

**FINAL REPORT**

**Alternating Current Losses in Ag-Sheathed BSCCO (2212 & 2223) Tapes  
and  
Wires and YBCO (123) Coated Conductors**

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## **TABLE of CONTENTS**

I.	Introduction	4
	A. Overview	4
	B. Objectives	7
	C. Background	8
	D. Methodology	10
	E. Loss Components	11
	F. Measurement Techniques	12
II.	Results and Discussions	14
III.	Summary and Conclusions	17
IV.	Acknowledgements	17
V.	References	18
VI.	Graphs	19

## INTRODUCTION

### Overview

In this study, we focus on the examination of ac losses in conductors utilizing  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}$  [BSCCO (2223)] high  $T_C$  superconductors (HTS). In addition, we seek to assist other facilities such as the University of Wisconsin-Madison Applied Superconductivity Center (UW-ASC), Brookhaven National Laboratory, and other DoE facilities investigating the use of HTS in electric power applications (e.g., generators, motors, and transformers). To accomplish this we will develop an ac losses capability at Clark Atlanta University to complement the established ac losses efforts at Brookhaven National Laboratory (BSCCO) on BSCCO/Ag and various material characterization efforts taking place at the UW-ASC. Our goal is through this effort to gain a greater understanding of the effects on ac losses due to parameters such as ac/dc current,  $J_C$ , tape geometry, voltage tap placement, field orientation, material anisotropy, surface irregularities, percolations and filament coupling effects. As a result, we expect to better understand how to minimize ac losses in applications requiring real or practical conductors.

HTS conductors based on BSCCO-2223 are now being routinely produced in industrial lengths of high quality. Vendors such as Southwire and ASC are producing multifilamentary tapes in lengths of 6 km or more carrying critical current densities of up to 3 kA/cm<sup>2</sup> at 77°K. While this is approaching the level of performance where some large-scale applications are considered to be economically viable, a number of problems remain to be solved. The remaining issues include:

- rapid reduction in  $J_C$  in magnetic fields; and
- power dissipation due to varying magnetic fields or currents ('ac losses').

The challenge of developing more cost and performance efficient electric power systems has enhanced interest in the conductors of the systems. Conventional conductors such as copper are plagued by large energy losses due to power dissipated in the form of Joule heating. Superconductors, in principle, without loss under dc conditions do develop finite loss under ac conditions, though still permitting operation at current densities much higher than are possible with copper. This feature highlights the essential nature of the critical current density in the superconductor. Improvements in  $J_C$  up to  $10^6$  A/cm for YBCO (123) coated conductors and near 0.06 MA/cm for BSCCO (2223) short tapes continue to generate optimism that we will eventually incorporate high temperature superconductors in power applications [1,2]. Continued improvements in  $J_C$  are inevitably expected to significantly reduce the cost of the km-length tapes and wires needed for electric power applications.

Traditional magnetic and transport methods are corroborated with techniques used by Ashworth and Suenaga at BNL to measure ac losses in BSCCO 2212 and 2223 tapes and

wires. Generally, loss measurements are derived from the induced voltage of the time-dependent magnetic flux penetration (magnetic) and the induced ac voltage from the self-field (transport) current, which are developed in pick-up coils placed close to the sample being tested. Power dissipation is then determined from the time average of the product of the in-phase voltage and applied field or current. These methods are very useful because they are well suited for analyzing the behavior of a superconductor in ac fields. In addition, the induced loss voltage waveforms and hysteretic **B-H** loop can be observed and analyzed. Phase shifts that may occur due to matrix eddy currents can also be observed.

If the magnetic field inside a superconductor changes then an electric field is generated in the presence of an electric current, which causes power to dissipate. The changing magnetic field may be due to either a varying applied field, self-field of a varying transport current in the superconductor or some combination of both. The resulting power dissipation leads to heat generated within the superconductor, which, for stable operation, must be removed by a refrigeration system. For refrigeration at 77°K, every watt of power generated in the superconductor requires 10 – 100 watts to be expended in refrigeration (efficiency depends on the scale of the application, e.g., larger machines tend to be more efficient). Thus, the magnitude of ac losses can significantly impact the economics of large-scale superconducting applications. It is possible to reduce ac losses in a number of ways through design. The design considerations can be made in terms of the:

- system (minimizing field and field changes at the superconductor); and
- conductor (isolated filaments, higher  $J_C$ ).

However, in both cases, it is still necessary to accurately predict the losses of a given conductor in a combination of varying fields and currents. Although significant progress has been made, challenges still remain.

The effect of a dc magnetic field on the losses of an ac current carrying conductor are well documented, although not fully explained in the case of highly anisotropic conductors. The change in losses due to an ac field on a dc current conductor is less clear. On BSCCO-2223 Ag sheathed tapes, experimental results indicate a drastic increase in transport losses due to external transverse magnetic fields, (dc and ac) caused by the lowering of the critical current density [3,4]. Since the conductors in electric devices such as generators and motors experience magnetic fields of up to a few Tesla, dynamic resistance loss (loss due to the interaction between the dc transport current of the rotor and the external ac field) must be considered along with the hysteresis and current losses of the conductor.

Two important factors that can seriously impact dynamic resistance measurements are:

1. complex structure and morphology of HTS ceramics which prevents the homogeneous distribution of transport current; and

2. tape geometry common to HTS conductors, which can cause the transport loss voltages measured in the center and along the edges to differ by an order of magnitude or more, making the dynamic resistance loss very difficult to measure [4].

Fukunaga et al showed that the placement of voltage taps is critical because the in-phase voltage can significantly vary as a result of the positioning of the voltage taps for superconductors obeying the Bean critical state model for slab geometry [4]. Larbalestier et al have shown that the critical current density at the edges of a tape is much higher than at the center [5]. The dynamic resistance and the combination of ac fields and ac currents present significant experimental and theoretical issues that must be addressed.

In this effort, our emphasis is placed upon individual conductors, not assemblies. Loss measurements will follow the techniques used by Orehtsky et al and Fukumoto, in which sections of tapes whose faces are parallel to the applied magnetic field are placed in a pick-up coil [6]. Voltage tap separation optimization will be pursued in this study. The sample will have both of its ends soldered to the current electrodes with the two voltage taps attached in the middle of the sample. The ac measurements will be performed at liquid nitrogen temperature (77°K) at various frequencies initially under zero dc magnetic field.

This effort will utilize the theoretical implications of the Critical State Mode relative to tape measurements that are:

1. parallel to the applied dc field with  $J_C$  constant and carrying an ac current;
2. parallel to the applied dc field,  $J_C$  varied as a function of B and carrying an ac current;
3. parallel to the applied ac field,  $J_C$  constant and carrying an ac current.

From these measurements, calculations will be made of the flux profile and ac losses and signal from voltage taps and pick-up coil. A slab geometry is assumed along with no demagnetization effects on the applied field.

Although the above three measurements can be repeated for other geometries such as the thin ellipse geometry or oblate shapes, where the superconductor changes the external magnetic field (i.e., fields are perpendicular to the tapes), the slab geometry will remain our focus.

BSCCO 2223 tape samples were provided by Southwire, BNL, and UW-ASC. UW-ASC also provided samples that were microstructurally examined.

## **Objectives**

The stated objectives are to:

- Train students who can assist DoE, academia, and industrial efforts in the study of ac losses. As a result, we expect to develop a pool of potential employees and/or graduate students who can immediately contribute to research efforts that require an understanding of ac losses.
- Facilitate a better understanding of ac losses through both the computational and experimental study of ac losses using existing and new methodologies.
- Evaluate the applicability of existing theoretical models to layered HTS conductors.

## Background

Current passing through a conductor is well known to generate a magnetic field. Conversely, by increasing the current, the magnetic field strength is also enhanced. The field is strongest near the conductor, which becomes an important issue within a number of important applications, including the electric motor, whose operation is based upon the effect that the magnetic field has against a conductor (wire) carrying an electric current. The current through the wire generates a magnetic field around the wire that distorts the flux lines that exist between the two magnetic poles. The flux lines will tend to move to the side of the wire in the same direction of the wire's lines of force, which leads to flux distortion. The distorted flux lines seek to straighten and as a result exert a repelling force on the wire. The wire is pushed out of the field where the flux lines are weakest—the defining principle of electric motor operation. A torque is produced by a loop of wire that is connected through a commutator to a battery. In this case, the current in the wire will generate magnetic fields that will be repelled by the magnet's flux lines.

Another example is the basic generator, which functions opposite to the motor. In this case, the rotor is turned mechanically instead of introducing a current in the rotor windings to produce a magnetic field. Magnetic energy forces current to flow in one direction when the rotor windings pass through the flux lines. It is noted that as the wire traverses down the field, current flows in a single direction. However, as the wire travels up the field, current flows in the other direction. In a dc generator, the commutator switches the wires outside the generator while the rotor turns, which in effect, keeps the current flow in the same direction. In the event that a commutator is not used, the current leaving the generator will then change direction as the loop turns—hence, an ac generator. Alternating current is used because it is much cheaper and can be used more easily than direct current. In addition it can be used in a wider range of applications. Electric power plants are limited to where they can be built, including generally near natural energy sources like large rivers and not near residential districts, industrial plants, agricultural environments, i.e., densely populated or health sensitive areas. As a result, the generated power must be sent over long distances to the users—which leads to large power losses if direct current (dc) is used.

The energy being used outside of the load corresponds to loss or wasted power that usually appears in the form of heat. At issue in power transmission is that when wiring between the source and load is very long (i.e., power transmission of electric power from the power stations to the users losses can be quite significant). The distances can very well be in some cases up to hundreds of miles in length. In the transmission of electric power, part of the power is converted into heat along the length of the transmission line. This heat defines losses to power transmission, but can be reduced by either lowering the current ( $I$ ) in the transmission line, the resistance ( $R$ ) of the conductor or both. Unfortunately, users at the end of the transmission line need large currents driving the need to seek relatively low currents along the transmission lines that are converted to

high currents at certain points within the transmission line yielding large currents at the ends of the lines.

Ac voltage is generated when physical motion and magnetism is combined by ac generators. When a conductor is moved through a magnetic field to cut through flux lines, current is then generated by a voltage or emf ( $\mathcal{E}$ ). This voltage has characteristic waveforms that describe the output voltage of the generator during one full cycle (revolution) of the armature, starting from zero, when the armature is not cutting any flux lines. The voltage increases from zero to its maximum in one direction as the armature turns. At some time later, the voltage decreases until it reaches zero again. The voltage reverses polarity at this time and increases causing the generator armature to go through a complete or full revolution. The voltage of note is generated at any point in the armature's transition and is proportional to the sine of the angle between the magnetic field and the direction of motion of the armature.

When ac current flows in a conductor, the resistance offered to the current by the conductor is larger than the resistance offered to dc current by the same conductor. This is due to ac current flowing in a conductor, which causes voltages to be set up inside of the conductor. As a result,

- Eddy currents, and
- Current that flows near the conductor's surface

can take effect; both of which can diminish the power due to eddy currents (which flow through the resistance of the conductor, consume power, and ultimately yield a power loss via resistance increase). In addition, the surface currents generated can decrease the cross-sectional area of the conductor—another noted cause of increased resistance called the “skin effect”. Both of these effects are directly proportional to the frequency of the current flowing in the conductor. Hence, increases in frequency translate directly into increases in eddy current and skin effect losses. This point is significant because they can be problematic when frequencies are high. Power cable configurations largely negate contributions due to skin effect losses because the cumulative surface areas of all of the individual wire strands are greater than that of the surface area of the solid conductor.

It is noted that when an alternating current flows in a conductor, the current constantly varies in strength, which causes the magnetic field around the conductor to change constantly in magnitude. Hence, the field strength is increased as the current is increased. The magnetic field reverses its direction as the alternating current changes its direction. The magnetic field around the conductor builds up and collapses as the alternating current in the conductor goes through a complete cycle. As the magnetic field begins building up from zero, the flux lines expand from the conductor center outward or cut through the conductor. As the field moves outward or collapses through the conductor, a current flow of its own is produced and induces an emf in the conductor—self-induction. The induced emf has magnitude, which is determined by the

- Rate at which the magnetic field collapses, or
- Value of the current.

For the alternating current, which is varied as a sinusoidal function, the frequency determines how fast the current changes. The magnitude of the induced emf depends on the frequency and magnitude of the current. From an energy standpoint, self-induction corresponds to the removal of energy from the circuit when the current increases and the return of energy to the circuit when current decreases. An inductor is often introduced to oppose changes in current within the circuit.

Ideal vs. real applications: superconductor has negligible losses under dc conditions (i.e., constant current and zero field). However, in the real world, practical applications like power engineering incorporates conductors that must carry current under the influence of a magnetic field. Since, the either of the following can realistically occur, including:

- Field can change with time;
- Current can change with time;
- Both field and current can change with time,

It should come as no surprise that energy losses and heat generated within the superconductor do happen. The following causes have been identified, respectively, including:

- Inconsistent output in dc current supplies;
- Time-varying magnetic fields and currents.

Careful attention must be paid to the following, including:

- Sinusoidal variations in magnetic fields and transport currents;
- Power supplies drive both current and field (which is good if and only if the current and field vary at the same frequency and are in phase or either constant);
- Energy losses of the two supplies measurement coordinated with the superconductor sample (otherwise the interaction of the two power supplies must be considered);
- The effect of phase variation on losses is very important.

## **METHODOLOGY**

Traditional models like the mean field and monoblock models focus on the calculation of losses due to a determination of the flux distribution and motion within the superconductor. The emphasis is placed on determining a voltage and ultimately the losses in a system. This approach creates problems due to questions with regards to how

to use the voltages resulting from pick-up coils and voltage taps to determine the losses. The difficulty arises in identifying which fluxes correspond to the field and to the current. In the method proposed by Ashworth that will be used in this study, the focus is on determining the voltages in the respective power supply units responsible for driving the currents through the sample and magnet [6]. It is proposed that it may be a much simpler process that can reveal more consistent results by considering the energy losses of the power supply units instead of flux contributions. In this regard, the user simply needs to calculate the rate of change of flux linked in the power supply unit (note: ohmic losses in external wiring, etc. are ignored). This approach depends not on where the flux originates, i.e., from the magnet or transport current. If it links the circuit, the psu must provide a voltage to overcome its movement in order to drive its required current—a voltage component in phase with the drive current represents an energy loss [7]. It is again reiterated that this approach lends itself to a quick approximation of ac losses without the cumbersome and tedious methods involving the determination of the flux distribution in the conductors (a much more uncertain process).

## **LOSS COMPONENTS**

### **Hysteresis**

The ability of Type II superconducting filaments to sustain a nonzero electric field is responsible for hysteretic loss and is illustrated by the following example. A transformer consisting of a magnetized conductor core experiences changes in the direction that the core is magnetized each time the magnetic field around the windings expands and collapses. The molecules of the conductor act as “individual magnets” but do not follow exactly the reversals of the magnetic field. The molecules are aligned in the direction of the field when the core is initially magnetized. However, when the magnetic field collapses to zero, the molecules do not return to their original random orientation. A magnetic force must be applied by the magnetic field and the field must reverse direction in order for the core to return to its original unmagnetized state. When this happens, the molecules then reverse and orient themselves in the new field direction. The energy required for the molecules to redirect and overcome the lagging behind the magnetic force corresponds to the hysteretic loss of the core. Hysteresis losses are directly proportional to the current frequency in the transformer.

### **Eddy Current**

The magnetic field of the transformer induces a voltage in the conducting core, which causes small currents (eddy currents) to flow within the core. These currents actually function as short-circuits given that the only resistance that they encounter is the core’s resistance. Dividing the core into insulated laminations or filaments can minimize the influence of eddy currents. When this occurs, the eddy currents can only flow within the individual filaments. The small cross-sectional area of the filaments greatly reduces the

resistance and ultimately the loss effects of the eddy currents. The power loss attributed to eddy currents is directly proportional to both current frequency and magnitude [8].

### **Coupling**

When a transport current or time-varying magnetic field induces interfilamentary (screening) currents within the matrix metal, resistance is generated. Filament coupling is undesirable because the screening currents can cross the matrix and by Lenz' law, the coupling flow will dominate uncoupled flow if there is a sufficient driving voltage to overcome the resistive drop across the matrix. This resistance depends on a number of factors including the: normal resistivity of the metal, composite's dimensions, and the longitudinal distance over which the transverse currents can flow. Unfortunately, a typical superconducting magnet contains a large distance of wire (e.g., several kilometers). Hence, the distance available for crossover currents can be quite large [9]. Coupling is also undesirable because it can facilitate flux jumping, a major source of disturbance in magnets. Coupling losses can be minimized through designs that stabilize conductors against flux jumping under practical operating conditions.

## **MEASUREMENT TECHNIQUES**

### **Transport**

Transport measurements are typically accomplished via a four-point probe setup in which the  $I_C$  (critical current) is derived from the I-V characteristic of the dc measurement. In this method, two leads are used to drive current through the sample while the voltage is measured via two separate leads. The voltage leads carry virtually no current, minimizing the effect of contact resistance. In these electrical measurements, the emphasis is placed upon measuring the net power supplied to the pickup coil. A lock-in amplifier is used to "lock" the appropriate current to the measured voltage. The method is faster and more versatile than the calorimetric method, but characterized by uncertainties in what is actually being measured. It is highly possible using the basic electrical measurement approach to miss loss components.

### **Calorimetric**

The Calorimetric setup at BNL is used in this study. Calorimetric measurements focus on rises in temperature in thermally insulated tape. Two measurements are required including, the measurement of the temperature rise and the determination of the unknown power dissipation. The temperature rise of the tape is measured using a differential thermocouple. Ac losses are determined through the comparison of the temperature increase after a fixed time of unknown ac and known dc power dissipation [10-12]. The calorimetric measurement is much less sensitive than the transport measurement.

## Magnetization

In magnetization setup, pick up coils are used to measure the flux in and out of the sample as the magnetic field changes. Two coils are used in which, one (generally the inner coil) carries current while the outer coil is used to record voltage. Generally, parallel and perpendicular field measurements are sought. In dc measurements, the field  $\mathbf{H}$  is measured as a function of  $I_{\text{solenoid}}$  ( $I_s$ ). While in ac measurements,  $V_H$  is measured as a function of  $I_s$  and frequency.

## Ac Loss Components and Related Parameters

Some of the fundamental attributes or properties associated with losses are shown in Table 1, below.

dc Losses	Hysteretic Losses	Eddy Current Losses
Frequency dependent	$\propto f I^3$ ( $I < 0.5 I_c$ )	$\propto f^2 I$
Contributions around $0.8 I_c$		
Norris Contributions: $V_{dc}$ vs. $I_{dc}$		
$\propto I^n$ (P Law dependence), $n: 10 - 20$		

**Table 1. ac Losses Attributes Relative to Categories.**

$$q_{eddy} = A f^2 I \quad (W/m) \quad (1)$$

$$q_{dc} = B I^n \quad (W/m), \quad n: 10 - 20 \quad (2)$$

$$q_{Hyster} = C f I^3 \quad (W/m), \quad (I < 0.5 I_c) \quad (3)$$

$$Q(J/cm) = \frac{q_e + q_H + q_{dc}}{f} \quad (4a)$$

$$= A f I + C I^3 + \frac{B I^n}{f} \quad (4b)$$

$$q_{Norris} = \frac{m_0 I_c^2}{4p} \left[ (1-i) \ln(1-i) + (2-i) \cdot \frac{i}{2} \right] \quad (5)$$

$$P(i) = q_{Norris} \cdot freq \cdot \frac{I_c(i)}{\sqrt{2}} \cdot \frac{V_{dc}(i)}{\sqrt{2}} \quad (6)$$

## Results and Discussion

In Table 2., shown below, we identify the steps used to prepare the BSCCO 2223 samples for measurement.

1.	Test with hand meter – current leads: $R \leq 0.5 \Omega$ Voltage leads: $R \leq 1.0 \Omega$ Voltage-current: $R \leq 1.0 \Omega$
2.	Current to Power Amp. Check $\perp$ at power amp is $\perp$ at the sample.
3.	Pass 10 – 20 % of $I_C$ through sample at the required frequency. <ul style="list-style-type: none"> <li>• Set the <u>phase</u> of the Lock-in Amplifier – connect LIA to inductor only (signal <math>\leq 10\mu\text{V}</math>);</li> <li>• Set appropriate <u>sensitivity</u>; time constant <math>\geq 1</math> sec;</li> <li>• ‘Autophase’ (at least two or more times, if required);</li> <li>• De-phase by <math>90^\circ</math>: <math>\rightarrow</math> ‘Loss’ in left window;</li> <li>• Check window: should go to zero; if not, adjust phase.</li> </ul>
B.	Null <u>inductive voltage</u> - connect LIA to sample + inductor <ul style="list-style-type: none"> <li>• Set the appropriate sensitivity;</li> <li>• Rotate inductor to null inductive voltage in right window—e.g.: inductive <math>&lt; 3 \times</math> loss @ <math>20\%I_C</math>.</li> </ul>
4.	Find I and max: signal <ul style="list-style-type: none"> <li>- Does it go positive? If it does not go positive, <math>2 \times +90^\circ</math> to change phase;</li> <li>- At <math>\sim I_C</math>, does signal stay on-scale (prob.: need <math>30 \mu\text{V}</math> @ <math>\sim 100\text{Hz}</math>);</li> <li>- Note the maximum pulse generator (PG) voltage required;</li> <li>- Ready to measure;</li> <li>- Decrease I back to lowest level;</li> <li>- Run measurement from <math>\cong 10\% V_{PG}(\text{max}) \rightarrow 120\% V_{PG}(\text{max})</math> (<math>0.1 I_C \rightarrow 1.2I_C</math>).</li> </ul>

**Table 2. New Sample Preparation**

It was necessary to define a “Clean” dc source for the experiment. As a result, it was necessary to modify the LakeShore 612 Power supply associated with the 7225 Ac susceptometer/dc magnetometer to accommodate the “clean” dc source requirement. The following information shows the conversion procedure that was used.

### Power supply connector

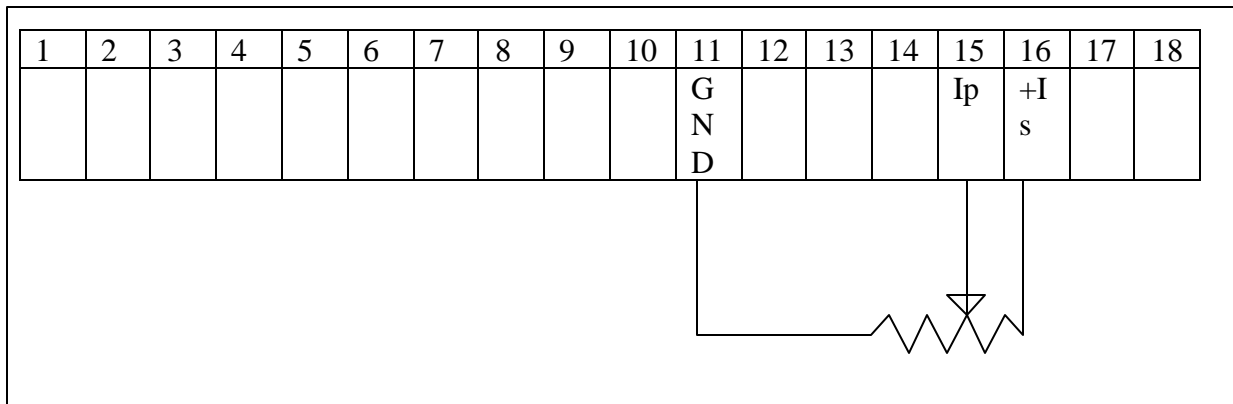
AC power is brought into the unit via a connector resembling a high current version of the IEC connector. This is a “C20” connector, while the standard is a “C13”. Special plugs could only be found through Lakeshore requiring 14AWG power cords.

### Remote Operation

The unit here is ½ of the standard 622/612-supply combination, missing the controller half. However, the power unit itself is intelligent and in the system is controlled by an RS232 connection to the PC. This setup was modified to achieve control via the Labview software and required connecting the 9-pin serial to phone plug (RJ-11) adapter to a free serial port on the PC, and plug the phone cord into the adapter and 612 box. The commands to be passed to the instrument, in addition to the details associated with functions such as baud rate, bits, stop, etc. were listed in appendix C of the Lakeshore 622 psu manual. A labview VI was developed with these commands.

### Local Operation

The connector strip on the back was used to insert a programming voltage for constant current operation. It was also necessary to set the current control switch, the right switch on the pair of white toggles to “Ext”. A 10KΩ pot was connected to pins 14 and 16 for bipolar operation and 16 and 11 for unipolar constant current operation. We settled on the unipolar setup. The wiper goes to pin 15. This is a slight variation on the connection shown in the manual, which makes the low side of the 10 KΩ pot to pin #14 or -Ip. Doing so would allow control voltages and hence output current negative, but isn’t needed here—see the figure shown below.



### **dc Power Source Modification**

The following sample information was determined for our experiments, including:

d ~ 11 mm corresponded to the separation distance used between the voltage taps.

Sample length ~ 50 mm

w ~ 3.5mm

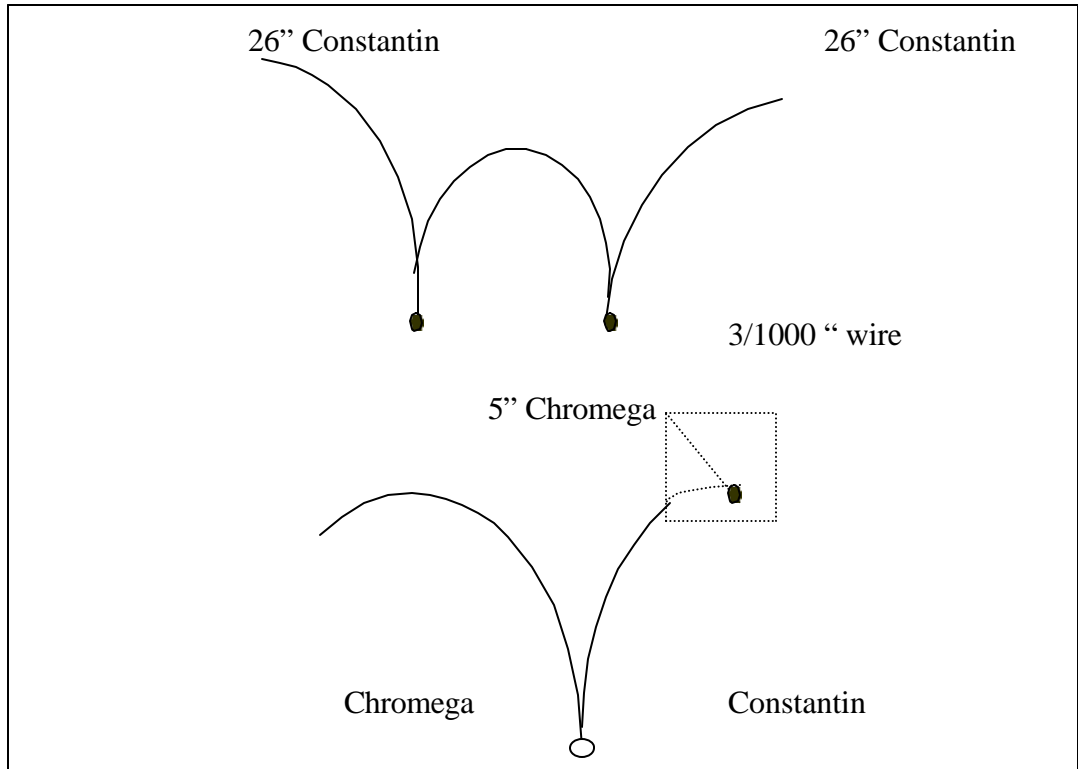
R (V<sub>Lead</sub>) ~ 0.6 Ω

R (I<sub>Lead</sub>) ~ 1.1 Ω.

Our calculations followed the standard representation of using a normalized current ( $i$ ) defined in terms of the critical current, including  $i = \frac{I}{I_c}$ . Losses were defined in terms of J/cm/cycle,  $P$  ( $i$ ). The Norris equation (ellipse) reflected the bounds for the loss curves in terms of the parameter,  $q_{\text{Norris}}$ . The dc transport current,  $I_c$  (dc), was found using the  $1\mu\text{V}/\text{cm}$ , E criterion @  $77^\circ\text{K}$ . Figures 1-5 show losses at different frequencies as a function of the normalized current,  $i$ . In Figure 6, we show the losses (at 30, 70, 100, 120, and 150 Hz) collectively are in good agreement with the Norris ellipse line.

### Calorimetric Measurements :

In the calorimetric study, we used Omega Precision Fine Chromega Constantin Type E Special Differential Fine Wire Thermocouples (connectivity shown in Figure 8) to measure temperature rise. At  $77^\circ\text{K}$ ,  $V_{\text{TC}}$  was found to be  $\approx 26\mu\text{V}/^\circ\text{K}$ .



**Figure 8. Calorimetric Setup Thermocouple Connectivity**

Temperature increases of up to  $\sim 50\text{mK}^\circ$  were observed. A voltage gain of  $1\text{E}(4)$  was used. The calorimetric results were in reasonably good agreement with the electric transport measurements.

LabVIEW Version 5.1, a graphical programming development environment based on the G programming language for data acquisition and control was used for data analysis and plot preparation. Kaleidagraph Version 3.09 was used to set up plots and graphs. The voltage was noted with respect to  $I_C$ , and employed within the Labview computer program wherein values ranging from approx. 5% – 105% of  $I_C$  were utilized. Hence, for example, readings were taken from 50 – 2200 mV in 25 mV steps. A chart length of 200 was used. Programs established at BNL by Steve Ashworth were modified and employed for the data collection in experiments at Clark Atlanta. The SRS 850 DSP Lock-in Amplifier (LIA) was used to address procedures associated with

- Time constant
- Sensitivity
- Phase
- Common Mode.

### **Summary and Conclusion**

The transport measurements were used predominantly to evaluate the ac losses in the BSCCO 2223 tapes. Additional work will be done to incorporate the magnetization measurement to corroborate it with the calorimetric and transport measurements. We are moving to adopt a smaller magnet setup that was recently constructed by the machine shop in the Department of Aerospace Engineering at Georgia Tech. We still however hope to be able to employ the magnets provided by BNL. The problem continues to be an inability to house the magnets (so large) so that they can be cooled. We also plan to incorporate other signal forms including exponential and sawtooth.

Mr. Chu Brown and Mr. Tarvis Holt have worked diligently over the last two years on the project, with Mr. Brown and Mr. Holt spending summers at the University of Wisconsin ASC under the direction of Dr. David Larbalestier. An additional faculty member in the Electrical Engineering program, Dr. Musa Danjaji, is now working with this effort. We expect to bring in new students beginning this fall 2001 semester.

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Figure 1. BSCCO 2223 Tape Losses at 30 Hz

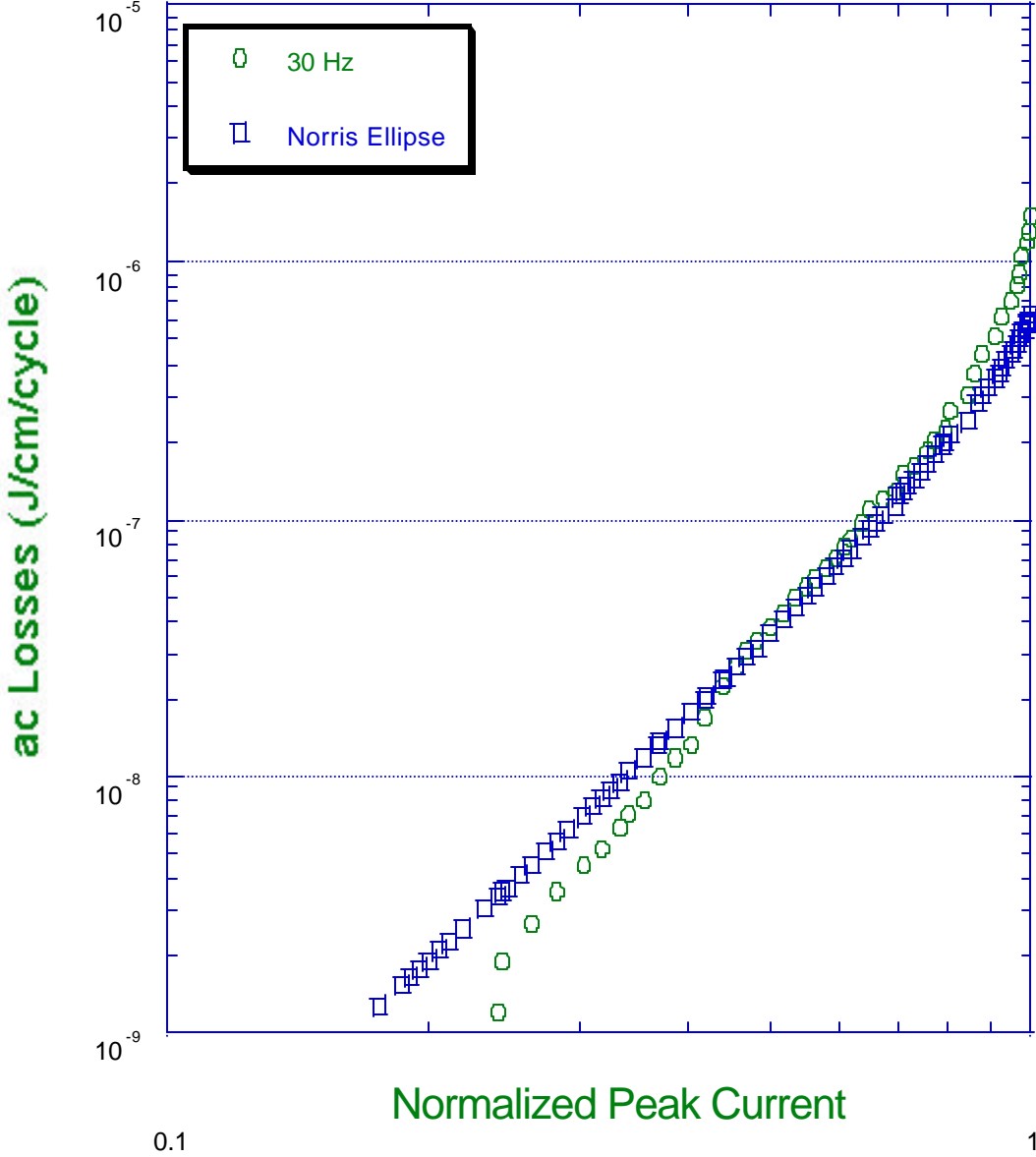


Figure 2. BSCCO 2223 Tape Losses at 70 Hz

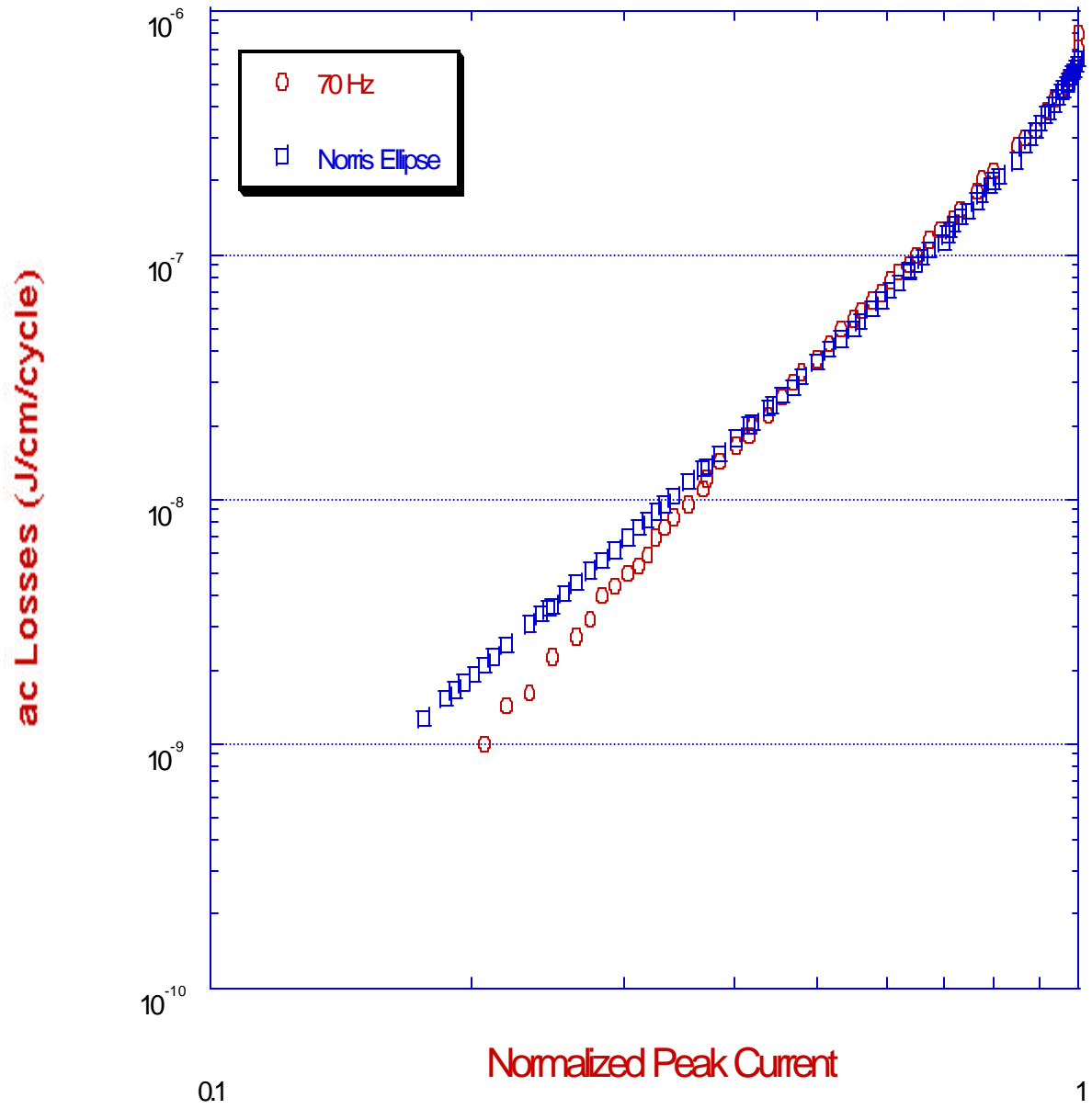


Figure 3. BSCCO 2223 Tape Losses at 100 Hz

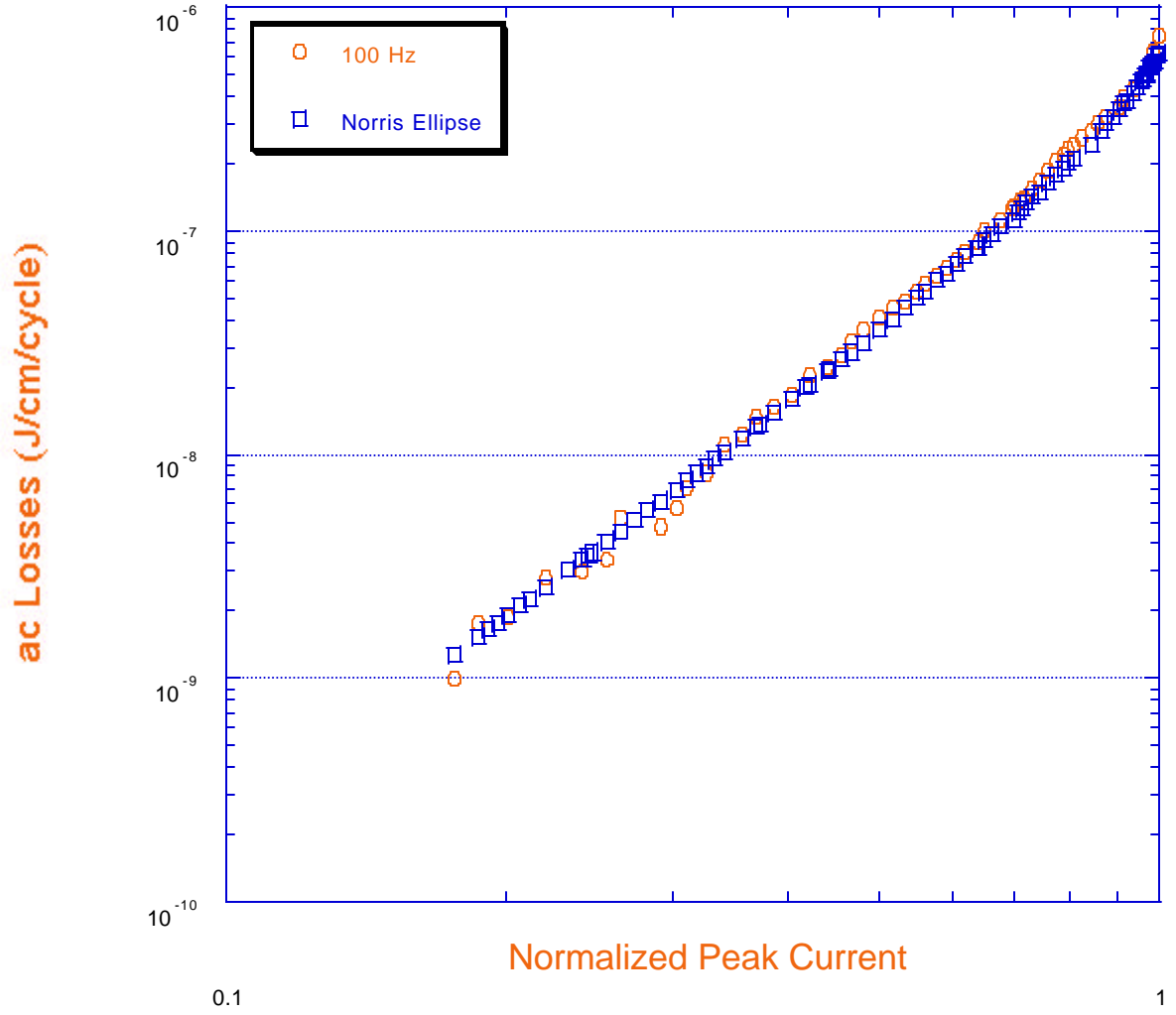


Figure 4. BSCCO2223 Tape Losses at 120 Hz

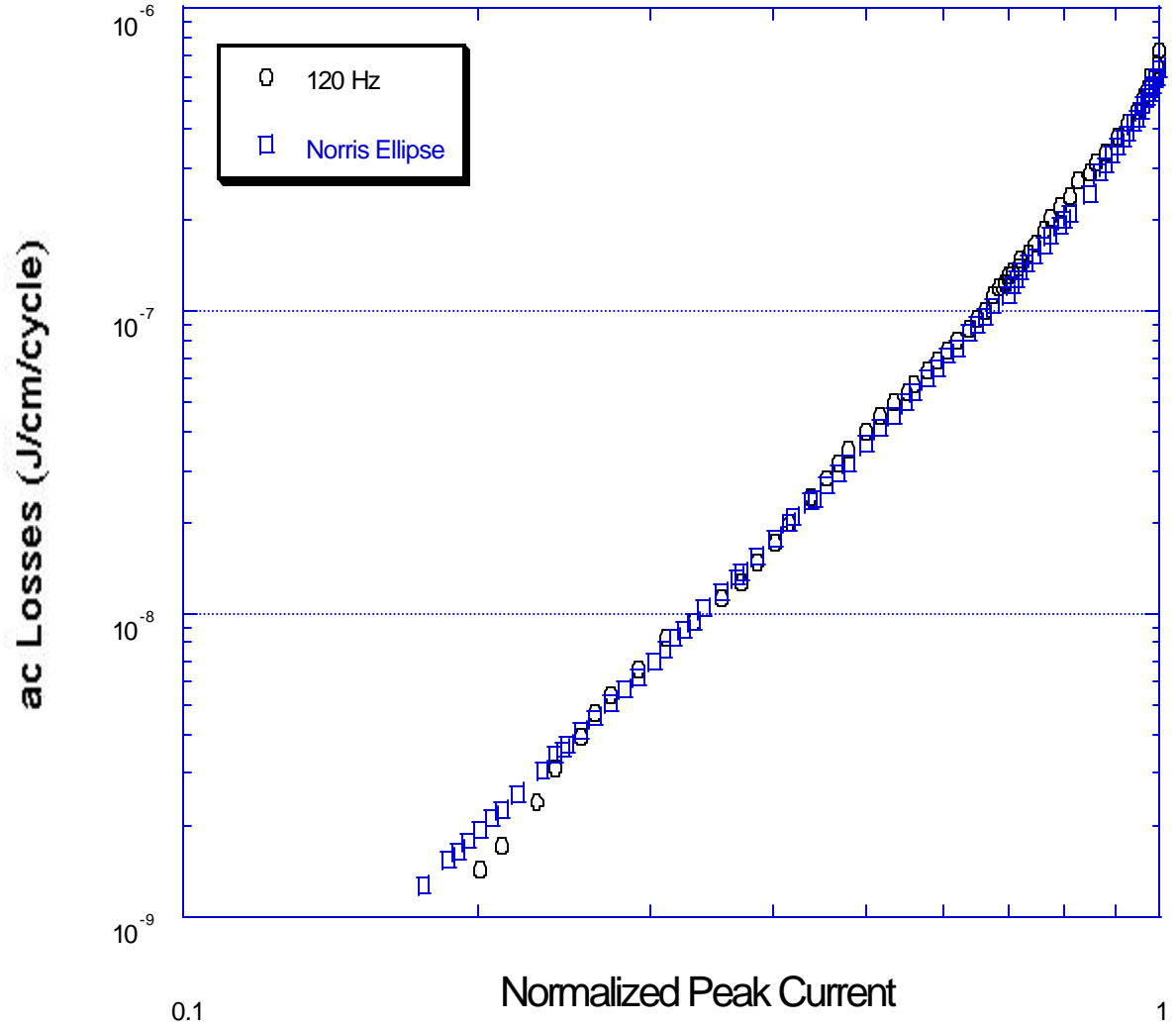


Figure 5. BSCCO 2223 Tape Losses at 150 Hz

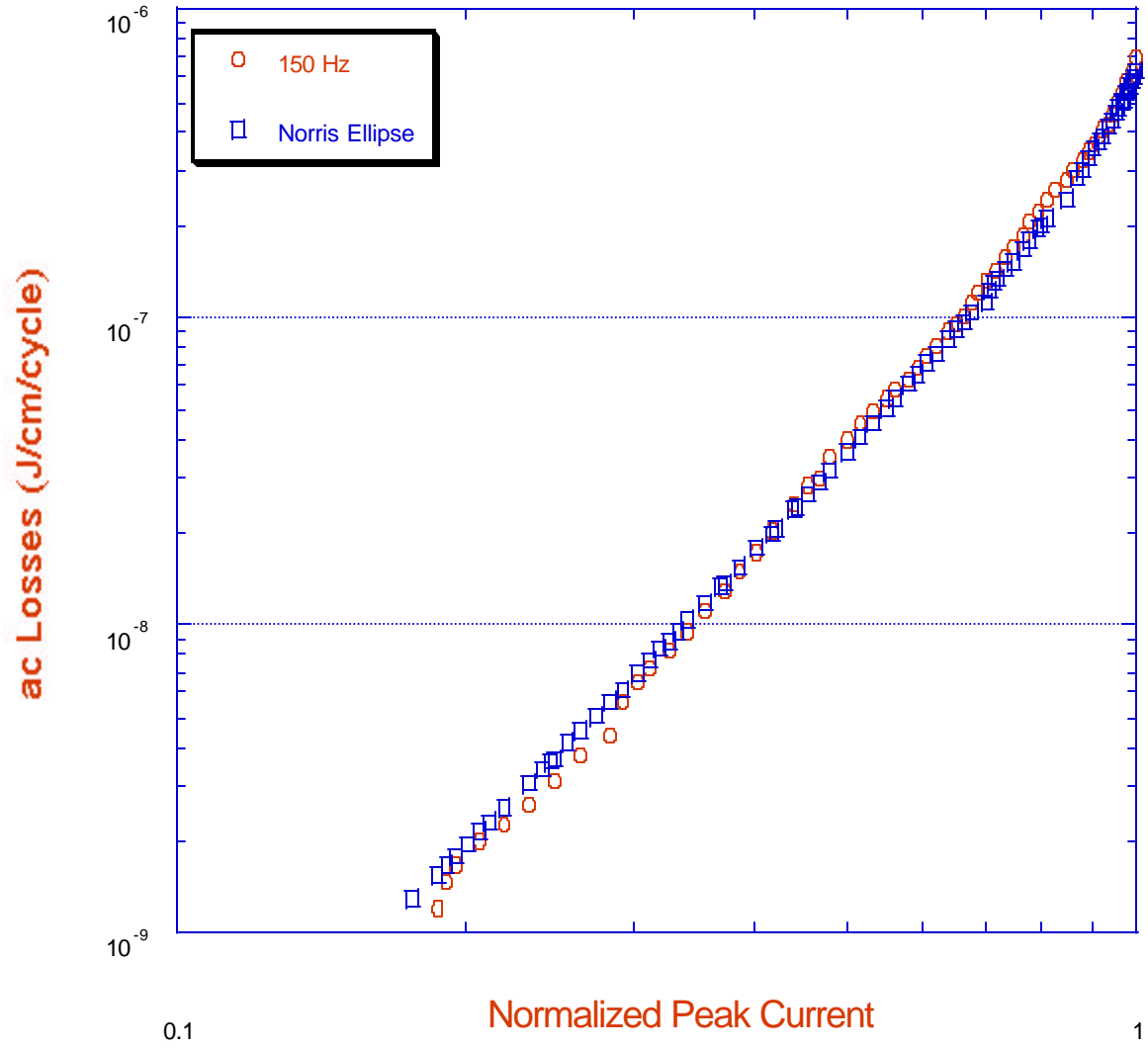


Figure 6. BSCCO 2223 Tape Losses at 30, 70, 100, 120, and 150 Hz

