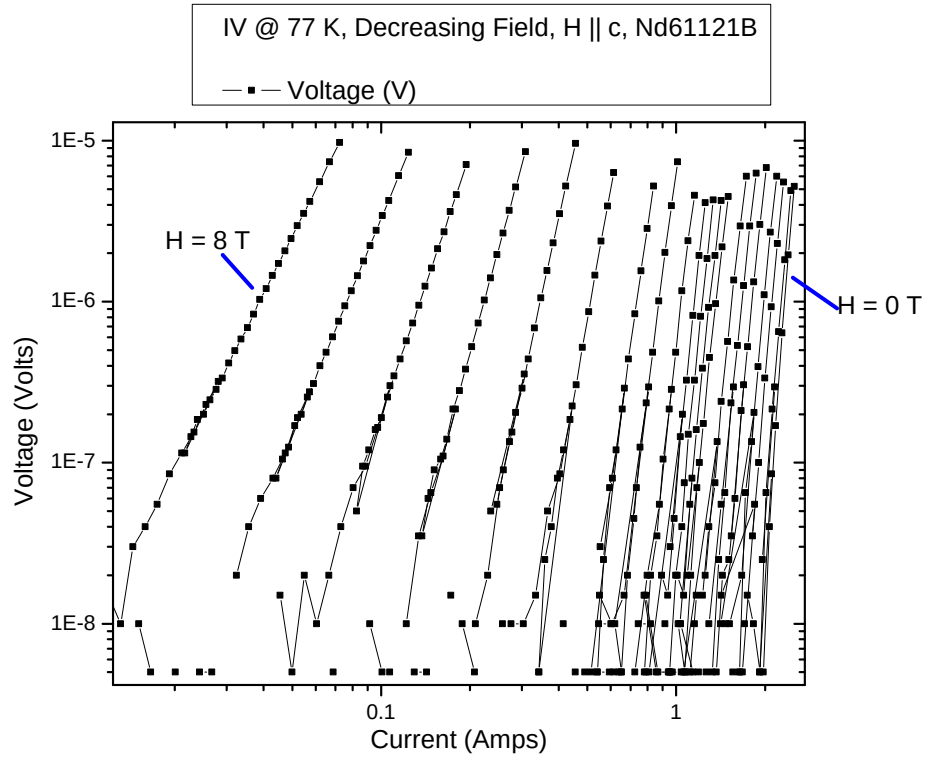


Figure 25: IV curve for sample Nd61121B taken at 77 K in a magnetic field of decreasing strength. The order and values of the magnetic fields are the same as those listed in Table 5

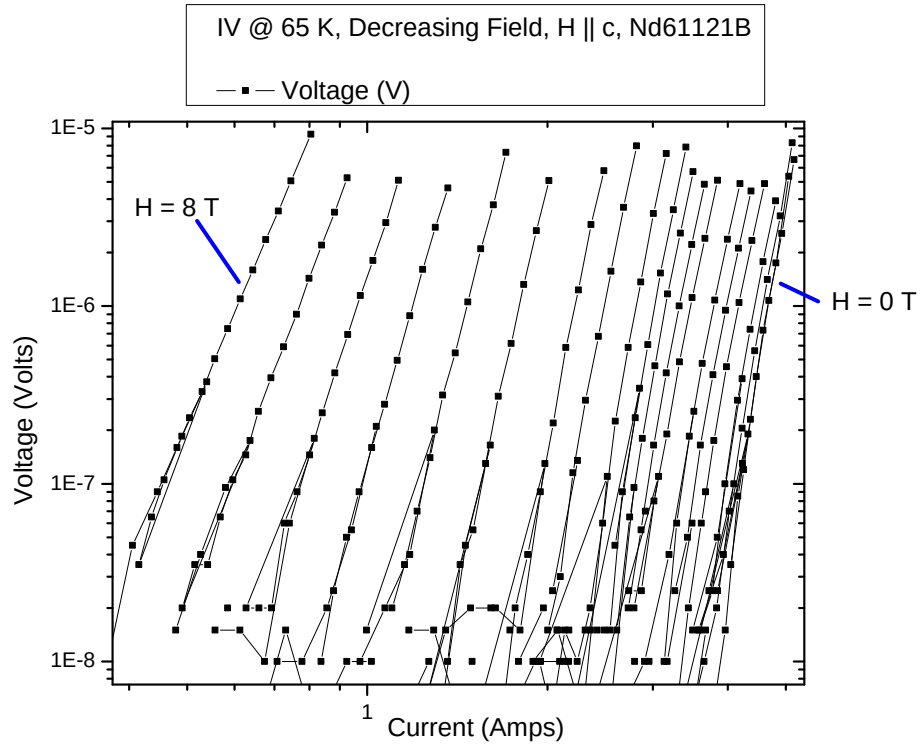


Figure 26: IV curve for sample Nd61121B taken at 65 K in a magnetic field of decreasing strength. The order and values of the magnetic fields are the same as those listed in Table 5

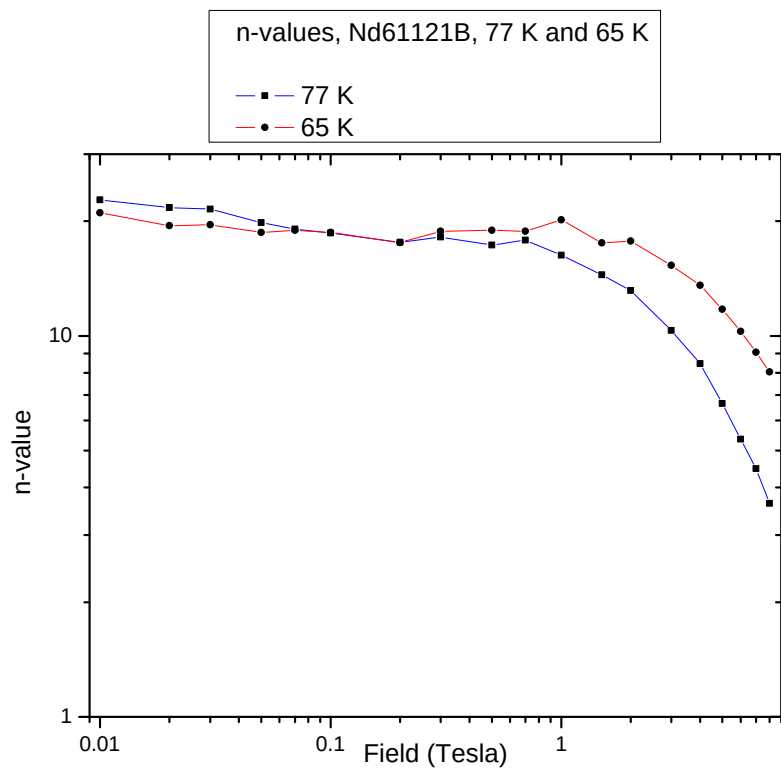


Figure 27: The n -values for Nd61121B shown at both 77 K and 65 K in relation to field

3.3 Critical Current vs. Field Data

To ensure that the orientation of the sample within the magnetic field for these measurements is clear, reference Fig. 28. One can clearly see that the sample was oriented so the magnetic field was perpendicular to the current, with the current traveling in the plane of the sample. This is done in order to ensure that the “Lorentz Force” that comes from taking $\vec{H} \times \vec{J}$ remains a constant that is independent of the sample orientation for any given field.

Next, the I_c versus H measurements were conducted, where the critical current is defined from the IV curves at a prescribed voltage criterion of $0.4 \mu\text{V}$. This is obtained since the industry standard voltage criterion is $1 \frac{\mu\text{V}}{\text{cm}}$, but the length of the sample bridge is 0.4 cm . From this measurement, the critical current density, J_c , was extracted by dividing by the superconductor cross-sectional area. The J_c data is plotted against H in Figs. 29 and 30.

Within the log-log graph, one will notice that a line has been drawn through the $J_c \sim H^{-\alpha}$ power-law portion of the curve. The α value that is shown is the slope of the line that is being measured. This value describes how sensitively the critical current decays with respect to the magnetic field. For larger α values, the critical current of the superconductor will dissipate faster at lower field strengths, while lower α values allow for higher fields before critical current levels drop. The aim is to get α as low as possible in order to accommodate useful current levels at the magnetic field levels needed for several power applications of superconducting wires (e.g., electric motors and generators operating at 3 - 5 Tesla). For instance, α for ORNL 281 is 0.84 at 77 K, and 0.72 at 65 K. Again, ORNL 282 is next with the appropriate J_c vs. H curves shown in Figs. 31 and 32, followed by Nd61121B with J_c vs. H curves shown in Figs. 33 and 34.

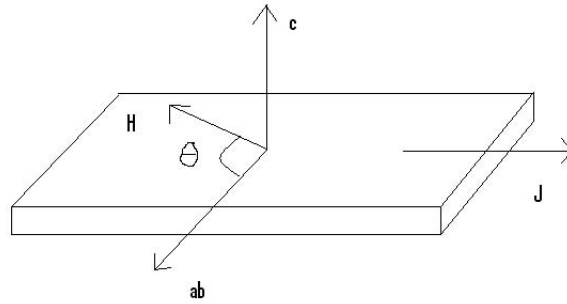


Figure 28: Sample orientation within the magnetic field during J_c vs. H measurements

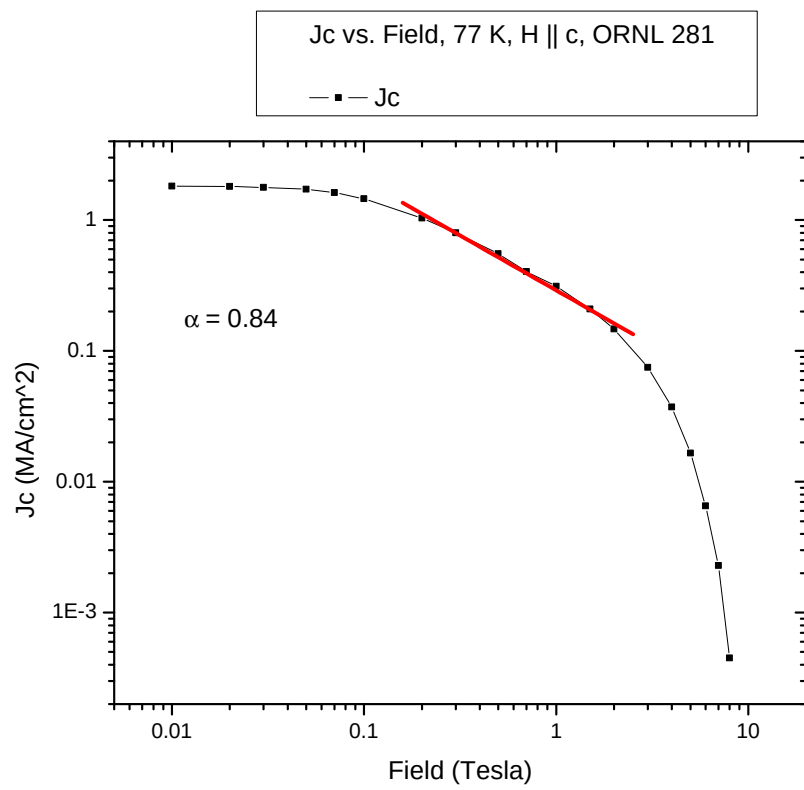


Figure 29: J_c vs. H for sample ORNL 281 at 77 K with the calculated α value

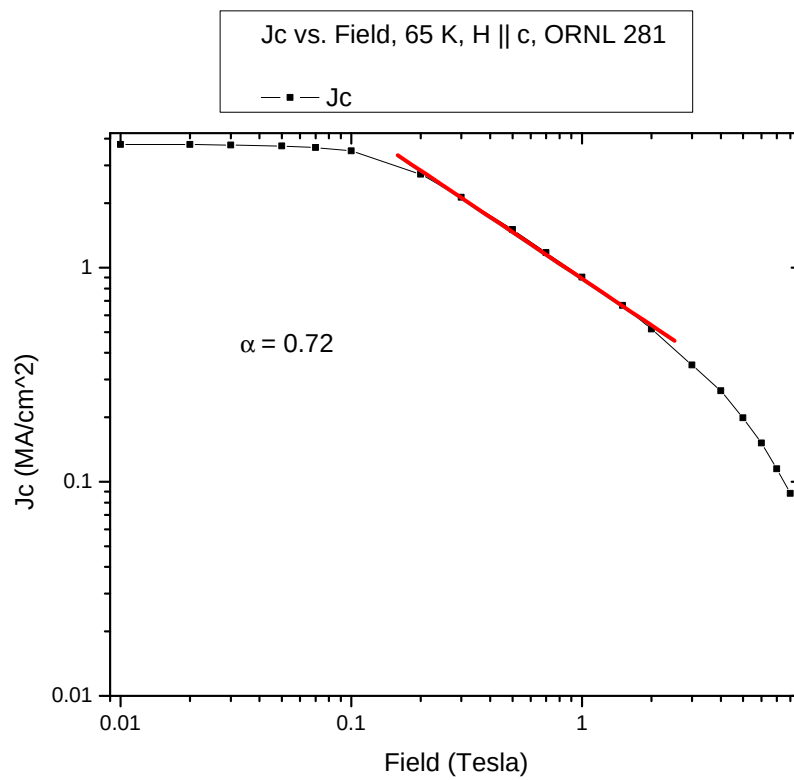


Figure 30: J_c vs. H for sample ORNL 281 at 65 K with the calculated α value

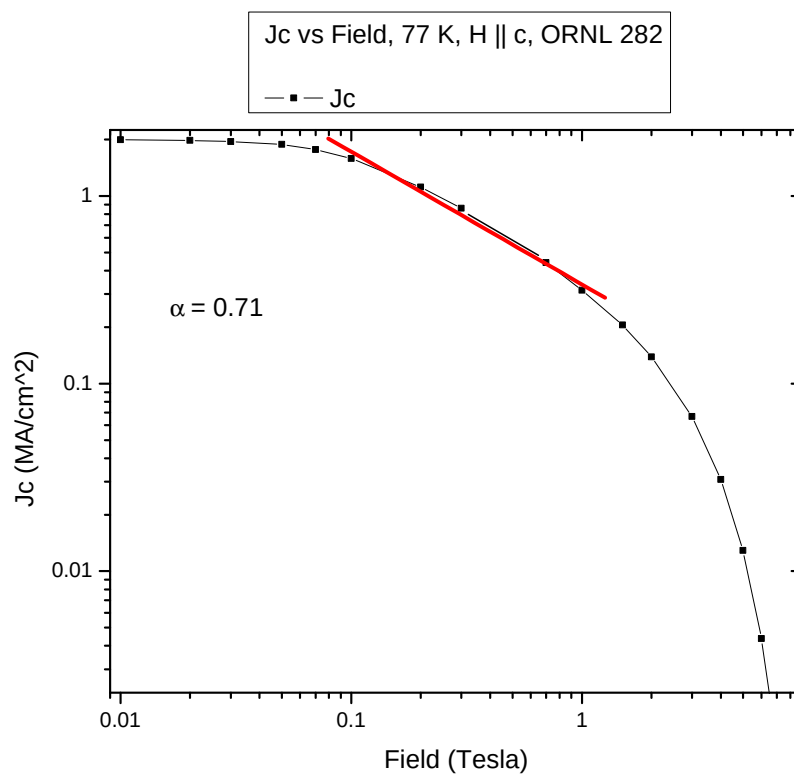


Figure 31: J_c vs. H for sample ORNL 282 at 77 K with the calculated α value

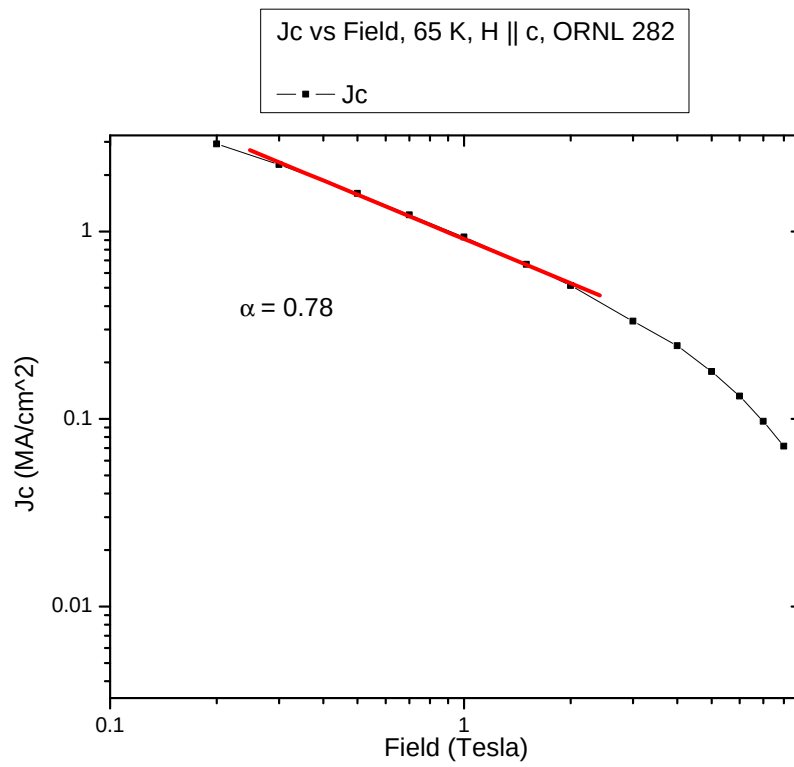


Figure 32: J_c vs. H for sample ORNL 282 at 65 K with the calculated α value

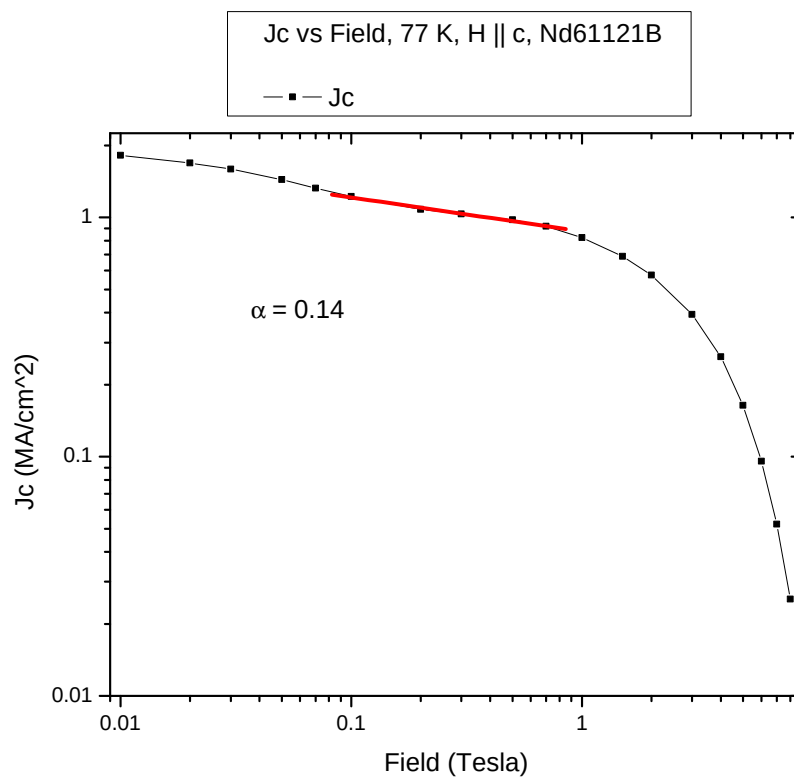


Figure 33: J_c vs. H for sample Nd61121B at 77 K with the calculated α value

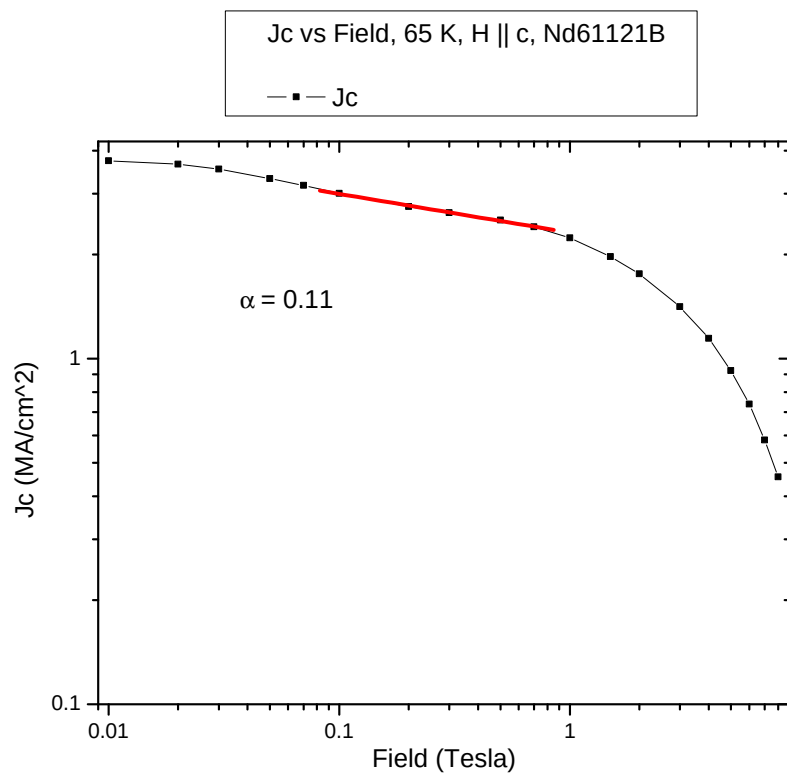


Figure 34: J_c vs. H for sample Nd61121B at 65 K with the calculated α value

3.4 Critical Current vs. Angle Data

The final sets of data comprise J_c versus θ measurements. Again, the measurements were done as I_c versus θ with the viable J_c values extracted from the data set of voltage-current relations. These graphs show the relationship between the angle of the sample in a magnetic field and the magnitude of the critical current density. For these runs, the temperature and magnetic field were both held constant throughout the measurement while the sample was rotated approximately 140 degrees through the magnetic field. The peak that is shown around the 10 degree mark for sample ORNL 281 corresponds to the magnetic field being perpendicular to the c -axis, while the relatively flat area between 90 and 110 degrees is the area where the magnetic field is parallel to the c -axis. The first run was done with a temperature of 77 K in a field of 1 T (Fig. 35), while the second and third runs were done at a temperature of 65 K at 3 T (Fig. 36) and 5 T (Fig. 37) respectively. These measurement conditions are motivated by the need to assess the materials at the potential operating conditions of power devices, as mentioned above.

Additional information was gathered comes from the IV curves for the above J_c versus H graphs. By taking the individual IV curve for specific angles, the corresponding n -values can be extracted. As can be seen in Figs. 38, 39 and 40, the n -values of these lines are essentially the same for all angles throughout the entire measurement. This means that the n -value of each sample is seemingly independent of orientation within a constant magnetic field. As a point of reference, a line with no data points has been drawn in to illustrate the slope given by the n -value. This is simply to show the overwhelming similarity seen in the n -values throughout the entire angular sweep of the sample measurement. The J_c vs. θ measurements for ORNL 282 are shown in Figs. 41 through 43, while the corresponding IV curves for varying θ measurements are in Figs. 44 through 46. The final sets of data come from sample Nd61121B and follow the same format as above with the J_c vs θ measurements followed by the IV curves of varying angles.

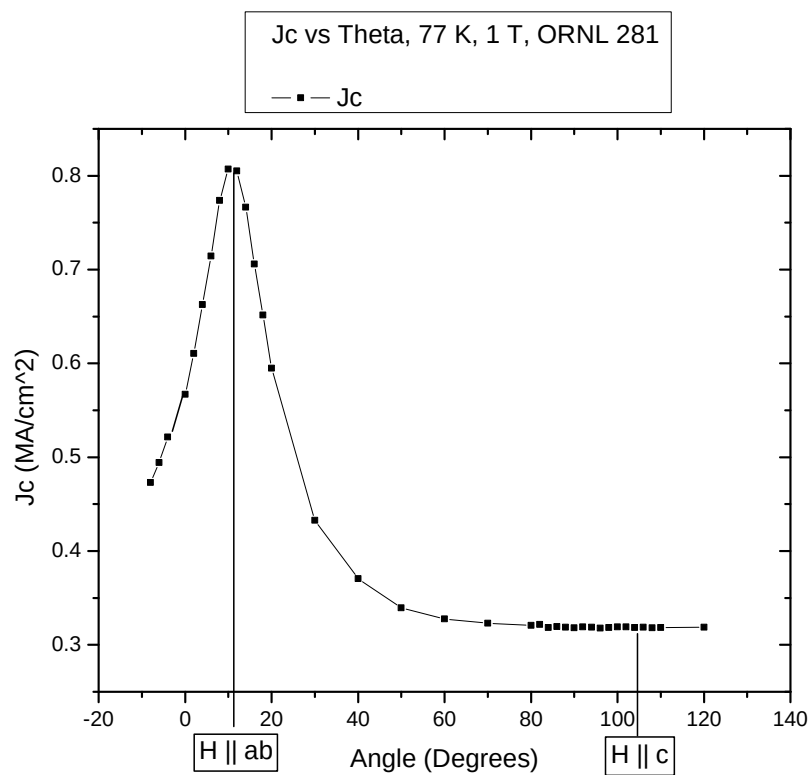


Figure 35: J_c vs. θ for sample ORNL 281 at 77 K in a 1 T magnetic field

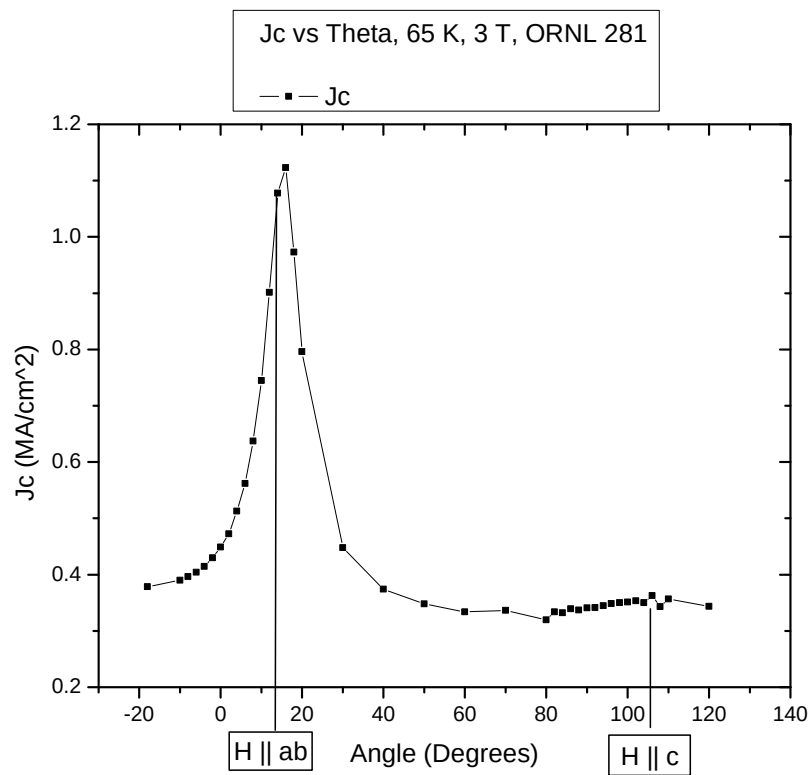


Figure 36: J_c vs. θ for sample ORNL 281 at 65 K in a 3 T magnetic field

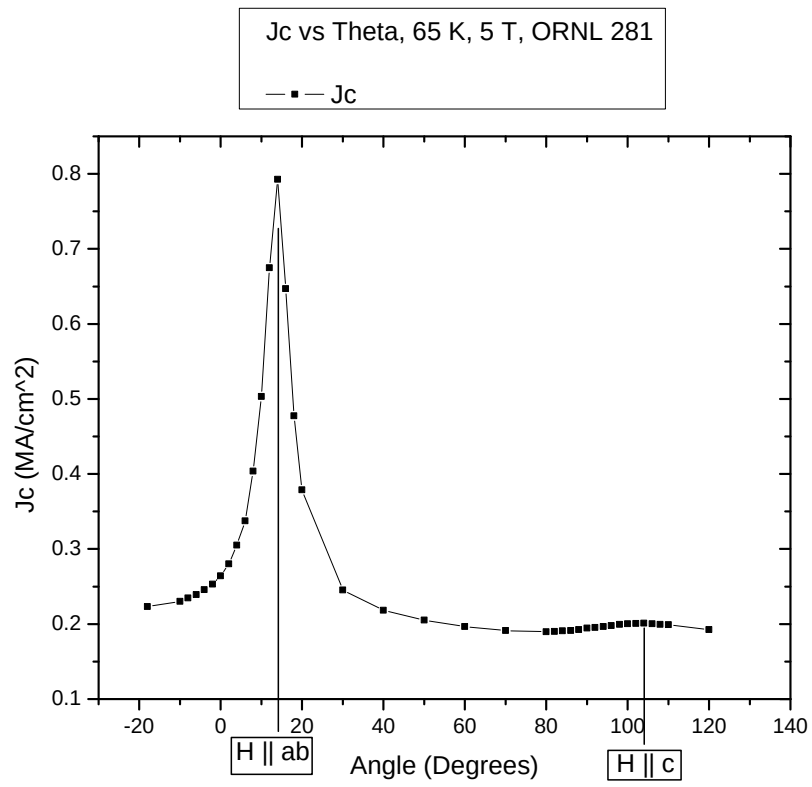


Figure 37: J_c vs. θ for sample ORNL 281 at 65 K in a 5 T magnetic field

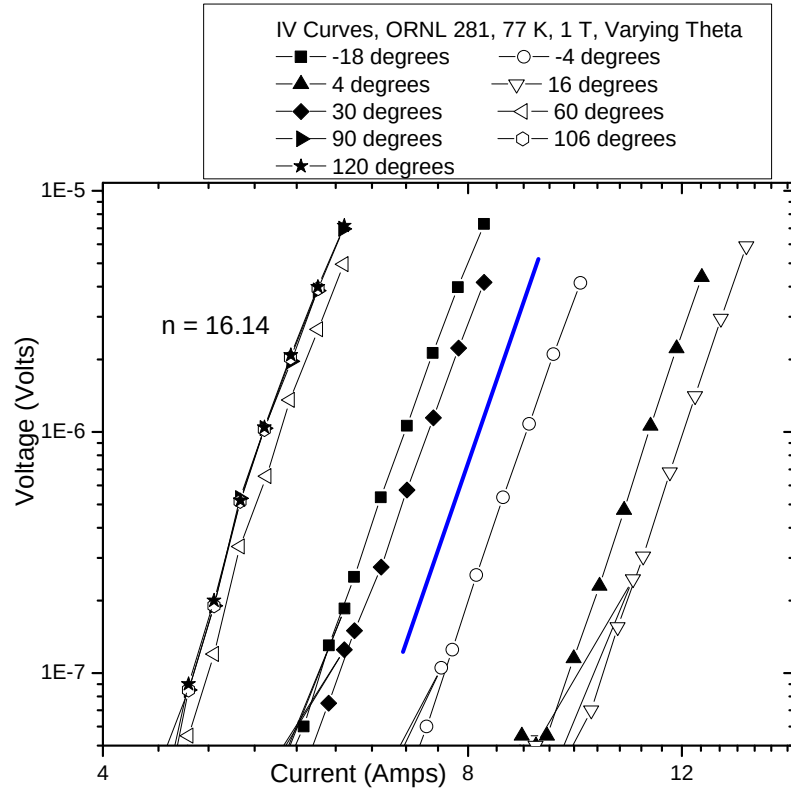


Figure 38: IV curves for sample ORNL 281 at 77 K in a 1 T magnetic field showing similar slopes in angular measurements of n -values

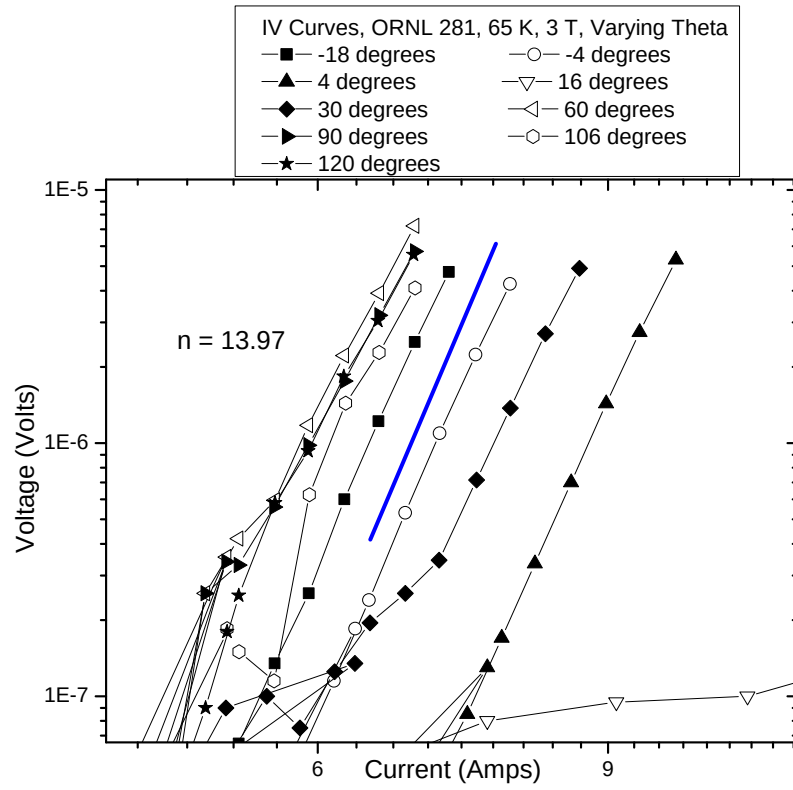


Figure 39: IV curves for sample ORNL 281 at 65 K in a 3 T magnetic field showing similar slopes in angular measurements of n -values

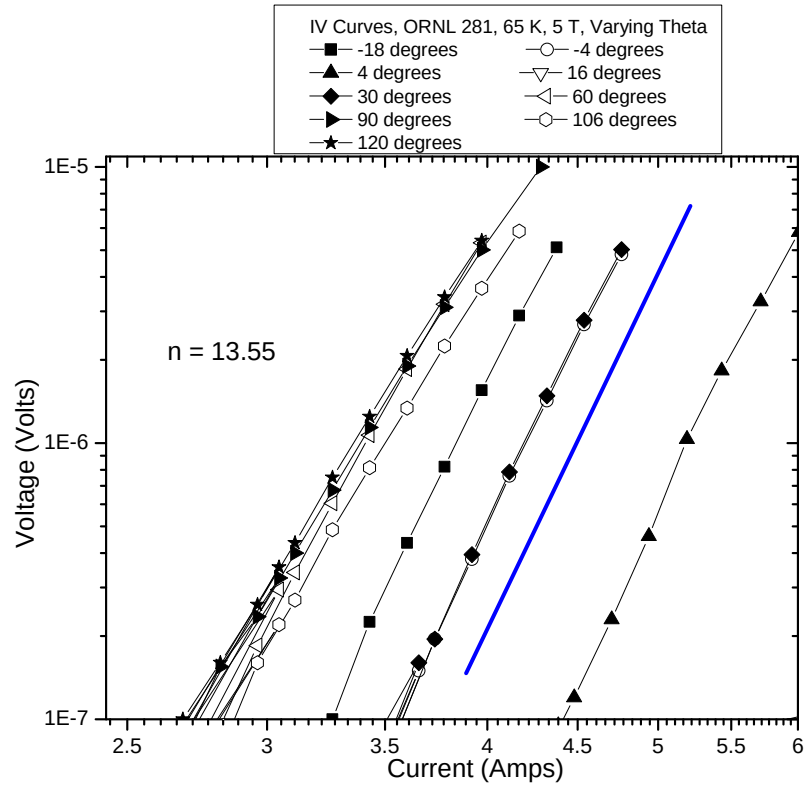


Figure 40: IV curves for sample ORNL 281 at 65 K in a 5 T magnetic field showing similar slopes in angular measurements of n -values

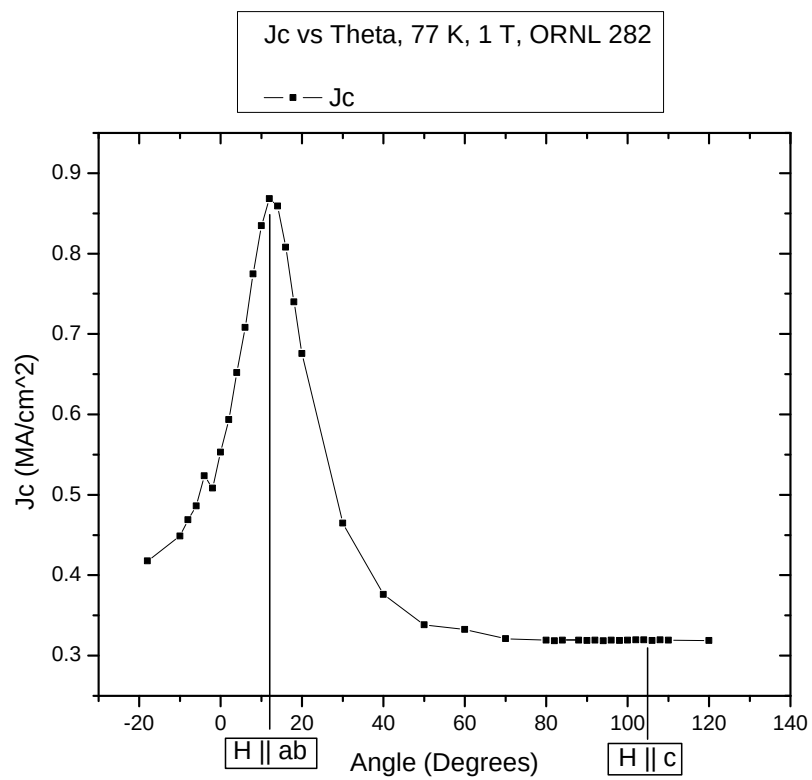


Figure 41: J_c vs. θ for sample ORNL 282 at 77 K in a 1 T magnetic field

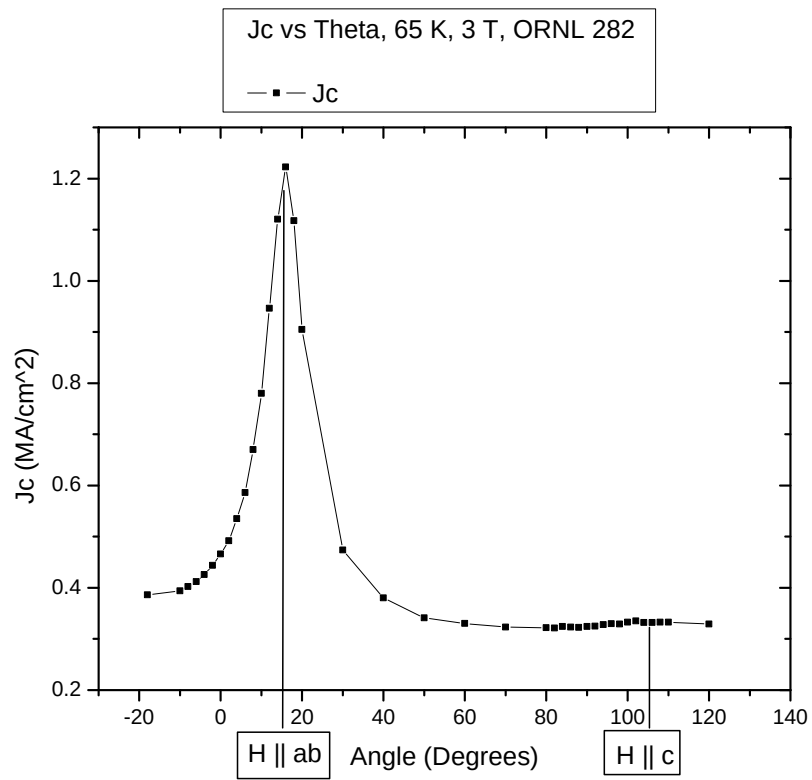


Figure 42: J_c vs. θ for sample ORNL 282 at 65 K in a 3 T magnetic field

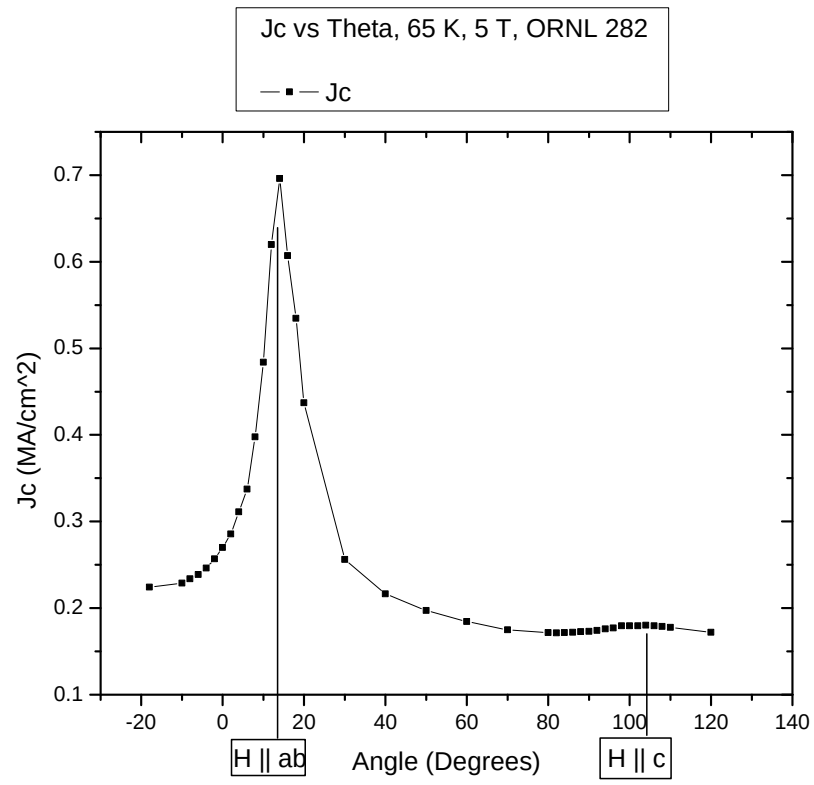


Figure 43: J_c vs. θ for sample ORNL 282 at 65 K in a 5 T magnetic field

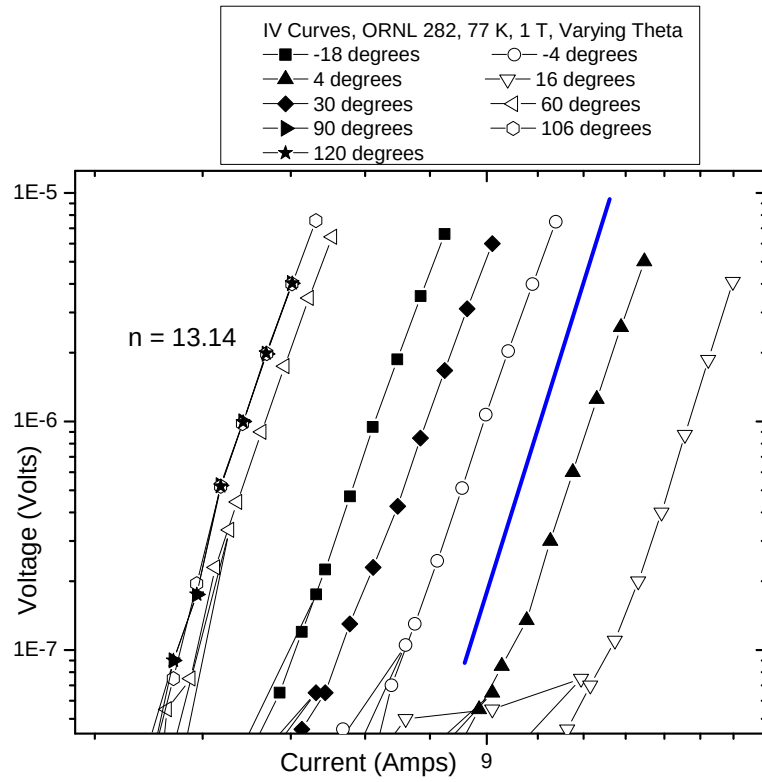


Figure 44: IV curves for sample ORNL 282 at 77 K in a 1 T magnetic field showing similar slopes in angular measurements of n -values

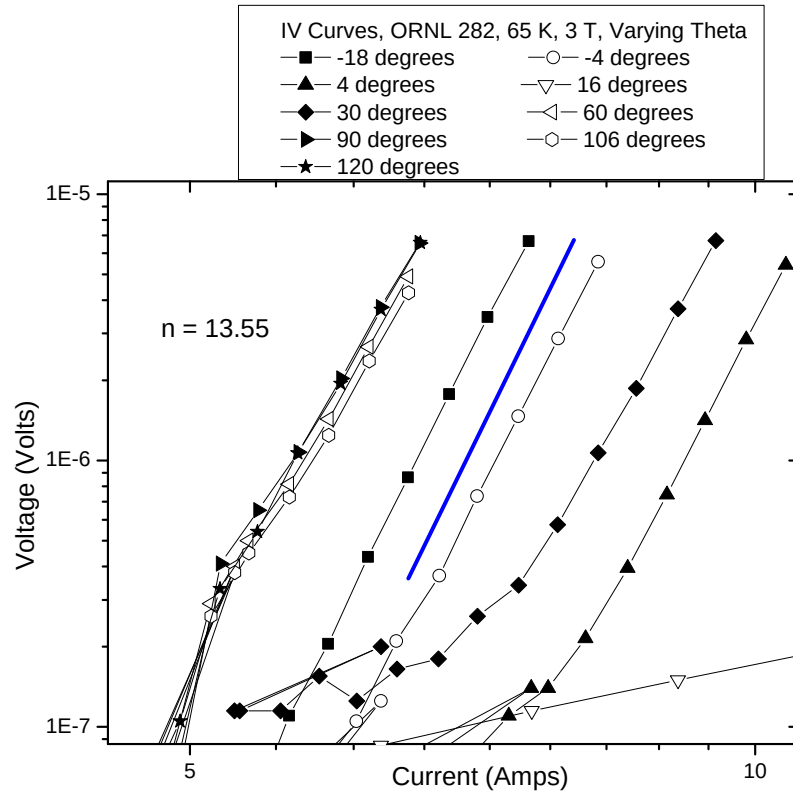


Figure 45: IV curves for sample ORNL 282 at 65 K in a 3 T magnetic field showing similar slopes in angular measurements of n -values

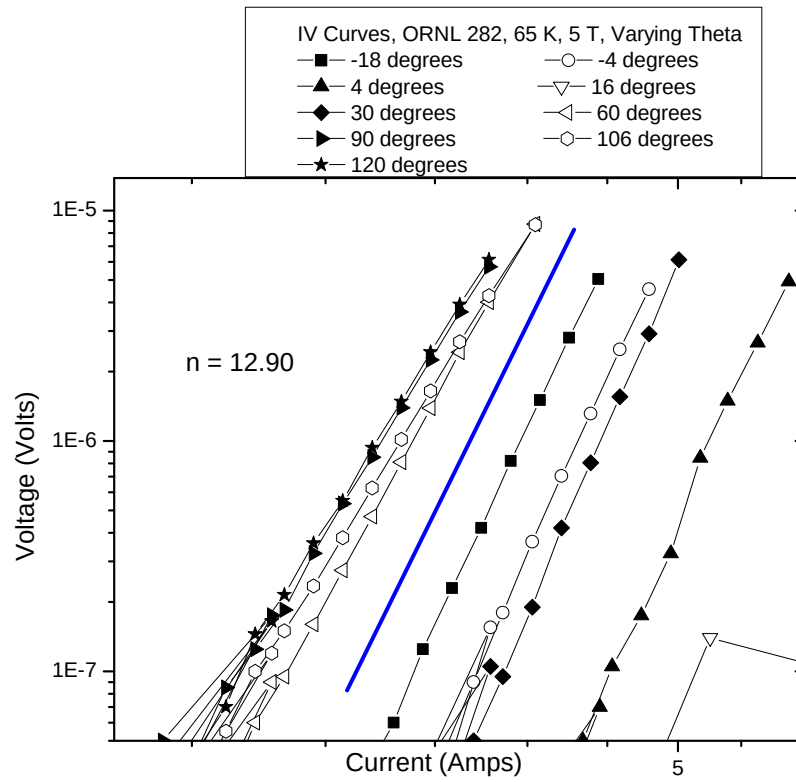


Figure 46: IV curves for sample ORNL 282 at 65 K in a 5 T magnetic field showing similar slopes in angular measurements of n -values

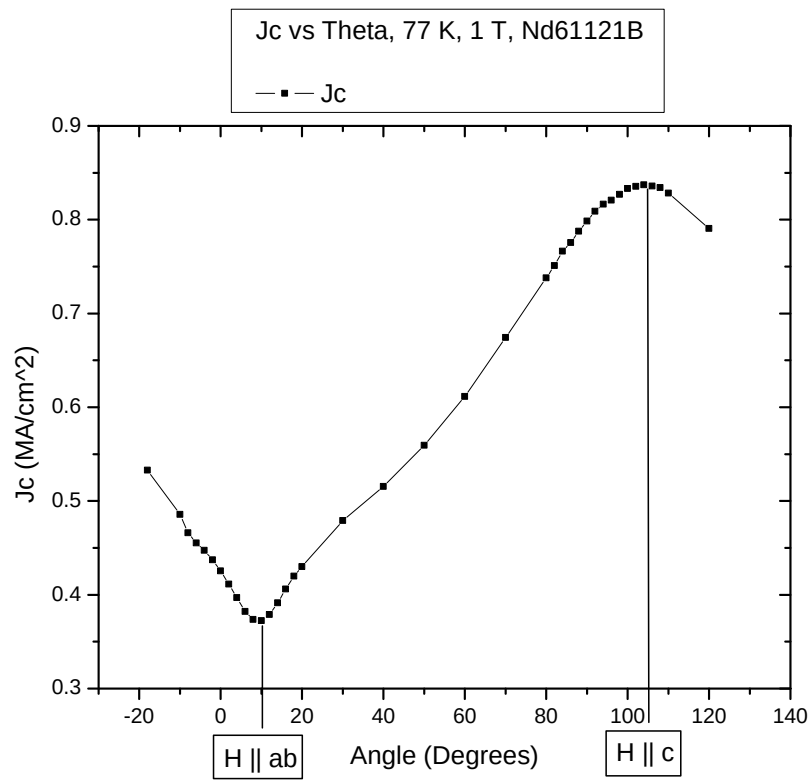


Figure 47: J_c vs. θ for sample Nd61121B at 77 K in a 1 T magnetic field

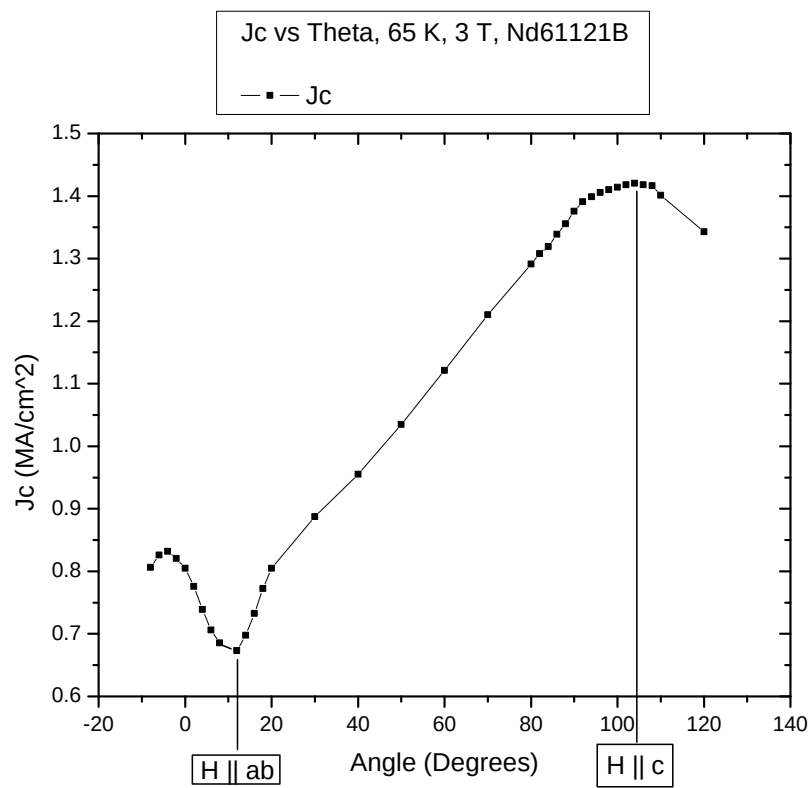


Figure 48: J_c vs. θ for sample Nd61121B at 65 K in a 3 T magnetic field

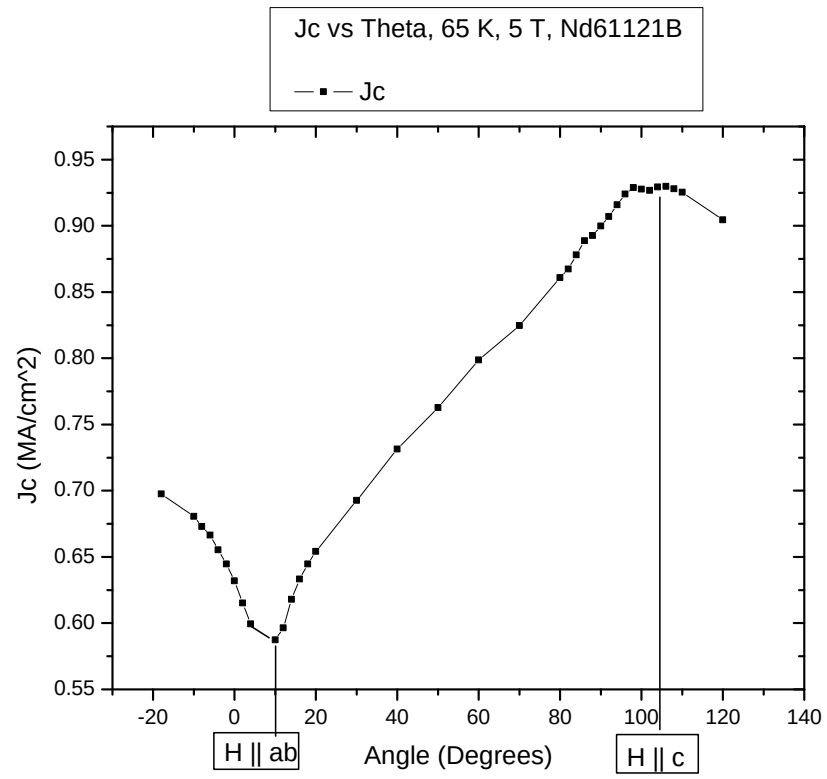


Figure 49: J_c vs. θ for sample Nd61121B at 65 K in a 5 T magnetic field

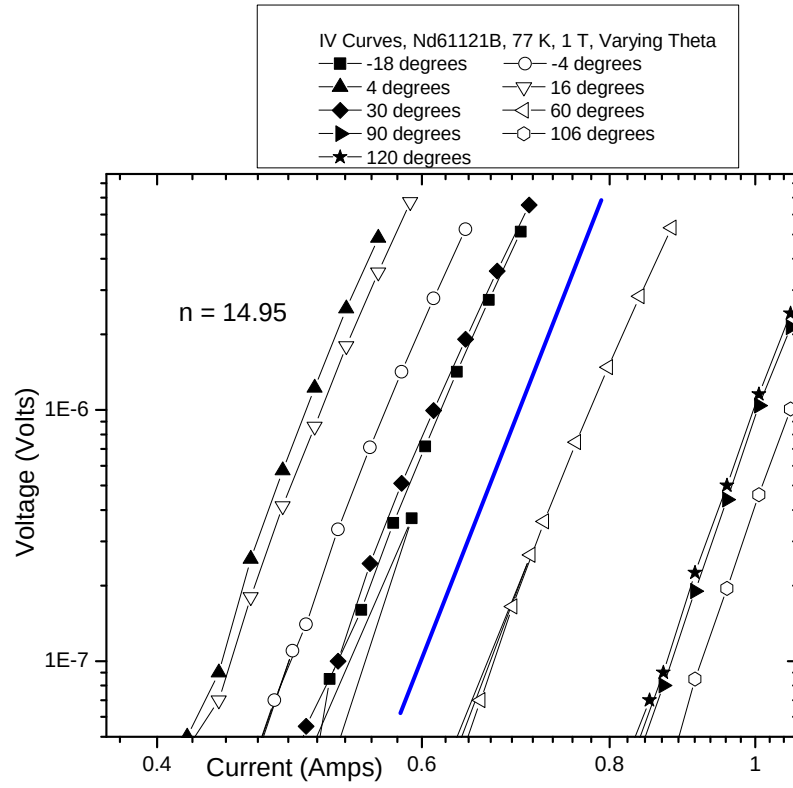


Figure 50: IV curves for sample Nd61121B at 77 K in a 1 T magnetic field showing similar slopes in angular measurements of n -values

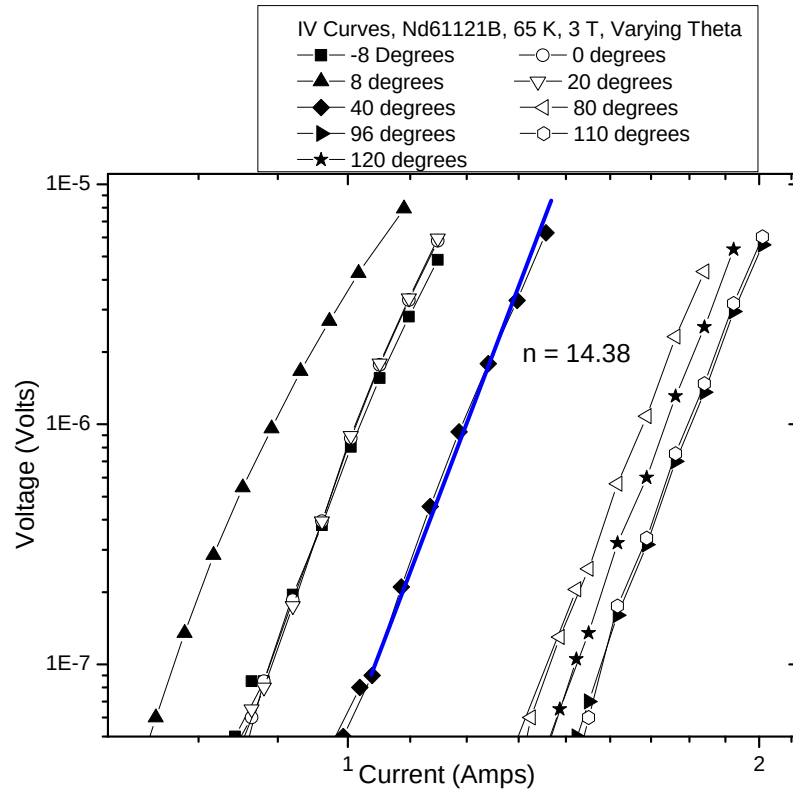


Figure 51: IV curves for sample Nd61121B at 65 K in a 3 T magnetic field showing similar slopes in angular measurements of n -values

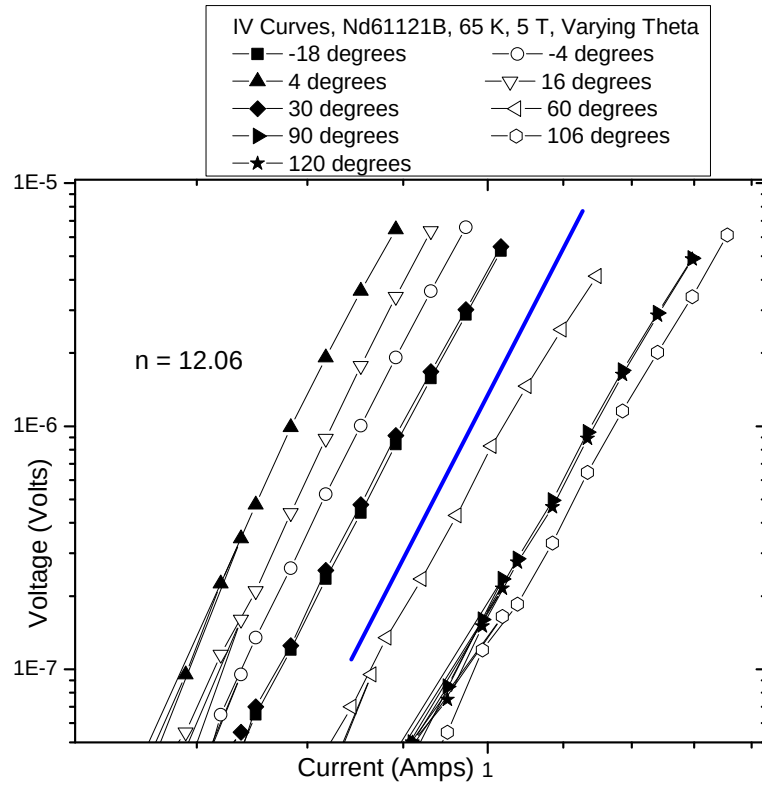


Figure 52: IV curves for sample Nd61121B at 65 K in a 5 T magnetic field showing similar slopes in angular measurements of n -values

4 Discussion

4.1 J_c vs. H

For each of the samples studied, the J_c vs. H measurements were all qualitatively similar. They all contained a plateau region in low magnetic fields, a power-law decay region with increasing field, and finally an H_{irr} fall-off as the irreversibility line is approached. The measurements at lower temperature were unable to reach H_{irr} since the field levels exceed the capability of the instruments. However, for the 77 K measurements, the H_{irr} level is essentially the same, with each sample having an H_{irr} in the region of 6.5 to 8 T. This similarity can be ascribed to two main factors. The first is the strong effects on pinning energy of the magnetic field. As the magnetic field increases, the pinning energy decreases, allowing for flux lines to move more easily throughout the sample, therefore diminishing superconducting capability. The second is due to thermal activation of vortices out of their diminished pinning energy wells. This scenario was discussed in section 1.5.1.

When looking at the relationship between the two ORNL samples and sample Nd61121B, one can see that the power-law decay of the ORNL samples from AMSC is much greater as shown by the α value. ORNL 281 has an α value of 0.84 at 77 K and 0.72 at 65 K, while ORNL 282 has α values of 0.71 and 0.78. However, Nd61121B has α values of 0.14 at 77 K and 0.11 at 65 K. These values are substantially smaller, and can be attributed to the BZO doping that is present within the Nd61121B sample. The significant difference indicates improved flux pinning due to the BZO, allowing for higher fields to be reached while still maintaining superconducting capacity.

4.2 J_c vs. θ

For both the ORNL samples, the main features of the angular dependence measurements are qualitatively similar to that discussed in the section on isotropic pinning. In other words, the maximum J_c comes with fields aligned with the ab plane of the sample, or $\theta = 0$. There is also either a very small or non-existent local maximum for the fields aligned along the c -axis at $\theta = 90$. One can see by comparison to figure 7 that they are the same in the basic features of the graphs.

Sample Nd61121B, however, has dramatically different features. There is a minimum with the field

parallel to the ab planes, while there is a broad, strong maximum in J_c when the field is parallel to the c -axis. These results reflect on the strong correlated pinning of the aligned BZO dopants. There are at least two possible explanations for the extreme differences. The first is that the BZO dopants are columnar along the c -axis and therefore are unable to pin the flux lines when the field is in the ab planes. Therefore, the vortices, either through thermal activation or the suppression of the pinning energy due to the magnetic field are able to easily escape the energy well when the field is perpendicular to the BZO dopants. The second explanation may be that the columnar defects effectively segment the vortices into very short lengths that are roughly the distance between the BZO columns. This distance is on the scale of 15-20 nanometers. The reason the length of these pinning sites is important is that the shorter segments are much more susceptible to thermal depinning since the total pinning energy is proportional to the vortex pinned length. Therefore, the total pinning energy may not be large when compared to the thermal energy $k_B T$, allowing thermal activation to easily liberate the flux lines from the pinning energy wells.

4.3 Angular n -values

As can be seen in section 3.4, the n -values calculated from the angular IV curves at a constant field value exhibit little variation with angle. This result was unexpected and surprising. It implies that the flux motion producing the measurable voltages are sampling a different pinning energy than that which determines J_c . One possible scenario is that the relationship of temperature to the pinning energy given by $\frac{U_0}{kT}$ is similar at all orientations, but that the shape of the pinning well varies. This is important since it is the shape of the pinning well that determines the pinning force, and therefore J_c . This would be found by taking the derivative $\frac{dU}{dx}$, giving J_c at all points throughout the pinning well. If this was indeed the case, one could perhaps find a nearly constant n equivalent to $\frac{U_0}{kT}$, while J_c appears to vary, approximately equal to $\frac{dU}{dx}$. Again, this is only a possible explanation for the results that have been observed.

5 Conclusions

It is shown through the above data that the sample Nd61121B with BZO dopants allowed for greater flux pinning than the ORNL samples that contained no dopants. This improved pinning allows for greater field levels before superconductive ability is diminished due to motion of magnetic field lines. In addition, the directionality of the dopants appears to have a significant impact upon the angular dependence of J_c . Finally, more intense study must be done on the angular dependence in relation to n -values. The findings that the n -values for these three samples depend only weakly on orientation comes as surprising and unanticipated. More study, as well as further theoretical advances regarding pinning, are necessary before these results can be fully understood.

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Appendix

A Tabulated Values for R vs. T and n

Table 2: R vs. T data for ORNL 281 showing T_c

Temperature (K)	Resistance (R)
99.354	3.8E-4
98.334	3.85E-4
97.323	3.65E-4
96.314	3.8E-4
95.306	3.65E-4
94.296	3.85E-4
93.295	3.65E-4
92.279	3.65E-4
91.263	3.55E-4
90.247	3.55E-4
89.231	5E-6
88.22	1E-5
87.213	-1E-5
86.204	-5E-6
85.192	0

Table 3: n -value data for ORNL 281

65 K	77 K	
n-value	n-value	Field (Tesla)
6.75082	1.17351	8
7.69802	1.77854	7
9.58823	2.48306	6
10.46857	3.68583	5
12.55218	4.96989	4
11.88706	4.0239	3
14.9308	9.9484	2
17.68895	12.01521	1.5
18.71123	15.12384	1
19.01262	15.12686	0.7
19.56915	16.17581	0.5
20.62042	17.51378	0.3
21.7882	18.65814	0.2
25.27403	21.02801	0.1
28.15959	22.96365	0.07
26.15778	27.30589	0.05
28.33129	27.12197	0.03
28.48076	26.60408	0.02
28.61915	28.7593	0.01
28.4204	27.62833	0

Table 4: R vs. T data for ORNL 282 showing T_c

Temperature (K)	Resistance (R)
100.773	5.2E-4
99.759	5.1E-4
98.752	5.15E-4
97.736	4.85E-4
96.734	5E-4
95.713	4.95E-4
94.701	5E-4
93.682	4.8E-4
92.675	4.75E-4
91.673	3.35E-4
90.671	0
89.559	0
88.544	0
87.511	-1E-5
86.414	0

Table 5: n -value data for ORNL 282

65 K	77 K	
n-value	n-value	Field (Tesla)
6.36441	1.06786	8
7.22592	1.72283	7
8.58258	2.57246	6
10.22766	3.62363	5
12.07586	4.93726	4
11.09051	7.05926	3
15.31004	10.14337	2
18.40537	12.63902	1.5
21.17328	15.79356	1
20.01831	16.2866	0.7
19.63668	-	0.5
23.27339	18.41655	0.3
21.99295	19.76669	0.2
-	22.01316	0.1
27.88504	24.25737	0.07
-	25.82656	0.05
-	27.9411	0.03
-	28.80606	0.02
-	28.00806	0.01
-	28.49597	0

Table 6: R vs. T data for Nd61121B showing T_c

Temperature (K)	Resistance (R)
105.973	0.10574
104.963	.10532
103.944	.10488
102.931	.10447
101.926	.10405
100.922	.10364
99.912	.1032
98.911	.1028
97.903	.10239
96.901	.10208
95.888	.10651
94.875	.04096
93.861	-1.5E-5
92.846	-5E-6
91.83	-5E-6

Table 7: n -value data for Nd61121B

65 K	77 K	
n-value	n-value	Field (Tesla)
8.04436	3.63155	8
9.05235	4.47898	7
10.26891	5.35771	6
11.74295	6.64799	5
13.56755	8.45701	4
15.32764	10.33898	3
17.72723	13.16781	2
17.53753	14.476	1.5
20.14659	16.27382	1
18.81632	17.8292	0.7
18.91823	17.31934	0.5
18.84225	18.18044	0.3
17.56907	17.62412	0.2
18.69469	18.61469	0.1
18.92761	19.06586	0.07
18.67145	19.83881	0.05
19.57123	21.49809	0.03
19.47539	21.71811	0.02
21.02765	22.75648	0.01
20.40285	26.63131	0

Vita

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