Usage of Bi-HTS in High Field Magnets

F. Hornung, M. Kläser, and T. Schneider

***Abstract*—At present, superconducting high field magnets built up of metallic Low Temperature Superconductors (LTS) like NbTi and ternary/quaternary Nb_3Sn are near to the upper limit of achievable field strength. Fields above approx. 23 T seem to be only reachable with LTS-HTS hybrid configurations consisting of an outer LTS section and a High Temperature Superconductor (HTS) insert. Commercially available Bi-HTS wires were investigated for their application in high field facilities like the HOMER II system with the goal of 25 T and in new generations of NMR magnets of 1000 MHz and above. Therefore the superconducting properties of the HTS wires were examined at 4.2 K in magnetic fields up to 10 T. The voltage-current relation was examined resistively using a high resolution four-point measurement technique. The dependence of the critical current and the n-value on the winding diameter, on the field alteration (increasing/decreasing), and on the field orientation to the wire is presented and discussed.**

***Index Terms*—BSSCO wires, critical current, hybrid LTS-HTS magnets, n-value.**

I. Introduction

A VERY advantageous application of superconductors is the generation of high magnetic fields. Compared to metallic conductors, coils made of superconducting materials show very little dissipation reducing the costs for electrical power and for cooling. Another advantage is the high time stability of the generated field, especially when the coil system is driven in persistent mode, i.e., short-circuited by a superconducting switch. Consequently, one can find superconducting magnets in experimental high field facilities like HOMER I and HOMER II as well as in high resolution NMR spectrometers [1].

The physical limit of field strengths achievable by a superconducting magnet system is determined by the upper critical or irreversibility field of the used materials. With coils built of classical metallic LTS like NbTi and ternary/quaternary Nb_3Sn fields above $\approx$23 T are hardly obtained. In contrast, Bi-HTS—like Bi-2223—show very high irreversibility fields at low temperatures (e.g., 4.2 K) and are therefore auspicious materials for future high field and NMR magnets [1], [2]. From a physical point of view, fields of 25 T and above should be reachable with LTS-HTS hybrid coil configurations.

In this paper we discuss the suitability of commercially available Bi-2223 tapes, produced by American Superconductor, AMSC, for building up high field insert coils. The critical current, I_c, and n-value of the wires at 4.2 K in external fields up to 10 T are presented in dependence on the winding diameter, the field alteration (increasing/decreasing), and on the field orientation to the tape (parallel as well as perpendicular).

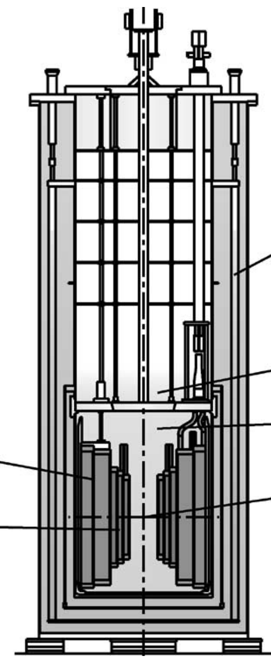

Fig. 1. Schematic drawing of the basic configuration of the HOMER II test facility.

II. The Facility HOMER II

A. Basic Magnet Configuration

The latest experimental facility in the High Field Magnet laboratory of the Institute for Technical Physics is HOMER II which is currently under construction. In a first step, a magnetic field of 20 T in a bore of 180 mm diameter is aspired. This basic magnet configuration consists of five concentric solenoid coils. The two outer coils are made of NbTi and produce $\approx$12 T. The contribution of the three inner coils made of ternary/quaternary Nb_3Sn is $\approx$8 T. The LTS section of HOMER II is already manufactured and ready to be tested. A cross sectional view of the basic configuration of HOMER II is given in Fig. 1.

B. HTS Insert Coil

To produce fields up to 25 T in a bore of 50 mm at 1.8 K, a HTS insert coil is currently under construction. This magnet section is composed of 16 stacked double-pancakes of Bi-2223 tape. Each double-pancake consists of 2 $\times$ 150 layers insulated by a co-wound capton foil. Compared to a single-pancake layout, the use of double-pancakes halves the number of normal conducting joints resulting in a lower dissipation of the insert magnet. As discussed later, we use the 'High Strength Wire' manufactured by AMSC as superconductor. The uniqueness of this Bi-2223 tape is its reinforcement by a lamination of two layers of stainless steel soldered on both sides.

TABLE I
DESIGN PROPERTIES OF AMSC Bi-2223 TAPE

	Reinforced wire	Non-reinforced wire
HTS material	Bi-2223	Bi-2223
Dimensions	4.1 mm × 0.305 mm	4.1 mm × 0.2 mm
Filaments	55	55
Matrix	Ag	Ag
Sheath	Ag-alloy	Ag-alloy
Reinforcement	2 layers of steel	none
Max. stress (77 K)*	265 MPa	65 MPa
Min. bending diameter*	70 mm	100 mm

*with 95% I_c retention

III. EXPERIMENTAL

In this paper data of three sets of measurements are presented. First, we report on a detailed investigation of a reinforced AMSC Bi-2223 wire. Second, we compare these results with those of an AMSC tape without reinforcement, and third the $I_c(B)$ data of the 16 Bi-2223 tapes used for the HOMER II insert coil are shown. The specifications of the wires can be found in Table I. For more detailed information check up [3].

All experiments were carried out in our facility JUMBO [1] at 4.2 K at different values of the external magnetic field, B, up to 10 T. For various samples, the voltage-current characteristics were measured under steady-state conditions using a high resolution four-point measurement technique.

According to the physics of the Bi-2223 tapes and the intended application as a wire for an insert coil, several specimen configurations were fabricated and tested. To investigate the dependence of $I_c(B)$ and $n(B)$ on the winding diameter, one-layer test coils with diameters of 90 mm, 60 mm, and 33 mm were manufactured. One part of these test coils was measured in antiparallel orientation of self-field and background field, i.e., without exposure to hoop stress, the other part with parallel orientation of the fields, i.e., under hoop stress. In real magnets, both the axial and the radial magnetic field components exist. Therefore the knowledge of $I_c(B)$ and $n(B)$ for magnetic fields parallel, $B_{||}$, and perpendicular, $B_{\perp}$, to the tape surface is important. To investigate these dependencies, short samples of approx. 9 cm length were tested in parallel and perpendicular orientation of the background field to the surface of the tape.

IV. RESULTS AND DISCUSSION

A. AMSC 'High Strength Wire'

In this section we present the results derived from a reinforced AMSC Bi-2223 tape. Fig. 2 shows the obtained $I_c(B)$ data for a test coil with a diameter of 90 mm at 4.2 K for increasing and decreasing external field B orientated antiparallel to the self-field of the sample. Details concerning the measurements and their analysis can be found in [4]. The critical current of $I_c = 910$ A at 0 T is quite impressive. This value is equivalent to a current density of 72 800 A/cm^2 based on the complete cross-sectional area and 111 000 A/cm^2 for the tape without steel reinforcement. In contrast to metallic LTS, the Bi-2223 $I_c(B)$ curves show a hysteretic behavior with higher I_c values for decreasing field. This enhancement of I_c can be understood by the flux penetrating the granular microstructure of the filaments. When decreasing the external field, the trapped flux in the superconducting grains leads to a reduced field in the intermediate weak links and for this reason to higher I_c values [5]. Reducing the winding diameter to 60 mm does not degradate the 'High Strength Wire' as demonstrated earlier [6].

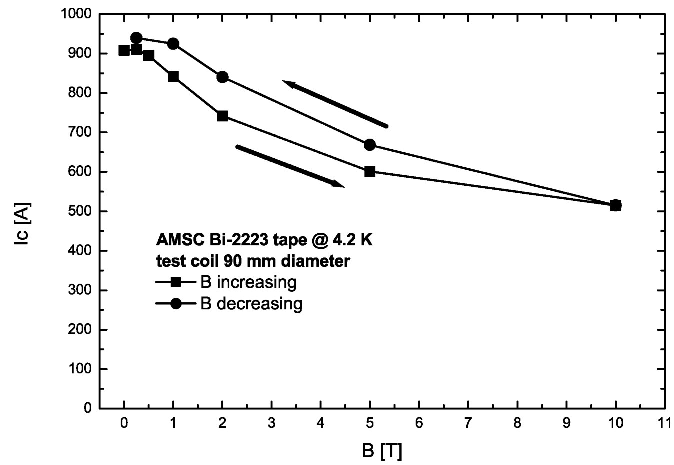

Fig. 2. $I_c(B)$ for increasing and subsequent decreasing external magnetic field B measured at 4.2 K for a test coil of 90 mm diameter made of reinforced AMSC Bi-2223 tape.

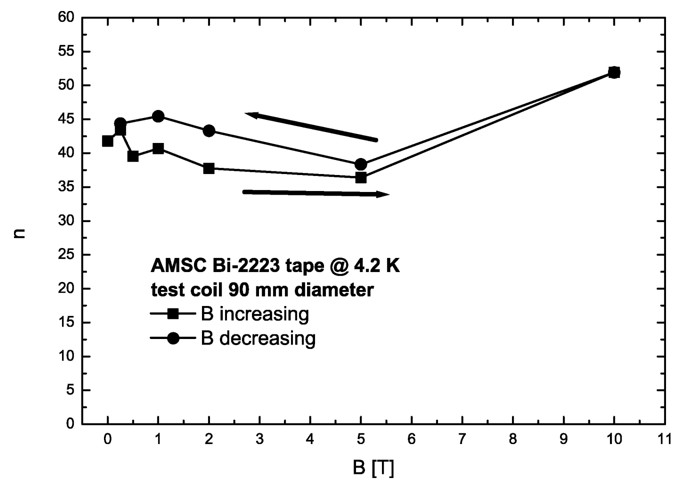

Fig. 3. $n(B)$ for increasing and subsequent decreasing external magnetic field B measured at 4.2 K for a test coil of 90 mm diameter made of reinforced AMSC Bi-2223 tape.

Using a power law fit for the voltage-current relation, one gets the exponent n as a measure for the steepness of the superconducting/normal conducting transition. In Fig. 3 the $n(B)$ data is given for the 90 mm test coil for increasing and subsequent decreasing magnetic field. The n-values are quite high reflecting a good quality and homogeneity of the Bi-2223 tape. Also, the $n(B)$ curve is nearly independent of the external field and there is also little splitting for increasing/decreasing field.

The impact of the field orientation, $B_{||}$ and $B_{\perp}$, on I_c can be seen in Fig. 4, where $I_c(B_{||})$ and $I_c(B_{\perp})$ measured at 4.2 K on two short sample test lengths are given for increasing external field. For comparison, the data of the test coil (only increasing field) is included. $I_c(B_{||})$ and $I_c(B_{\perp})$ show the well-known anisotropy of the tape-shaped wires. The cuprates with their superconducting CuO_2-planes are quasi two-dimensional

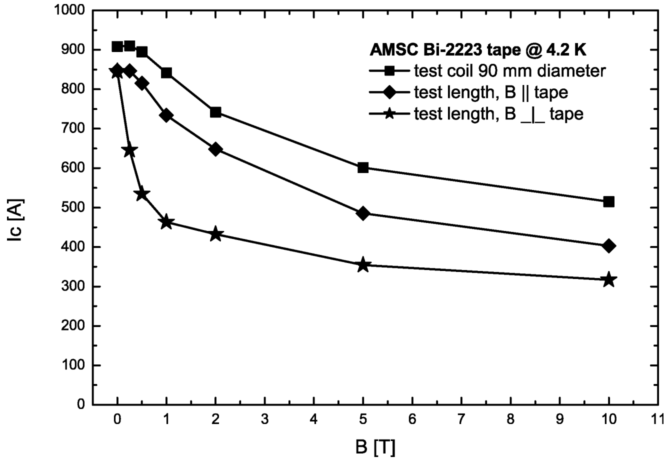

Fig. 4. $I_c(B)$ measured at 4.2 K in increasing external field B for a test coil of 90 mm diameter and short sample test lengths in parallel and perpendicular orientation. All samples are made of reinforced AMSC Bi-2223 tape.

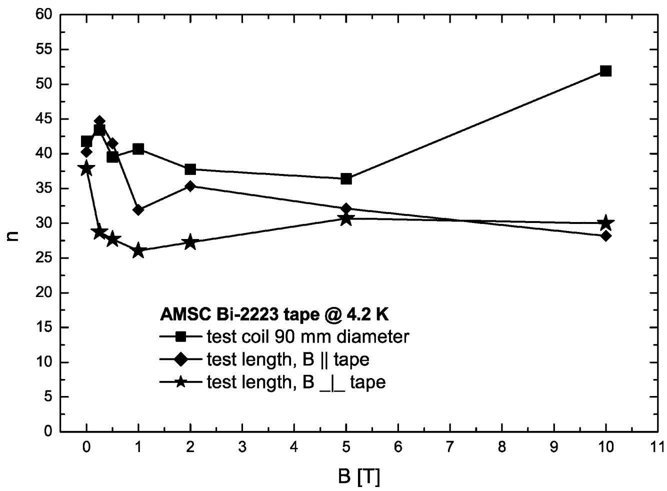

Fig. 5. $n(B)$ measured at 4.2 K in increasing external field B for a test coil of 90 mm diameter and short sample test lengths in parallel and perpendicular orientation. All samples are made of reinforced AMSC Bi-2223 tape.

superconductors. Due to the texture of the grains in the tape, the planes are aligned parallel to the tape surface. Because the flux-pinning is stronger for parallel field, $I_c(B)$ in that configuration is higher compared to the perpendicular case. As the tape of the test coil is arranged parallel to the external field, one should have expected concurrent $I_c(B)$ curves for the test coil and the test length parallel to B as observed in earlier measurements [6]. Surprisingly, in Fig. 4 $I_c(B)$ measured for the test coil lies significantly higher. Probably this is caused by the non uniform tape performance as indicated by AMSC's certification [7].

The corresponding $n(B)$ curves for the above three test objects are given in Fig. 5. The adversarial perpendicular arrangement again represents the lower limit of the group of curves. Again, there is only a weak dependence of the n-value on the external field.

B. AMSC Non-Reinforced Wire

To analyze the effect of the steel reinforcement of the wire, we investigated a batch of nonreinforced AMSC Bi-2223 tapes. As

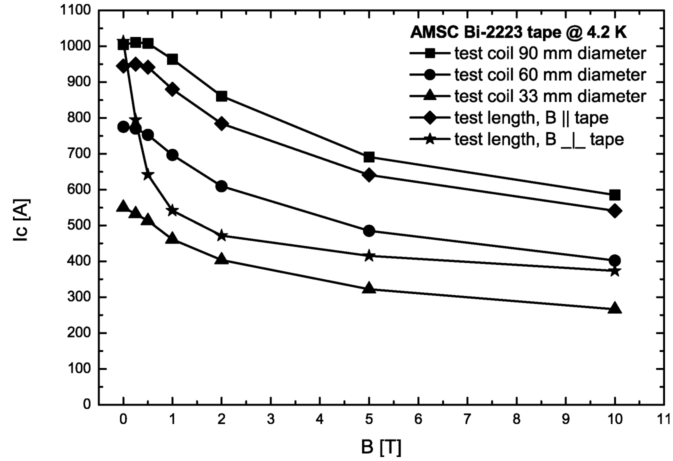

Fig. 6. $I_c(B)$ measured at 4.2 K in increasing external field B for test coils of 90 mm, 60 mm, and 33 mm diameter and short sample test lengths in parallel and perpendicular orientation. All samples are made of nonreinforced AMSC Bi-2223 tape.

it can been seen from Table I, the build up of this tape is the same as for the reinforced wire except for the two layers of stainless steel soldered on both sides. We present data measured for one layer test coils with diameters of 90 mm, 60 mm, and 33 mm and for short samples parallel and perpendicular orientated to the external field B. All measurements were performed at 4.2 K. The test coils were examined in antiparallel field configuration, i.e., without exposure to hoop stress.

In Fig. 6 the $I_c(B)$ characteristics measured for the different samples are given for increasing external field B. With 1005 A in self-field, equivalent to an over all current density of 122 560 A/cm^2, the critical current for the test coil of 90 mm diameter is considerable. Reducing the winding diameter to 60 mm, the current carrying capacity decreases to about 70% apparently caused by the degradation of the granular microstructure by occurring cracks. This is in contrast to the reinforced AMSC tape, where in earlier measurements no degradation was observed at a winding diameter of 60 mm (see [6]). Further reduction of the winding diameter to 33 mm is accompanied by further I_c degradation. The short sample specimens orientated parallel and perpendicular to the external field show the anisotropic behavior like the reinforced tape. Again, the difference in $I_c(B)$ of the test coil of 90 mm diameter and the short sample aligned parallel to the external field can be explained by the non uniform tape performance of this more experimental wire. In decreasing field, all the samples show the hysteretic $I_c(B)$ behavior as already seen at the reinforced wire (for reasons of lucidity not shown in Fig. 6).

The n-values given in Fig. 7 mirror the findings for $I_c(B)$. The $n(B)$ curves can be divided in two groups: The upper group of intact samples (test coil of 90 mm diameter and the two short samples) and the group of samples with low n-values of about 20 (test coils of 60 mm and 33 mm diameter). Due to the under-run of the critical bending diameter the latter group exhibits a degradated microstructure and therefore reduced n-values.

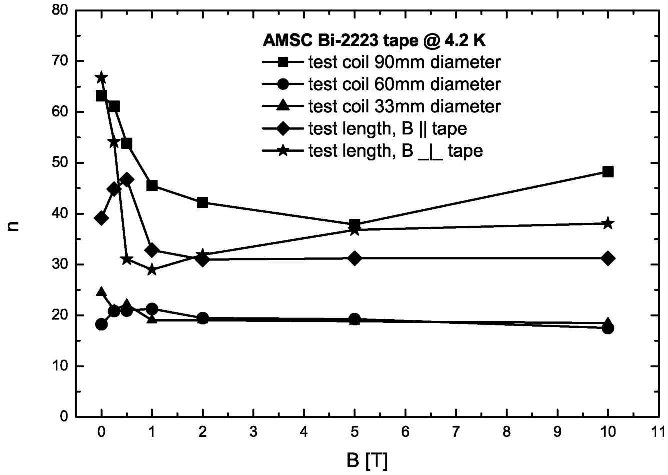

Fig. 7. $n(B)$ measured at 4.2 K in increasing external field B for test coils of 90 mm, 60 mm, and 33 mm diameter and short sample test lengths in parallel and perpendicular orientation. All samples are made of nonreinforced AMSC Bi-2223 tape.

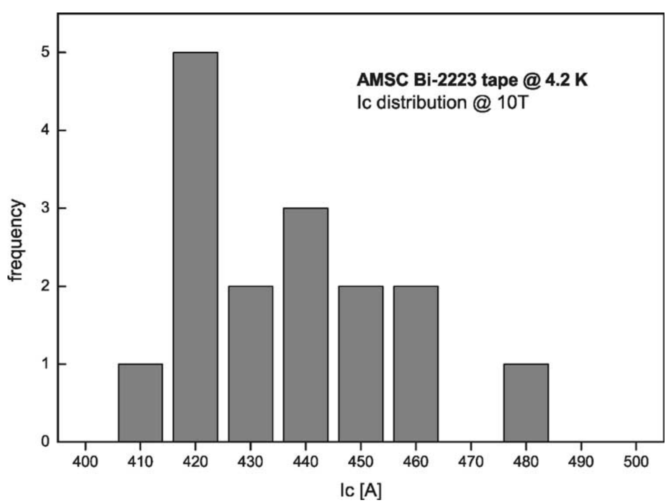

Fig. 8. Distribution of I_c measured at 10 T and 4.2 K for the 16 AMSC Bi-2223 tapes used to fabricate a HOMER II insert coil.

C. AMSC Tapes Used for HOMER II Insert Coil

For the fabrication of a stacked double-pancake insert coil for HOMER II, 16 reinforced AMSC tapes were purchased. As acceptance test, a test coil of 90 mm diameter was fabricated from each unit length and examined in external fields up to 10 T at 4.2 K. As occurring in a magnet, the measurements were performed under hoop stress, i.e., in parallel orientation of self-field and background field. Stresses up to 176 MPa were reached for the wire with the highest current carrying capacity. No degradation was observed. Fig. 8 shows the histogram of critical currents at $B = 10$ T measured for the set of 16 samples. In Fig. 9 the mean value and standard deviation of the $I_c(B)$ curves is given. Compared to the previous presented wires, tapes with marginally lower critical currents have been purchased to optimize the cost-to-performance ratio of the insert coil.

The extrapolation of the flat running $I_c(B)$ curve to the desired field of 25 T yields in critical currents well above 250 A for

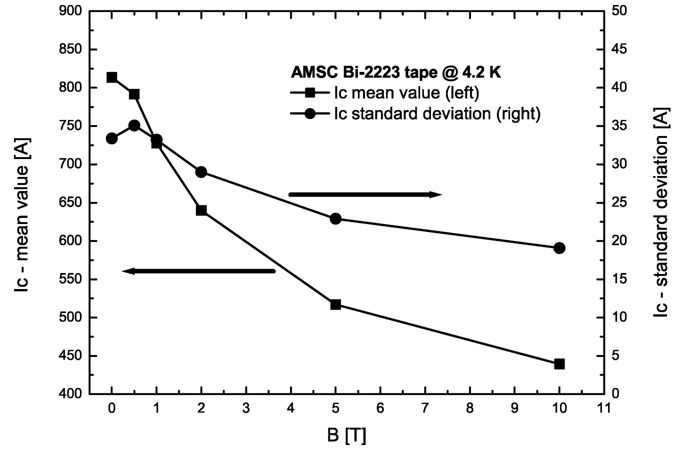

Fig. 9. Mean value and standard deviation of $I_c(B)$ measured at 4.2 K for the 16 AMSC Bi-2223 tapes used for HOMER II.

all 16 wires. This current is more than sufficient to obtain this field with the proposed stacked double-pancake configuration. Also the calculated stress is below the specification of 265 MPa given by AMSC. Currently the manufacture of the insert coil for HOMER II is in progress using the audited Bi-2223 tapes.

V. Conclusion

To generate magnetic fields up to 25 T in our facility HOMER II, an insert coil made of HTS is currently under construction. For this purpose we investigated Bi-2223 tapes fabricated by American Superconductor. The wires show high critical currents up to more than 1000 A in self-field and up to nearly 600 A in external fields of 10 T (all values at 4.2 K). These high critical currents are accompanied by high n-values above 30. Due to the reinforcement by two layers of stainless steel, the wire is able to withstand the occurring hoop stress. In addition winding diameters of 60 mm are possible without degradation. For the fabrication of the stacked double-pancake insert coil, a set of 16 reinforced Bi-2223 tapes was purchased and tested. As all wires meet the required specifications the winding of the insert coil is currently in progress.

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