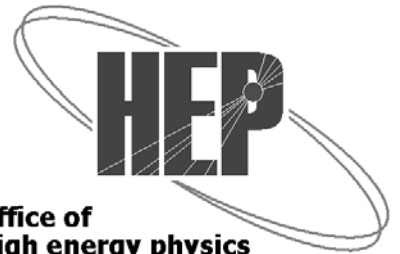
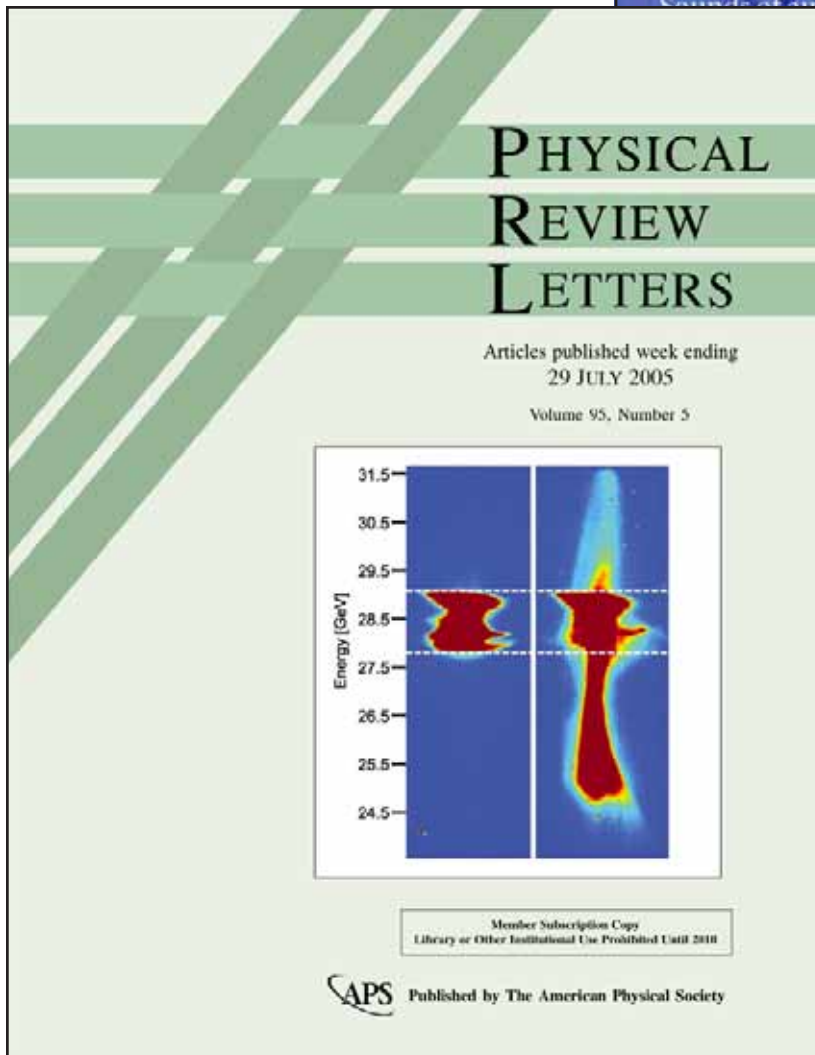


Advanced
Accelerator
Research &
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2005



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Critical-Current Metrology for Nb₃Sn Conductor Development

Loren Goodrich

National Institute of Standards and Technology - Boulder

Summary

This National Institute of Standards and Technology (NIST) project is a world leader in developing and creating measurement standards for superconductivity. It develops standard measurement techniques for critical current, residual resistivity ratio, and hysteresis loss, and provides quality assurance and reference data for commercial high-temperature and low-temperature superconductors. Project members assist in the creation and management of international standards through the International Electrotechnical Commission for superconductor characterization covering all commercial applications, including electronics. The project currently focuses on measurements of variable-temperature critical current, residual resistivity ratio, magnetic hysteresis loss, critical current of marginally stable superconductors, and the irreversible effects of changes in magnetic field and temperature on critical current. This project is jointly supported by Department of Energy/High Energy Physics (DOE/HEP) and DOE/Office of Fusion Energy Sciences, by purchase orders from U.S. companies and national laboratories, and internally by NIST.

For the HEP program, this research project provides critical current metrology for high-performance Nb₃Sn conductors. The requirements of the HEP high-field conductor development program call for conductors with higher-current densities, larger effective filament diameter, less stabilizer, and, in some cases, larger wire diameters than ever before. In addition, some of the conductor designs and heat treatments cause the residual resistivity ratio (*RRR*, ratio of room temperature resistivity to the resistivity at 20 K) of the stabilizer to be less than 20. These requirements create a series of challenges for routine, short-sample, critical-current (*I_c*) testing. Laboratories (including NIST) are now commonly observing early quenches that may result from damaged regions near the current contacts, conductor instability, conductor inhomogeneity, contact heating, or sample motion. We think that wires of 1 mm diameter and larger and/or wires that have less than 50 % stabilizer may require a new technique for measurement of *I_c*. The new technique may pay more attention to sample mounting details and additional measurements of contact resistance and voltages generated between the current contacts and the central voltage tap region. These wires will have critical currents from 800 to 2000 A at 12 T. The higher currents cause many minor problems to become significant engineering challenges. The focus of this work is to help develop a routine measurement technique for high-performance conductors and to provide feedback of conductor performance to the community.

Recent Accomplishments

- We participated in an interlaboratory comparison of critical-current (*I_c*) measurement on high-performance and more stable reference Nb₃Sn conductors.
- Started making voltage-field measurements to help determine the relative low-field (flux-jump) stability of conductors. The community is trying to find an easy measure of stability.
- Started measuring the effect of current ripple and spikes on critical current and the shape of the voltage-current curve (*n*-value), which may explain part of the interlaboratory differences.

- Provided hysteresis loss measurements of high-performance Nb₃Sn wires for the HEP community.
- Made variable-temperature, variable-angle, critical-current measurements on commercial Bi-2212 wires (0.81 mm diameter) with transport current up to 775 A.
- Made variable-temperature, variable-angle, critical-current measurements on commercial dip-coated and Ag-sheathed Bi-2212 tapes with transport current up to 845 A.
- We compared methods of measuring the residual resistivity ratio (RRR) of high-purity Nb using transport current. RRR indicates the purity and the low-temperature thermal conductivity of the Nb, and is often used as a material specification for superconducting radio-frequency cavities.

Supplemental Information

We participated in an interlaboratory comparison of critical-current measurement on high-performance and more stable reference Nb₃Sn conductors. This comparison was organized by personnel from Lawrence Berkeley National Laboratory. Both conductors had nominal wire diameters of 0.8 mm. This was the first comparison on these high-performance conductors that push the limits of stability, which we term marginally stable. The average critical current of the marginally stable sample was 759.5 A at 12 T and 4.2 K with a standard deviation of 27 A (3.6 %). The biggest difference was in n -values that varied from about 50 to 100 at 12 T. We measured the high-performance wire from 8 to 16 T with currents up to 1475 A and the stable reference wire from 2 to 14 T with currents up to 1200 A.

Recently, researchers have started to use measurements of voltage-field (V - H) curves at constant current (I) to investigate low-field instabilities (flux jumps) that have been observed in magnetization measurements and in some high-performance Nb₃Sn wire applications. V - H measurements may overcome some of the extrinsic conditions that limit the high-field V - I curve measurement. It also may give a more quantitative measure of the relative stability of conductors once we understand the best way to conduct these measurements. It is important to understand that some portion of the magnet windings will always (regardless of the central field) be at low field where the flux jumps occur and thus, can limit the performance of the magnet. We and the community have limited experience with V - H curve measurements, so these results are not very quantitative at this time. There is much uncertainty about the repeatability, reproducibility, and stability correlation of these measurements. However, going through this period before these aspects can be determined is informative and necessary. Our approach to the V - H curve measurement was to use the same equipment and specimen mounting conditions as used in V - I curve/ I_c measurements. This meant trading off specialized high-speed acquisition for lower-speed, lower-noise acquisition.

We studied the systematic effect of current ripple or noise on the determination of n -value, the index of the shape of the voltage-current (V - I) curve. Commercial Nb₃Sn wires were measured with controlled amounts of a.c. ripple. A battery-powered current supply was used to provide the d.c. and ripple currents. The frequencies of the ripple current were 60, 120, and 360 Hz to represent common electrical power harmonics in high-current power supplies. A previous study focused on the effect on d.c. critical current (I_c). The current study focuses on how ripple changes the n -value. Recent high-performance Nb₃Sn wires have n -values as high as 80 at 12 T. These high n -values are more difficult to measure and this study shows that ripple has a larger effect on n -value than on I_c . We have examined models and measurements on superconductor simulator circuits to attempt to reproduce and explain the effects observed in

measurements on superconductors. We think that current ripple, noise, and spikes are one source of differences in n -values measured at different laboratories.

We have measured magnetic hysteresis loss on about 180 samples during this reporting period. Some of these measurements were done using a method that we developed to suppress the flux-jumps that occur in some high-performance conductors. This method improves the accuracy of the loss measurement under these conditions.

We made variable-temperature, variable-angle, critical-current measurements on commercial Ag-sheathed Bi-2212 wires (0.81 mm diameter) with transport current. Bi-2212 wires have been used in some of the highest-field superconducting magnets and may be used in specialty HEP magnets. Critical current depends on temperature, magnetic field, and, in many cases, the angle of the magnetic field with respect to the conductor cross section. The current-carrying properties of these round wires had never been systematically studied to determine how significant the angle dependence was until these measurements were made. NIST's results indicated that the angle dependence was insignificant and that applications could be operated at higher magnetic fields and temperatures than for other cross sections such as that of tape conductors. We made measurements in magnetic fields up to 8 T, at various magnetic-field angles, and temperatures from 4 to 30 K. NIST is the only laboratory in the U.S. that has such a multi-parameter and high-current variable-temperature measurement capability. The largest transport current applied to the wire samples was 775 A. No variable-temperature measurements at high current had been performed on these wires before. These data will be used to set the safe operating limits of the magnet system.

We made variable-temperature, variable-angle, critical-current (I_c) measurements on a commercial dip-coated and Ag-sheathed Bi-2212 tape, using a transport current. We measured at 4, 10, 15, 20, and 27 K. I_c at 1 μ V/cm was 845 A in self field and 4 K. The tape specimens were straight and the angle with respect to the magnetic field was held and rotated with a worm gear drive. The field was always perpendicular to the tape axis and current. The highest I_c was measured when the field was parallel to the wide face of the tape, and this angle was defined as 90°. The lowest I_c was at 0°. I_c at 70° was less than the average of the lowest and highest I_c at all fields and temperatures measured, which indicates a strong angle dependence near the peak in I_c . The I_c hysteresis with field and angle sweep directions decreased with increasing temperature. These data allowed for optimization of magnetic field and operating temperature, as well as optimization of using or not using flux guides to control the angle of magnetic field in the application.

We compared methods of measuring the RRR of high-purity Nb using transport current. RRR indicates the purity and the low-temperature thermal conductivity of the Nb, and is often used as a material specification for superconducting radio-frequency cavities in HEP accelerators. Our experimental study is intended to answer some fundamental questions about the best measurement method for RRR and the biases that may exist among different measurement methods, model equations, and magnetic field orientations. Two common ways to obtain the extrapolated normal-state resistivity at 4.2 K are: (1) measure the normal-state resistivity as a function of field at 4.2 K and extrapolate to zero field and (2) measure the normal-state resistivity as a function of temperature in zero field and extrapolate to 4.2 K. Both approaches have their associated difficulties. We also compared data taken with the magnetic field both parallel and transverse to the specimen current, and we measured magnetoresistance at various temperatures from 4 to 16 K. We combined all of these data to estimate the RRR using an approach based on the Kohler empirical rule regarding magnetoresistance. The Kohler rule

imposes the shape of the magnetoresistance curve at higher temperatures to better predict the extrapolated normal-state values at lower temperatures.

Publications (2003-2005)

1. L. F. Goodrich and T. C. Stauffer, "Variable-Temperature Critical-Current Measurements on a Nb₃Sn Wire," *IEEE Trans. On Appl. Superconductivity*, **15**(2): 3356-3359, 2005
2. L. F. Goodrich, T.C. Stauffer, J. D. Splett, and D. F. Vecchia, "Measuring Residual Resistivity Ratio of High-Purity Nb," *Advances in Cryogenic Engineering Materials*, **50A**: 41-48, 2004
3. L. F. Goodrich, T. C. Stauffer, J. D. Splett, and D. F. Vecchia, "Unexpected Effect of Field Angle in Magnetoresistance Measurements of High-Purity Nb," *IEEE Trans. Appl. Superconductivity*, **15**(2): 3616-3619, 2005

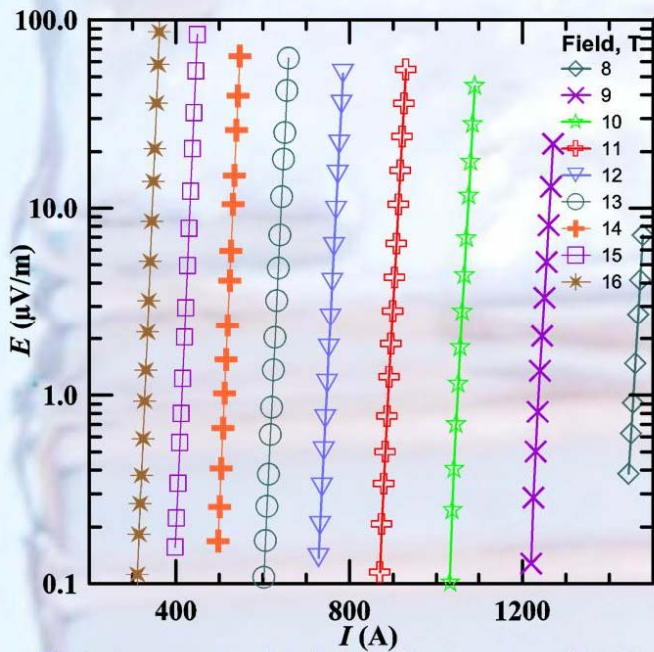
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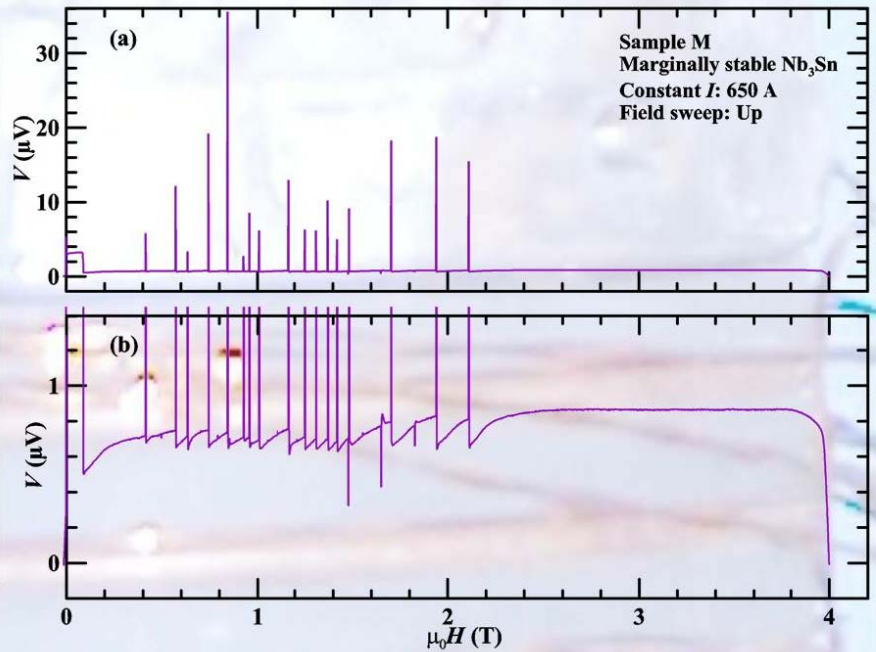
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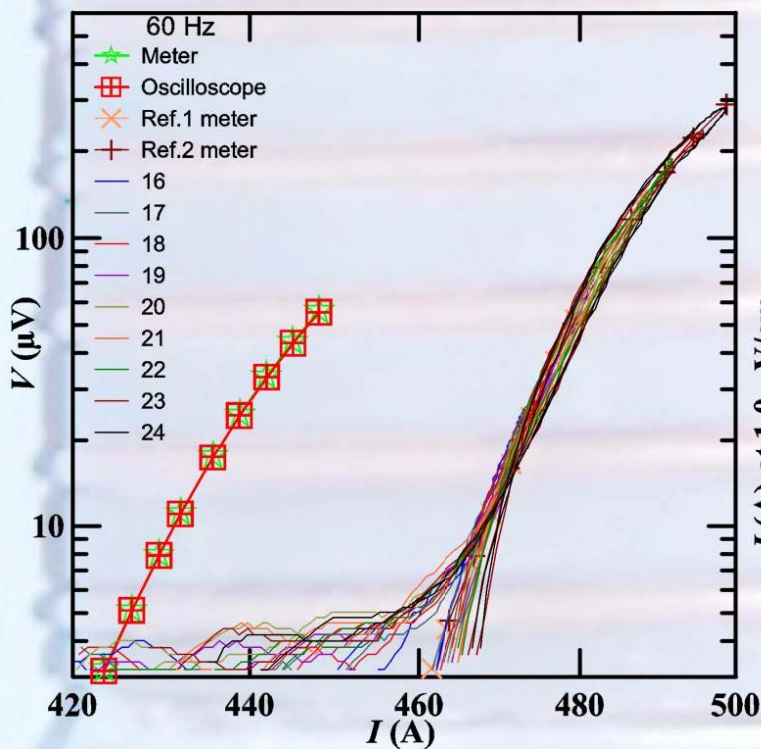
Critical-Current Metrology for Nb₃Sn Conductor Development at NIST



***E-I* curves for high-performance Nb₃Sn wire. Determines maximum current carrying capacity.**

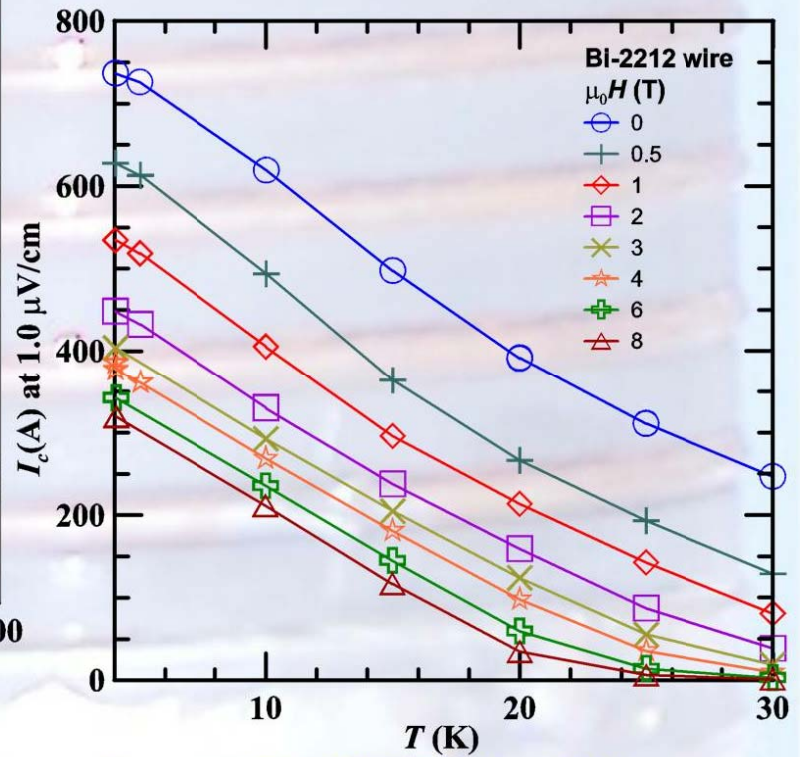


***V-H* curves for high-performance Nb₃Sn wire showing low-field flux jumps. Possible method to determine relative stability.**



Full logarithmic *V-I* curves with and without a.c. ripple, showing average and instantaneous curves. Noise and spikes may be a source of differences in interlaboratory comparison.

NIST



***I_c* versus *T* for Bi-2212 wire (0.81 mm diameter). Determine the safe operating limits versus *T* and *H*.**