USA Interlaboratory Comparison of Superconductor Simulator Critical Current Measurements

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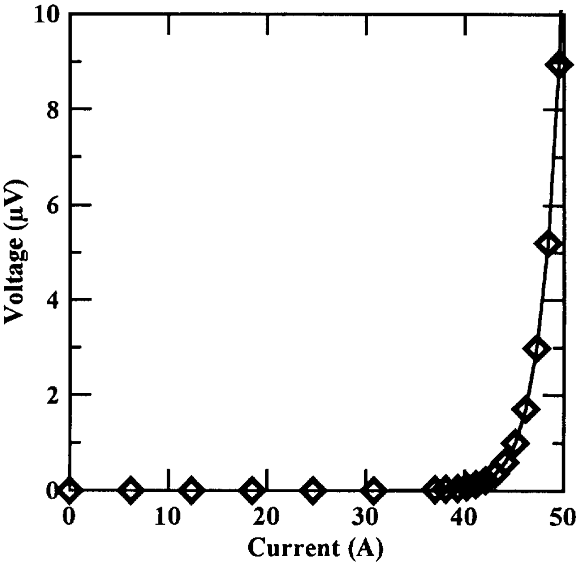
Abstract-An interlaboratory comparison of critical current (I_c) measurements was conducted on the superconductor simulator, which is an electronic circuit that emulates the extremely nonlinear voltage-current characteristic of a superconductor. These simulators are high precision instruments, and are useful for establishing the integrity of part of a superconductor measurement system. This study includes measurements from participating US laboratories, with NIST as the central, organizing laboratory. This effort was designed to determine the sources of uncertainty in I_c measurements due to uncertainties in the measurement apparatus, technique, or the analysis system. The participating laboratories measured the superconductor simulator with a variety of methods including dc and pulse. This comparison indicated the presence of systematic biases and higher variability at low voltages in the I_c determinations of the measurement systems. All critical current measurements at a criterion of 10 μV on the I_c simulator were within 2% of the NIST value for nominal critical currents of 2 and 50 A. These results could significantly benefit superconductor measurement applications that require high-precision quality assurance.

I. THE HYBRID SUPERCONDUCTOR SIMULATOR

The hybrid superconductor simulator emulates the extremely nonlinear voltage-current (V-I) characteristic of a superconductor along with its other major electrical properties by using passive circuit elements such as resistors and a diode [1]. The diode provides the nonlinearity necessary to generate the V-I characteristic. The simulator contains an active temperature controlled oven to maintain the diode temperature near 35°C. The term *hybrid* refers to the fact that each simulator consists of passive and active (only the oven) components. The simulator can be used as a sample substitution box that is measured at room temperature. Each simulator contains two separate circuits: one has an I_c of 2 A, and one has an I_c of 50 A . The n-value of the V-I curve is about 24 [2].

The simulator can be used to test the integrity and accuracy of a complex measurement system because it has highly reproducible electrical characteristics. For example, the change in critical currents during this experiment for two out of the three simulators was less than 0.04%; the third simulator was still in circulation at the time of this writing.



1. V-I characteristic of the 50 A superconductor simulator circuit.

Fig. 1 shows a typical V-I curve for a 50 A simulator with an n-value of approximately 24. We calibrated each simulator to verify the linearity of the temperature dependence of the I_c

In the calibration procedure, we obtained five V-I curves at diode temperatures of approximately 31, 33, 35, 37, 39, 39, 37, 35, 33, and 31°C for a total of 50 curves. We analyzed each V-I curve and determined I_c at a number of criteria. Fig. 2 shows the NIST I_c determinations on a 50 A simulator circuit, at a voltage criterion of 1 μV, as a function of temperature. The plot also shows a linear fit (solid line) of these 50 data points. Fig. 3 shows the percent difference of the critical current determinations from the linear fit in Fig. 2. This variation (or precision) is less than ±0.02% for all temperatures at a voltage criterion of 1 μV. The total estimated uncertainty of the NIST critical-current measurements is ±0.2%.

II. INTERLABORATORY COMPARISON

A number of laboratories were invited to participate in this intercomparison. The 12 participating laboratories (listed in the Acknowledgments) were divided into three groups, and a simulator was circulated within each group. Each laboratory was asked to report ten determinations of critical current at voltage criteria of 0.1, 1, 10, and 100 μV. Since the voltage tap separation has no physical meaning for the simulator, we use voltage criteria instead of electric field criteria. The laboratories

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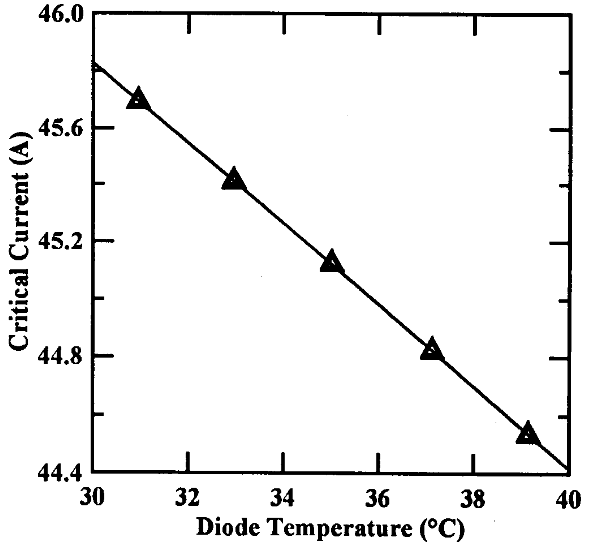
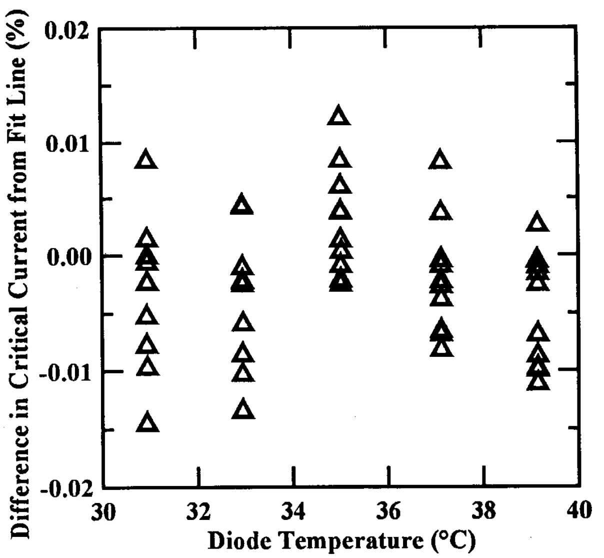


2. NIST I_c determinations versus temperature for the 50 A simulator circuit at a voltage criterion of 1 μV. The solid line indicates a linear fit of the data.



3. The deviation of the NIST I_c determinations versus diode temperature from the linear fit line shown in Fig. 2. The variation is less than ±0.02%.

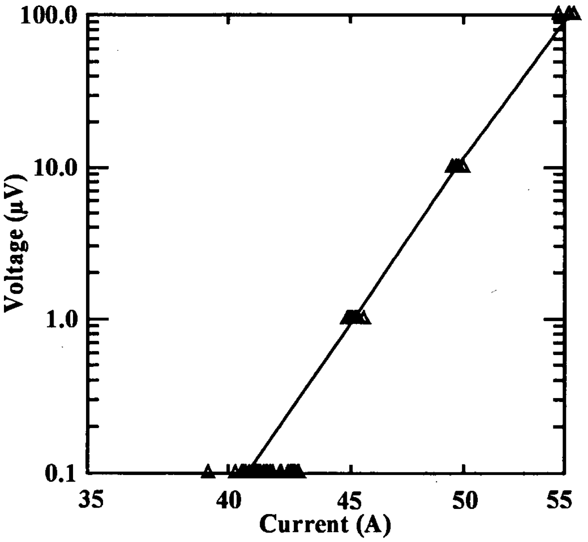
were requested to perform the measurements, report the results, and ship the simulators to the next participant within two weeks. The participating laboratories complied with these instructions to varying degrees. Similar comparisons are being conducted independently in Japan and Europe [3,4].

III. RESULTS AND DISCUSSION

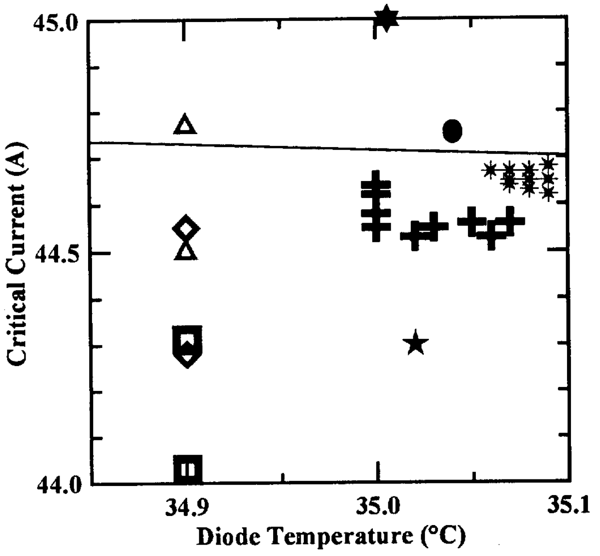
Fig. 4 shows a logarithmic plot of the voltage-current characteristic of a 50 A circuit using data from the participating laboratories. The figure indicates that the variability in the data reduces at higher voltages. The solid lines were generated using NIST data. The slope of the curve indicates the n-value.

Fig. 5 shows the critical current as a function of temperature on a 50 A simulator circuit at a voltage criterion of 1 μV for four laboratories. There are eight symbols on the plot because some laboratories used multiple measurement systems. The solid line indicates the linear fit of the NIST data. The clustering of the repeat determinations within a laboratory's measurement system, at some distance from the NIST data line, indicates a measurement bias. The spread of this cluster indicates the variability. This plot is typical of the data observed at other voltage criteria and with other simulators. The three symbols at the lowest temperature in Fig. 5 were from the same laboratory using three different measurement systems. There were 10 determinations taken on each measurement system and in each case, nearly half of the determinations were clustered around two distinct points. This may be an artifact of the laboratory's analysis technique. The measurements of at least one other laboratory also showed this behavior.

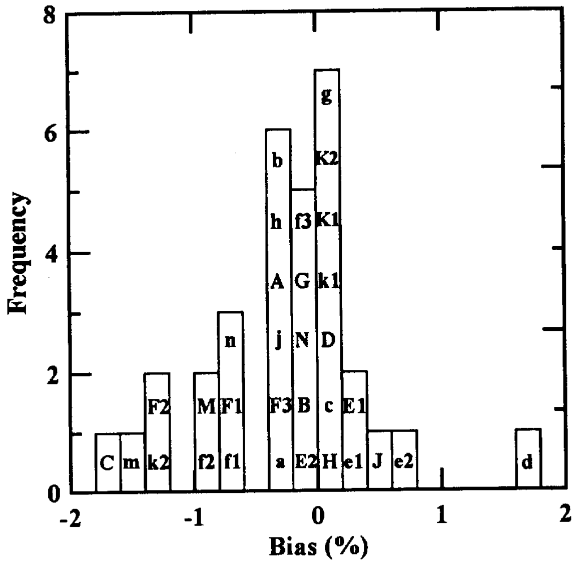
Fig. 6 shows a histogram of bias (the average difference from the linear fit of NIST data) of the participating laboratories at a voltage criterion of 10 μV. There are a total of 32 points in this distribution, including both the 2 and 50 A circuits on each measurement system. The measurements made at the lower voltage criterion of 1 μV have higher variability (see also Fig. 4) so the measurement bias is not as apparent at 1 μV. The spread in the distribution is less than ±2%. There was no significant systematic difference between the 2 and 50 A simulator circuits. The letters in the histograms indicate the



4. Logarithmic plot of the voltage as a function of current for one 50 A simulator circuit used in the interlaboratory comparison.



5. Critical current as a function of temperature as measured by four different laboratories for the 50 A simulator at a voltage criterion of 1 μV.

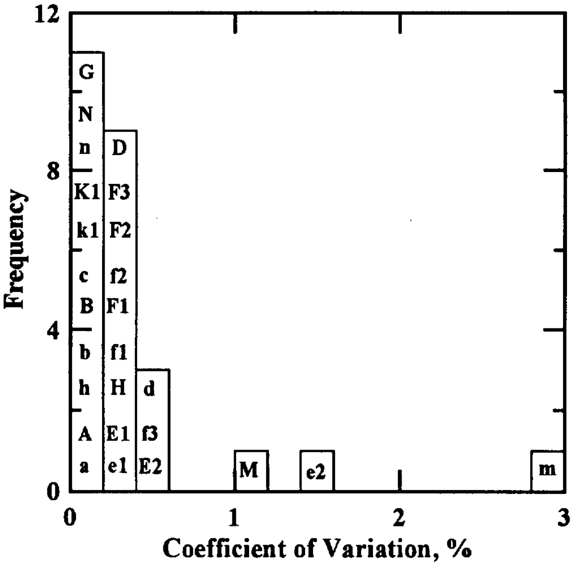


6. Histogram of the bias of the average of the I_c determinations made by the participating laboratories at a voltage criterion of 10 μV.

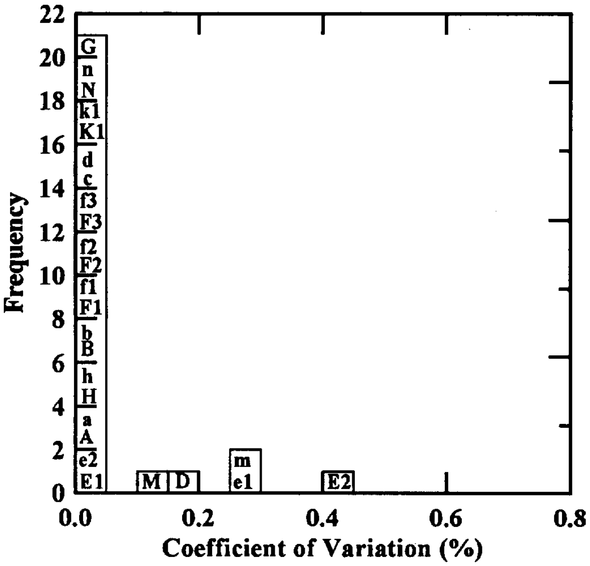
laboratory, the lower case letters denote data from the 2 A simulator circuit, upper case indicates the 50 A simulator circuit, and the number beside a letter indicates the measurement method. Thus, a symbol f1 indicates laboratory f, 2 A simulator circuit, and measurement method 1.

Fig. 7 shows a histogram of the coefficients of variation for the participating laboratories' determinations using a given measurement system at a voltage criterion of 1 μV. The coefficient of variation is defined as the ratio of the standard deviation of a set of determinations to the average determination. We did not compute this coefficient if we received fewer than 3 determinations. The distribution indicates that 23 out of the 26 measurement systems had a coefficient of variation less than 0.6%. At this voltage criterion, the measurement variability is high enough that it can significantly affect the observed distribution of bias.

Fig. 8 shows the distribution of the coefficients of variation at a voltage criterion of 10 μV. At this criterion, the measurement variability is lower; therefore most of the coefficients cluster at a value less than 0.05%. Of the 26 measurement systems, five systems' variations were higher than this value.



7. Histogram of the coefficient of variation of the I_c determinations made by the participating laboratories at a voltage criterion of 1 μV.



8. Histogram of the coefficient of variation of the I_c determinations made by the participating laboratories at a voltage criterion of 10 μV

Table I shows the summary statistics of the interlaboratory comparison for both the 2 and 50 A simulator circuits. The average bias, standard deviation of the biases, and range of the biases are shown at voltage criteria of 0.1, 1, 10, and 100 μV. The number of measurement systems is also given. In this table, the average bias and associated standard deviation are computed from the biases of each measurement system. Therefore, the average bias is the percentage difference between the mean of the participating laboratories' measurements and the NIST measurement.

A few laboratories used the hybrid superconductor simulator to test their multiple measurement systems and techniques. Some laboratories used different systems or techniques to measure the two circuits, 2 and 50 A. The complexity of the measurement systems and techniques used vary considerably.

Perhaps the best example of a laboratory comparing techniques was one that used the hybrid simulator to compare their pulse current and dc methods. This laboratory found that the self and mutual inductance of the simulator prohibited pulse durations of 2 to 200 μs, which are the typical durations that they use. However, that laboratory was able to measure the simulator at a pulse duration of 3 ms for the 2 A circuit and 10ms for the 50 A circuit. This is consistent with the fact that we designed the simulator to be measured with 3 ms pulse durations. Although it may be possible to design a simulator with a response time that is 10 times faster (or more) by decreasing the physical size of the components, it would be difficult and may require that the dc method be prohibited due to over heating of the components. The laboratory still found the simulator extremely useful for testing their methods over a wide range of transport current: 2 to 50 A.

IV. CONCLUSIONS

In this interlaboratory comparison all critical current measurements at a criterion of 10 μV on the I_c simulator were within 2% of the NIST value for nominal critical currents of 2 and 50 A. The critical current measurements at 1 μV were within 3% of the NIST value, but the coefficient of variation of individual determinations of a few measurement systems were larger than 1%. The observed variability at 1 μV may be sufficient for routine measurements; however it can contribute to the variation in an interlaboratory comparison of short, high temperature superconductor samples at 1 μV/cm.

TABLE I
SUMMARY STATISTICS FOR THE INTERLABORATORY COMPARISON OF CRITICAL CURRENT MEASUREMENTS ON THE HYBRID SIMULATOR

	0.1 μV	1 μV	10 μV	100 μV
# Measurement Systems	29	32	32	25
Average Bias, %	0.56	-0.15	-0.25	-0.17
Standard Deviation of the Biases, %	2.10	0.70	0.66	0.62
Range of the Biases, %	7.57	4.11	3.47	3.30

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