HIGH CRITICAL-CURRENT MEASUREMENTS IN LIQUID AND GASEOUS HELIUM*

L. F. Goodrich, L. T. Medina, and T. C. Stauffer

National Institute of Standards and Technology
Boulder, Colorado 80303, USA

ABSTRACT

We compared variable-temperature critical-current, $I_c(T)$, measurements up to 200 A on samples immersed in liquid helium to those on samples in flowing helium gas. Multifilamentary Nb-Ti and Nb_3Sn samples were used in this study. $I_c(T)$ measurements above 5 K are difficult because these measurements need to be done in helium gas and the heat generated during the measurement and conducted down high-current leads can raise the sample temperature significantly. This creates a large uncertainty and perhaps a sample dependent bias in the sample temperature that occurs even if the measurements are made meticulously. $I_c(T)$ measurements at a constant magnetic field are needed to determine the temperature margin of magnet applications and performance data for cryogen-free applications. The comparison of $I_c(T)$ data in liquid helium to data in gaseous helium, over the temperature range of 4 to 5 K, allows for the inference of sample temperature uncertainty and biases. Agreement to within 30 mK was obtained.

INTRODUCTION

The temperature margin of the operating current is an important consideration in the design of superconducting magnets. The temperature margin is the difference between the operating temperature and the temperature at which the critical current, I_c, is equal to the operating current. When a magnet is operating in the superconducting state, transient excursions in magnetic field or current are not expected; however, many events or effects such as wire motion, ac losses, and radiation could cause transient excursions to higher temperatures. This is why the temperature margin is important. A number of new cryogen-free magnet applications are designed to operate in a gas or vacuum environment rather than in a liquid cryogen. These cryogen-free applications also require variable-temperature critical-current,

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$I_c(T)$, measurements. Difficulties in making these types of measurements do not arise or are not as pronounced in cryogen-free applications. For example, it is necessary during the measurement (but not during the application) to have sufficient sample current so that there is a voltage drop along the sample. This generates heat that can cause the sample temperature to rise. The upper temperature of measurements in liquid helium is limited by the critical temperature of liquid helium (5.22 K) and, since the latent heat of vaporization is very low above 5 K and the specific heat of the sample and other cryostat materials is also very low at this temperature, small amounts of heat can significantly increase the sample temperature. Resistance at the current contacts is another unavoidable source of heat that can raise the temperature of the sample. In making $I_c(T)$ measurements it is difficult to maximize the current contact area due to the limited experimental space in the bore of the background magnet, whereas the contacts in applications can be much larger with lower resistance and better thermal anchoring.

The motivation of this study is to determine the precision and accuracy of $I_c(T)$ measurements when the sample is in a gaseous environment rather than in a liquid cryogen. One of the regions in which the comparison between liquid and gas measurements can be made is between 4 and 5 K. There are other possible temperature ranges (using liquid neon or liquid nitrogen) where this can be accomplished; however, for this comparison we require a region where the I_c is a strong function of temperature. These higher temperatures would require the use of high-temperature superconductor (HTS) samples which have less stable critical currents and more thermo-magnetic hysteresis[1] than low-temperature superconductor (LTS) samples. Therefore we have chosen to perform measurements on LTS samples in helium. For the remainder of this paper, the terms liquid and gas will be used to refer to the state of helium in which the sample is immersed.

Other studies of the temperature dependence of the I_c of LTS samples[2-5] have been made. In contrast to these previous studies, this study focuses on a detailed, direct comparison between measurements in liquid and gas. Assuming the temperature is known, the estimated accuracy of these I_c measurements is ±2 % with a precision of ±1 %. An electric-field-strength criterion of 0.1 μV/cm was used to determine all of the I_c data presented here.

PROCEDURE

Apparatus

The cryostat used in this study is a research device and a detailed description is beyond the scope of this paper. However, a few important details need to be mentioned. This is a helium gas-flow cryostat which can also be filled with liquid helium. The cryostat is inserted into the 86-mm-diameter bore of a 12 T magnet. The helium gas flow rate can be adjusted with a typical rate of 0.3 L/s, at standard temperature and pressure, providing a temperature range of 4.1 to 20 K. When operating with liquid helium, the cryostat can be sealed off from the background magnet dewar. The cryostat is pressurized and the liquid is heated to come into thermal equilibrium at temperatures as high as 5 K. Whether the cryostat is operated with gas or liquid, the background magnet operates near 4.02 K, which is the normal liquid helium boiling point at the atmospheric pressure of this test site.

The salient features of the variable-temperature cryostat are: a primary temperature control and measurement of one current contact with the heater equally split between the two current contacts, a secondary control circuit that keeps the two contacts at the same temperature with separate balance heaters on each current contact, a preregulator control circuit that converts the in-flowing helium liquid to gas and warms the gas to near the target sample temperature, and gas flow that is routed over the current contacts and sample. The two

current contacts and the gas flow path were designed to be as symmetric as possible. The contacts were also designed to be as large as possible with extended surface areas for the gas to flow over. The secondary control uses one thermometer in each current contact and software that sends an analog signal to a dual heater control circuit which delivers power to one of the two balance heaters. Typically, this power is much less than 0.1 W. The preregulator software monitors the primary sample heater power and adjusts the temperature set point of the preregulator heater to attempt to achieve a target primary sample heater power. A typical target for the primary sample heater power is 0.15 W. With this target and a helium-gas-flow rate of about 0.3 L/s (at standard temperature and pressure), the typical preregulator heater power is about 1 W. This relatively high gas flow rate is considered necessary to achieve a more uniform temperature along the length of the sample between the current contacts. The purpose of the preregulator is to preregulate the gas temperature which allows for more precise temperature control of the entire length of the sample. Additional details are not included here since this apparatus is a research device that has many features which may not be necessary for routine measurements.

Thermometry

Temperature control for the measurements can be achieved using a resistive thermometer that has a low magnetoresistance effect or a capacitance thermometer that has a very low magnetoresistance effect. However, for this study, the need for precise control and precise measurements precluded the use of a capacitive thermometer. Because a capacitive thermometer can not be calibrated, it can be used only by setting the temperature at zero field using a calibrated thermometer, and then controlling the temperature with the capacitive thermometer as the field is swept. This method is not efficient for acquiring data at many temperatures and one field. The data presented here were taken using a resistive thermometer to achieve precise control, precise measurement, and efficiency. To maintain the most direct comparison of liquid and gas data, no magnetoresistance correction was applied to the temperature data. The estimated corrected temperature would have been within 10 mK at 4 T and 80 mK higher at 12 T.

Samples and Mandrels

Two different multifilamentary superconducting wires were measured on different sample holders for this study: a Nb_3Sn conductor and a Nb-Ti standard reference material (SRM 1457).[6] The active length (distance between the current contacts) of the samples is about 30 cm. The relatively long length of the wire sample makes it difficult to know the average sample temperature, which makes accurate measurements difficult. The voltage tap separation was 10 cm. All measurements were made on coil samples that were mounted on sample mandrels with similar geometries but made of different materials. The samples were soldered, using non-superconducting solder, to a copper ribbon to provide extra sample stability. The copper ribbon was 0.36 mm by 2.29 mm with a residual resistivity ratio of approximately 131. All sample mandrels had copper current contact rings on each end. The middle part of the mandrels were made of two different materials: thin-walled stainless steel (AISI type 304) tube and thin-walled Ti-6Al-4V (% by mass) tube.

Data Acquisition

The method used for obtaining the voltage-current characteristics (V-I curve) was designed to reduce the temperature rise from contact and sample heating. It involves delivering a series of discrete, approximately 1 s, current pulses to the conductor with a recovery time

between pulses and increasing the amplitude of each successive pulse. The current pulse has a trapezoidal shape with time, that is, it starts at zero, ramps up at a finite and relatively constant rate, holds, and then ramps back down to zero. Voltage and current readings are acquired before, during, and after each pulse. Analysis of these readings was used to correct the thermoelectric voltages over a short time period. This medium-duty-cycle (MDC) method is a compromise between the pulse and dc methods. Most of the data presented in this paper were taken with the MDC method. The pulse method minimizes heating and thermoelectric voltages but does not have measurement sensitivity and there can be problems with sample motion. In the pulse method, the current is pulsed, with typical durations of 1 to 10 ms in duration with very fast ramp rates. Large inductive voltages and short settling times can lead to a biased and varying signal. The dc method does have measurement sensitivity with little sample motion but does not minimize heating and thermoelectric voltages. The dc method is a sample-and-hold method, similar to the MDC method but without the current returning to zero between the current levels, which results in a stair-step pattern of current versus time. Measurements made using these different techniques were compared to determine if agreement could be achieved.

RESULTS

I_c measurements were made in liquid and gas at various temperatures and magnetic fields. The magnetic fields for all measurements vary from 0 to 12 T. The temperature of liquid measurements varied between 4 and 5 K while the temperature of gas measurements varied between 4.1 and 18 K. Typically, three determinations of I_c were made at each temperature setting.

Figure 1 shows all the data for a Nb_3Sn multifilamentary superconducting wire which was mounted on a Ti-6Al-4V mandrel. Figure 2 is a closer view of the 12 T data for the Nb_3Sn

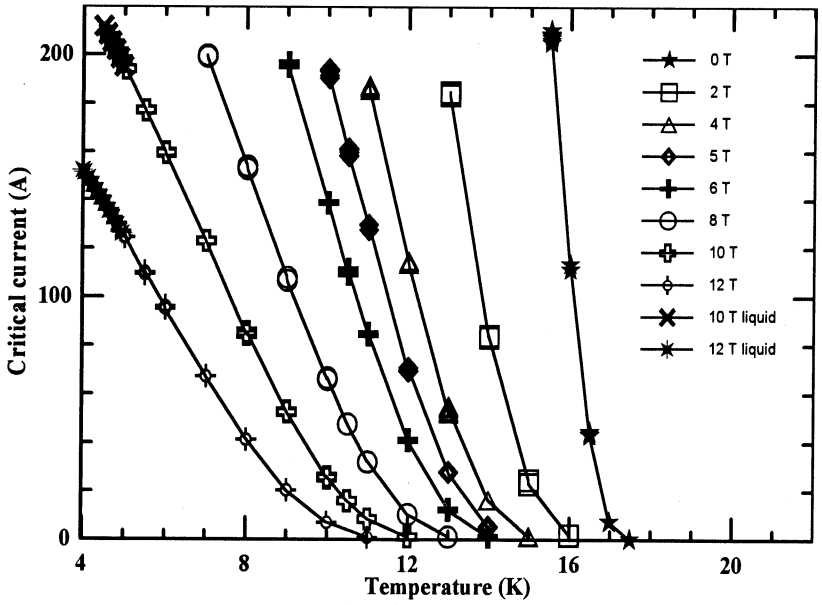

Figure 1. Critical current versus temperature for a multifilamentary Nb_3Sn superconducting wire. Measurements were made at magnetic fields from 0 to 12 T in both liquid and gaseous helium environments. The legend indicates the field and whether the measurements were made in liquid. All other measurements were made in helium gas.

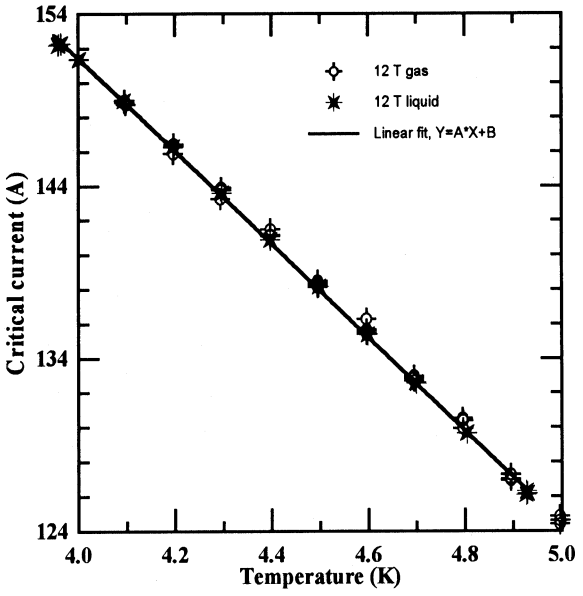

Figure 2. Critical current versus temperature for a multifilamentary Nb_3Sn superconducting wire at 12 T. These data consist of measurements made in gaseous and liquid helium between 4 and 5 K. A linear fit to the liquid data is shown.

sample. This plot compares liquid and gas data for the temperature range of 4 to 5 K. A linear fit line is drawn through the liquid data. The fitted parameters and the difference between data sets are expressed in terms of temperature. The standard deviation of the liquid data (37 points) from this fitted line was 6 mK (range of 21 mK). There may be some curvature to these data, however a linear fit was used for simplicity and is still accurate in this range. The standard deviation of the gas data (37 points) from this fit was 10 mK (range of 47 mK). As seen in the plot, the data for the measurements taken in gas agree well with the liquid data. A linear fit was also made to the gas data and the standard deviation of the gas data from the gas-data fit line was also 10 mK (range of 47 mK). Although the V-I curve of this sample in the normal state was ohmic, it did have an effective I_c of 0.03 A at 12 T due to the conductivity of the copper in the sample, the stabilizer, and the mandrel. This is a measure of the small bias that the added stabilizer and conductive mandrel had on the measured I_c.

Figure 3 is similar to Figure 2, but displays the results of the Nb-Ti SRM mounted on a stainless steel mandrel at a magnetic field of 4 T. The data presented here were from measurements made near the present upper current limit of the apparatus. The standard deviation of the liquid data (35 points) from the fitted line was 4 mK (range of 12 mK). The standard deviation for the gas data (34 points) is 8 mK from the liquid-data fit line (range of 39 mK). The standard deviation for the gas data from the linear fit line of the gas data is also 8 mK (range of 39 mK). The effective I_c of the SRM in the normal state was 0.13 A at 0 T and 0.07 A at 4 T.

Thermo-magnetic hysteresis

Measurements of thermo-magnetic hysteresis were made in different ways. First, the I_c was measured after cooling the sample in zero field and then ramping to field. Then the sample was measured after ramping the temperature at a nonzero constant field. Measurements were also made at various temperature along the path of increasing temperature and while

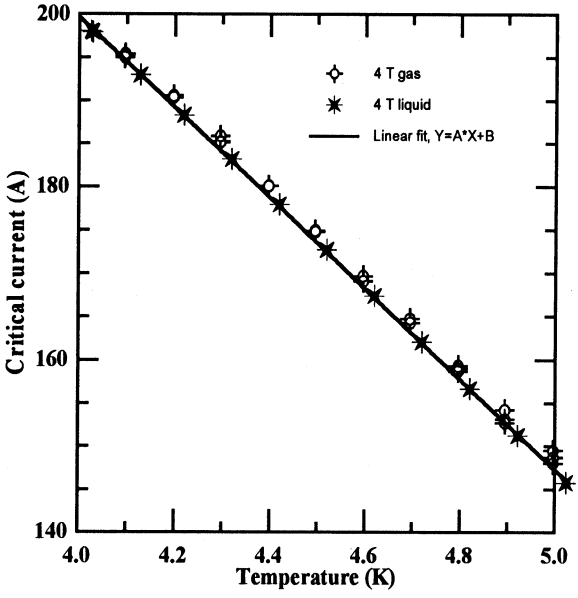

Figure 3. Critical current versus temperature for a Nb-Ti (SRM) superconducting wire at 4 T. These data consist of measurements made in gaseous and liquid helium between 4 and 5 K. A linear fit to the liquid data is shown.

decreasing the temperature. The combination of these methods of acquiring data provides a basis to determine how hysteresis affected the measurements in this study.

The Nb-Ti SRM was measured under different conditions to show this low hysteresis effect. In a portion of the measurement of this sample, it was cooled to near 4 K in zero field (zero-field-cooled), then the field was raised to 4 T and measurements in gas were made from 4.1 to 8 K (sample was normal at 8 K and 4 T), then the sample was cooled to 4.5 K at 4 T and measured again. The average difference between the zero-field-cooled data at 4.5 K and the 4 T-cooled data at 4.5 K was 9 mK. This type of hysteretic cycle also occurred between the gas and liquid data sets. These data indicate the very low thermo-magnetic hysteresis effect in this Nb-Ti sample.

The I_c was measured during three other thermo-magnetic hysteresis cycles that are indicative of the cycles that a sample experienced through this study. These included measurement sequences where the initial data were taken with increasing temperature and the final data taken with increasing or decreasing temperature. In all cases, for the Nb-Ti and Nb_3Sn samples, the temperature shift of the I_c data for the latter part of the hysteresis loop was less than 31 mK.

DISCUSSION

The comparison of the liquid and gas data has provided crucial feedback for the development of this measurement system. This feedback has guided the evolution of hardware, software, and operating conditions necessary to attain this accuracy. Approximately a factor-of-10 improvement in the liquid/gas comparison has been achieved through this process. In the absence of the liquid/gas comparison, comparing data acquired with various duty cycles of the sample current can provide an indication of measurement uncertainty. The techniques developed through this study may be applicable to HTS in the future. It will be necessary to

determine the necessity of heating the sample to the normal state periodically during the measurement sequence to remove thermo-magnetic hysteresis. This is an important parameter to investigate because this hysteresis effect is more significant in HTS than in LTS.

The results presented in this paper are typical of other samples mounted on various mandrels and at other magnetic fields. Measurements of samples on a fiberglass epoxy composite (G-10) were somewhat more variable. The conditions in which the measurements were made also had an effect on the results observed. The limitation of the apparatus allowed for measurements only up to about 210 A. Currents higher than 210 A may be possible with higher current leads and a higher-current power supply.

A comparison of critical currents measured using the MDC method and the dc method has indicated additional temperature variation when using the dc method. In the dc technique, the current is on for 10 to 25 s (depending on the settling time) while acquiring 23 discrete points along the V-I curve. The MDC technique has the current on for 1 to 2.5 s for each set point along the V-I curve. There were small systematic differences in the critical currents measured by these two techniques; however, an agreement of 50 mK was achieved for both samples under a variety of conditions. The dc method had noticeable systematic shifts in the measured I_c depending upon the settling time at each set current, which were consistent with a slight sample heating effect.

One observation during this study was that temperature variation problems were indicated if the V-I curve was not monotonic. This was the only observed feedback, during the measurements, for the degree of variation in sample temperature. By the nature of the acquisition, the points along the V-I curve acquired with the MDC technique are more independent from each other than the points acquired with the stair-step pattern of the dc technique. Thus, the MDC technique is more sensitive to variation in sample temperature, which makes it a more stringent technique. The MDC method is still expected to provide more accurate measurements of I_c in helium gas and may be necessary at currents higher than 200 A.

A comparison of critical currents measured using the MDC method and the pulse method has indicated that the shortest pulse duration (time at target current for each pulse) for which reliable data could be acquired was about 73 ms. This minimum duration is necessary to allow an adequate settling time after the current ramp and before the voltage and current data are acquired over one power line cycle. The current-ramp rate used for the pulse method was 5000 A/s, at which a 40 ms ramp would reach 200 A. A voltage-tap pair with a 10-cm separation has a mutual inductance of about 30 mH and would have an induced voltage of about 150 μV at a current-ramp rate of 5000 A/s. The settling time (56 ms) allows for this voltage, the sample current, and the interfering voltage from slight sample motion caused by the pulse in the Lorentz force to settle below the noise level of the pulse method. For the lower noise level of the MDC method, a settling time of about 0.5 s was necessary. Therefore the minimum duration for the MDC method was about 0.8 s allowing 0.3 s to acquire the voltage and current data. Accurate I_c measurements were made with the MDC method using current-ramp rates from 250 to 2000 A/s; thus the current is on for 1 to 2.4 s. The pulse method provides a valuable check of the measured I_c with a factor-of-10 shorter current duration than the MDC method; however, the pulse method lacks voltage sensitivity, which leads to additional variability in the measured I_c.

The variable-temperature cryostat used in this study had sample heaters to achieve temperature control over the length of the sample and to allow for faster changes in the sample temperature set point. Some cooling power at the sample is necessary to handle varying heat loads and to balance the temperature of the two current contacts; however, too much cooling power can cause the sample temperature to be lower than that of the current contacts and thermometer. This was the motivation for the relatively low target sample heater power. Further improvements in the feedback of the preregulator are planned to achieve target sample heater powers of less than 0.1 W and reduce this supercooling effect.

CONCLUSIONS

The measurements performed in this study provide valuable comparisons between critical currents when measured in helium gas and in helium liquid. These comparisons provided an important evolution of the measurement apparatus which lead to the verification of $I_c(T)$ measurements in helium gas with agreement to within 30 mK for the Nb-Ti and Nb_3Sn samples at currents up to 200 A. This relatively low temperature uncertainty is needed to achieve reasonable accuracy for low-temperature superconductors. The measurements made here are dependent on the details of the cryostat design, operating conditions, and the data acquisition techniques. The research apparatus briefly described here was designed to overcome the problems of high-current I_c measurements at various temperatures and may allow for currents significantly higher than 200 A. Through the course of this study, high-current variable-temperature critical-current measurements proved to be difficult and even meticulous efforts can lead to biased results. The ultimate success of this study, however, demonstrates the capability of developing of a reference conductor that could be used to verify the performance of other variable-temperature I_c measurement systems.

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