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Characterization of High-Current, High-Temperature Superconductor Current Lead Elements*

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Abstract—The refrigeration loads of current leads for superconducting magnets can be significantly reduced by using high-temperature superconductor (HTS) leads. An HTS conductor type that is well-suited for this application is a laminated sintered and stack of HTS powder-in-tube (PIT) tapes. The superconducting conductor elements are normally characterized by their manufacturer by measuring critical currents at 77 K in self field. Additional characterization, which correlates electrical performance at 77 K and at lower temperatures with applied magnetic fields, provides the current lead designer and the conductor element manufacturer with critical information. For HTS conductor elements comprising a laminated and sintered stack of Bi-2223 PIT tapes having an alloyed Ag sheath, this characterization uses variable applied fields and operating temperatures.

I. INTRODUCTION

Use of high-temperature superconductors (HTSs) for current leads to deliver power to superconductor devices operating at liquid He temperature has the potential to reduce refrigeration loads to values significantly below those achievable with conventional leads, which introduce heat into cryostats by thermal conduction and Joule heating. It is desirable to minimize this heat input to reduce the amount of cryogenic fluid that is boiled off in an open system or to reduce the power consumption in a cryostat that is cooled by a closed-cycle refrigerator. Cryostat designers have been interested in optimizing current leads for some time, and several reviews of such efforts have been published [1], [2].

A lamination of Bi-2223 powder-in-tube (PIT) tapes is suitable as the conductor element of an HTS current lead. Advantages of PIT conductors include high critical transition temperature (T_c), high critical current density (J_c), that is relatively insensitive to applied field at low temperature and low applied fields, structural ruggedness with good strain tolerance, adjustability of Ag sheath thermal conductivity by alloying, improved protection capacity in interrupt condition,

and greater flexibility in meeting geometric constraints. The typical geometry of such a laminated conductor element is as shown in Fig. 1.

II. APPLICATIONS OF LAMINATED-CONDUCTOR ELEMENTS

An early application of laminated conductor elements was in the design of the Babcock & Wilcox (B&W) 16,000 A HTS current lead intended for SMES application [3], [4]. The HTS portion of the lead incorporates 18 parallel HTS conductor elements configured in a cylindrical array. The conductor elements are supported by an internal safety lead and are connected at their ends to current collectors. The geometry of the HTS portion of the lead is as shown in Fig. 2.
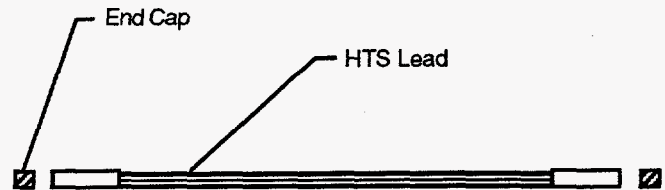

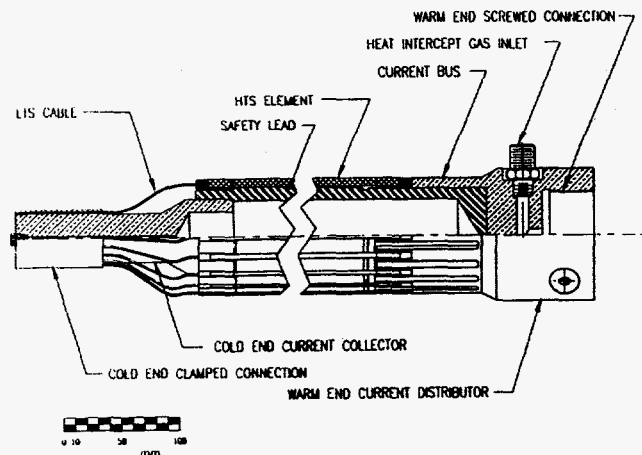Fig. 1. Typical geometry of HTS laminated PIT tape conductor element.

Fig. 2. Axial cross section of B&W 16,000 A HTS middle-stage current lead.

The major features of the B&W conductor element are PIT tape with a Bi-2223 multifilamentary core in an Ag + 3 at.% Au sheath, composite conductor of laminated PIT tapes fused together by sintering, critical current >1100 A @ 60 K in an applied magnetic field, 4-K heat load of ≤0.4 W/element, irreversible strain limit of >0.1%, thermal cycling results in <4% predicted degradation in critical current, size = 0.45 x 0.66 x 50 cm, and ends of unalloyed silver caps. Performance of the conductor elements, as manufactured by the American Superconductor Corporation, has been characterized [5], and their thermal and electrical stabilization has been considered [6].

A subsequent application of laminated conductor elements is in the American Superconductor Corporation CryoSaver™ family of current leads. This current lead employs multifilamentary HTS tapes to create a robust and reliable current lead that is designed to tolerate large numbers of thermal and electrical cycles. The multifilamentary composite conductor displays a high tolerance for strain and thermal cycling. Designed for conduction cooling, the lead requires no helium vapor flow. The conductor element is a composite that places HTS filaments in a low thermal conductivity matrix and that have a very high current density, which permits a small conductor cross section and keeps heat leakage low. The design places the conductor elements in a fiberglass housing to yield a structure that is robust and stress-tolerant. The current leads exhibit high tolerance for applied magnetic fields along two axes; a rigid fiberglass-epoxy support makes the conductor resistant to Lorentz I x B forces from high currents and magnetic fields. The lead has a high ability to ride through and recover from cooling system upsets without damage or burnout; the matrix metal in the conductor slows the temperature rise after a loss of cooling.

III. FABRICATION OF LAMINATED-CONDUCTOR ELEMENT

The HTS conductor is fabricated with standard methods for making the PIT BSCCO 2223 conductor. In the usual method (described in detail in [7]), a precursor powder is packed into a silver billet, which is then extruded and drawn to a metal-sheathed wire with a precursor powder core. This wire is then cut and bundled in a silver tube, which is then drawn down to a multifilament wire. A repetitive deformation-and-sintering (DS) schedule is then applied to the wire to form, align, and homogenize the superconducting phase. Rolling is the deformation process used to align the micaceous and highly aspected 2223 grains, and the end of the DS schedule yields a tape conductor. A final postdeformation heat treatment completes the formation of the superconducting phase.

Production of the laminated conductor elements is identical to the process described above, with two exceptions. First, a silver alloy is used as the matrix metal in place of pure silver to reduce the thermal conductivity of the laminate and make it a more effective current lead. Second, the tapes are assembled into a bus bar shape before the final heat treatment and then reacted. The high reaction temperatures for the superconductor (>800°C) sinter the tapes together and yield a monolithic structure without the use of solder.

For the conductor elements evaluated, the tape cross-sectional dimensions are approximately 4.3 mm wide x 0.25 mm thick. Each tape has 85 filaments, and the ratio of superconductor to matrix is approximately 1:2 (or ≈33% fill factor). The low-current leads (serial nos. 474 and 475) contained 8 tapes; the high current leads (serial nos. 472 and 473) contained 16 tapes. The end caps were milled from a copper block and had a final thickness of 0.36 mm. They were soldered to the laminated conductor.

IV. MEASUREMENTS OF CRITICAL CURRENT

The critical currents of the sample conductor elements were measured in liquid nitrogen (LN) at both the American Superconductor Corporation (ASC) and at ANL. Results of the measurements are summarized in Table I.

At ANL, critical current with variable applied fields and operating temperatures was measured in a facility consisting of a variable-temperature He cryostat, a conventional magnet, and a current pulser. The samples are placed in a variable-temperature cryostat with a 75-mm-diam cold bore. Samples up to 0.5 m long are installed as pairs connected electrically in series. Operation with liquid or gaseous He enables both gradients and uniform temperature along the sample length. Operation with LN is also possible. The variable-temperature cryostat was configured to contain two samples and could be rotated in the magnet to provide B//b and B//c applied-field orientations.

The sample bars were mounted with their c-axes in the same plane in the variable-temperature cryostat and were restrained to prevent movement during current pulsing. Distance between the samples (60 mm) was maximized to reduce the effect of bar self-field on the performance of the companion bar. The magnitude of field due to the companion bar is

TABLE I
CRITICAL CURRENT IN LIQUID NITROGEN (A)[a]

Measurement Facility	SN-472	SN-473	SN-474	SN-475
ASC[b,c]	560	560	300	300
ANL[d,e]	555	544	189[f]	270

Notes
a. In boiling LN with B = 0 T and 1 μV/cm criterion.
b. DC current.
c. Single element.
d. Pulsed current.
e. Series elements in variable-temperature cryostat configuration.
f. Conductor element deformed during handling.

≈2% of the applied field. The lower ends of the samples were electrically joined to one another by soldered Cu braid. Upper connectors of the bars were soldered to Cu electrodes extending through the cryostat to external cables. Placement of voltage taps, Si-diode temperature sensors, and thermo-couples is shown in Fig. 3. The bars were brought to the test temperature with He vapor. Sample temperature in the He gas environment was controlled by gas flow and electrical heaters.

The variable-temperature cryostat is installed in the bore of a conventional, water-cooled dipole electromagnet that is oriented with its axis vertical and has a 0.76-m-long, 102-x-127-mm-rectangular cross section, room-temperature bore. The magnet can provide horizontal dipole fields of up to 0.4 T. Field mapping has verified that applied field is uniform over the variable-temperature-cryostat sample-measurement volume.

The current used in evaluating the conductor elements was pulsed at a low-duty cycle to avoid errors caused by effects of current-contact heating and to allow the use of normal conductor cabling that is smaller than that required for con-tinuous current. Although the actual use of such conductor elements requires continuous current flow, the amount of contact heating will be affected by the contact and cooling particulars of the installed configuration, not all of which were simulated in the subject tests.

Pulse currents up to 1500 A, from a ground-isolated supply, were applied to samples as 280-to 500-ms-long uni-directional square waves at a duty cycle below 1%. Current amplitudes were measured by a 100 μΩ standard four-termi-nal resistance, a Stanford Research Model SR560 preampli-fier with a gain setting of 10 and low pass filter setting of 30 Hz, and a Hewlett-Packard Model 54600A digital storage oscilloscope. Voltages from superconductor samples were amplified by 1,000 with a second SR560 preamplifier set to reject noise at frequencies above 10 Hz or above 30 Hz, as appropriate; the output was measured by a second 54600A oscilloscope. For each measurement, the pulse height above the instant baseline was taken; thus thermal-voltage offset errors were avoided. To prevent common-mode errors, the standard four-point connection to the sample was supple-mented by fifth contact that provided a ground reference for differential measurement of sample voltages. A voltage cri-terion of 1 μV/cm was used to define the critical current.

The measurement operating points correspond to antici-pated values for HTS current lead applications and were spec-ified by ASC. Applied fields for $B//$b were $0 \leq B \leq 0.3$ T and for $B//$c were $0 \leq B \leq 0.15$ T. Operating temperatures were 60, 64, 70, and 77 K. Measurement accuracies were estimated to be <1% critical current, <1% applied field, and <0.5 K operating temperature.

During the critical current measurements, the temperature difference between the warm and cold voltage tap locations had a range of 1 to 5 K, with an average of 3 K. The
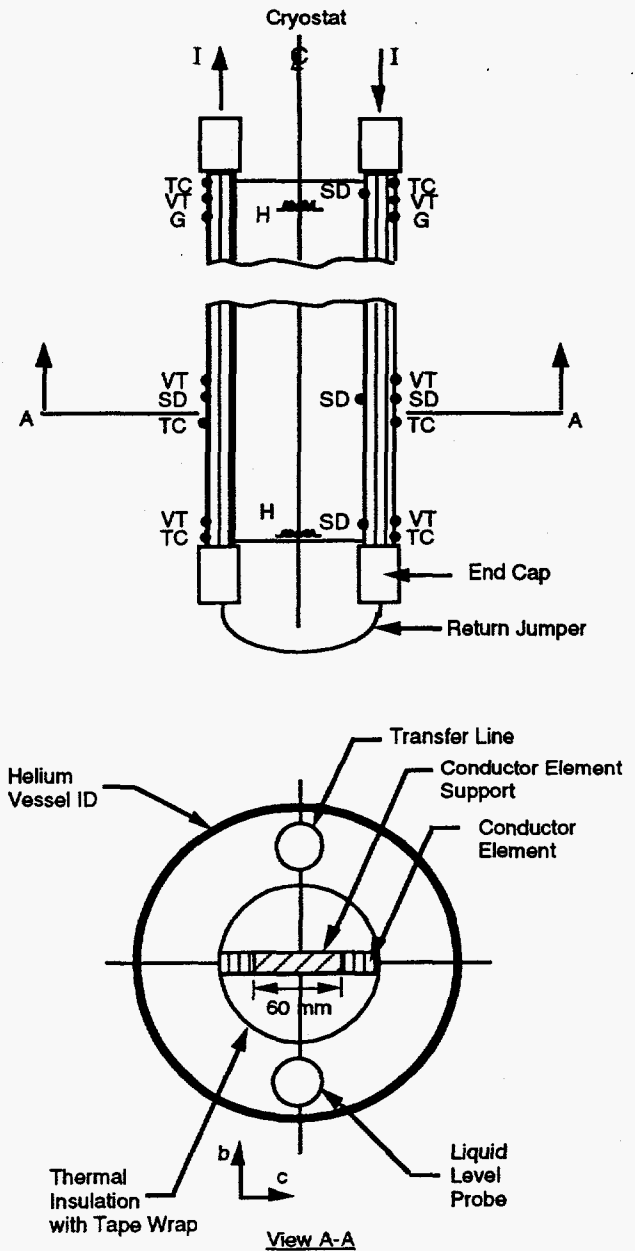

Fig. 3. Schematic diagram of instrumentation of critical current sample. SD = silicon diode; G = ground; VT = voltage tap; TC = thermocouple.

operating temperature value for the measurements was taken to be the arithmetic average of the measured warm and cold temperatures. Results of the measurements are as given in Figs. 4-7.

V. CONCLUSIONS

• HTS conductor elements consisting of a laminated and sintered stack of Bi-2223 PIT tapes having an alloyed Ag sheath are suitable for application as HTS current leads.
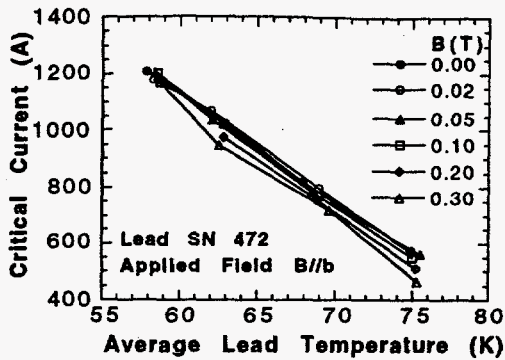
Fig. 4. Lead SN 472 measured critical current with B//b.
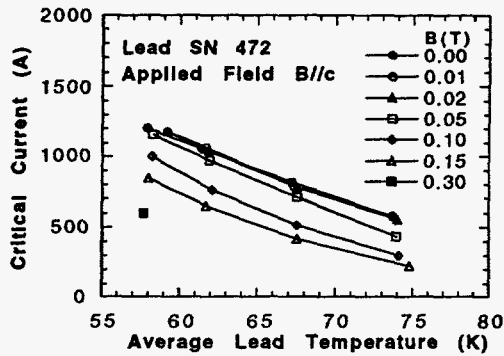

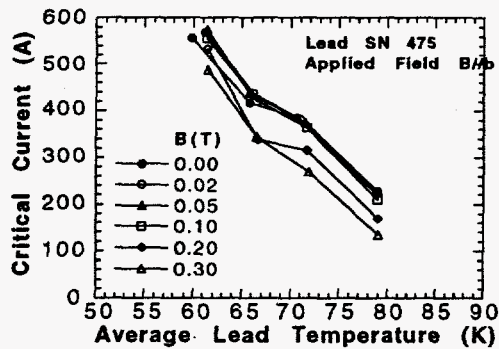Fig. 5. Lead SN 472 measured critical current with B//c.

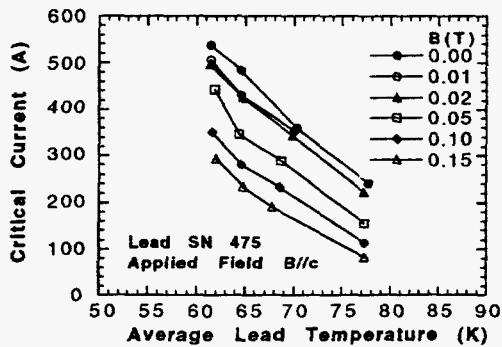Fig. 6. Lead SN 475 measured critical current with B//b.

Fig. 7. Lead SN 475 measured critical current with B//c.

- Sample conductor elements as manufactured by ASC have been characterized for critical current by ASC and ANL in LN @ 1 ATM without applied field and by ANL in gaseous He with variable applied field and operating temperature.

- Results of the characterization measurements will be applied to the design of HTS conductor elements and to the development of application guidelines.

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