Degradation of Bi-2223 Tape After Cooling With Superfluid Helium

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

Abstract—**Future superconducting magnets for fields of 25 T and above have to be composed of LTS-HTS hybrid coil systems. To obtain a higher field contribution and for reasons of stability, the outer low temperature superconducting (LTS) magnet section is cooled particularly with superfluid helium. In the classical set-up, the high temperature superconducting (HTS) insert is assembled together with the LTS outsert in a common bath, i.e. in our case it is cooled with superfluid helium. Our first 5 T Bi-2223 prototype insert coil was successfully operated and produced 5.4 T in a background field of 11.5 T. After warming up, ballooning was observed in the tape apparently caused by the penetration of superfluid helium. In this paper we investigate the impact of superfluid helium on the superconducting properties of the Bi-2223 tape used for our HTS insert. In particular, the voltage-current relation, $U(I)$, is examined. It is shown that the resulting critical current and the n-value, which is a differential variable, are not adequate to describe the widely degraded $U(I)$- curves. In addition, we suggest the use of an integral method. The measurement results and the interpretation of the $U(I)$-curves are presented and discussed.**

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

I. INTRODUCTION

THERE is a continuing strong demand for superconducting magnet systems in many areas. The wide variety of applications ranges from accelerators, detectors, fusion magnets, high field experimental facilities, etc. to magnetic resonance imaging (MRI) and nuclear magnetic resonance spectroscopy (NMR). In contrast to magnets made of normal conducting materials, superconducting magnets show no massive heat production, reducing the costs for electrical power and cooling. Furthermore, when operating superconducting magnets in persistent mode, i.e. using superconducting joints and a short-circuit by a superconducting switch, an otherwise nonfeasible excellent temporal stability of the magnetic field can be obtained. Thus the generation of magnetic fields is one of the most important applications of technical superconductors. A special and very demanding area is the generation of very high magnetic fields above 20 T with superconducting magnets. In this field there are two development directions. One is the construction of magnets operated in persistent mode for NMR-spectrometers with resonance frequencies of 1000 MHz and above, corresponding to magnetic fields of $\geq$23.5 T, the other is the construction of high field experimental facilities for basic research in high magnetic fields.

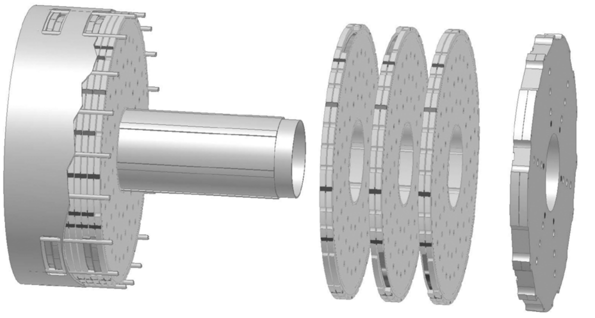

Fig. 1. Schematic drawing of the stacking of the double pancakes showing the core retainer, some of the double pancakes, the flange (on the right), the jacket tube (on the left), and some of the copper joints (at the openings of the jacket tube).

In this paper, we report on our first prototype of an insert coil made of high temperature superconductors (HTS) to be used as upgrade for our facility HOMER II. Our results of the test of the HTS insert lead to the main topic of the paper: The degradation of Bi-2223 tape after cooling with superfluid helium.

II. 5 T HTS INSERT COIL FOR HOMER II

The latest experimental facility of the High Field Laboratory of the Institute for Technical Physics is HOMER II. Its basic magnet configuration produces a magnetic field of 20 T in a bore of 185 mm at a helium bath temperature of 1.8 K. Details of the facility are described in [1] and [2].

In a future stage, it is planned to upgrade the magnet system of HOMER II by adding insert coils made of low temperature superconductors (LTS) and HTS to reach fields up to 24 T and 25 T, respectively, in a bore of 50 mm. As it can be seen e.g. in [3] and [4] advanced $\mathrm{Nb_3Sn}$ is able to produce 24 T and Bi-HTS 25 T. Considering the promising perspective of HTS for future projects to reach fields of even more than 25 T, our first prototype was built using Bi-2223 tapes. Due to the tape form of the Bi-2223 wire, a stacked double pancake layout for the HTS insert coil was chosen. 16 double pancakes were constructed using stainless steel reinforced "high strength" Bi-2223 tape manufactured by American Superconductor (AMSC) (see Fig. 1).

The test of the constructed insert coil was carried out in our superconducting magnet facility HOMER I which is described in detail in [1]. As it is intended to assemble the HTS insert together with the LTS outsert of HOMER II in a common helium bath at 1.8 K, the test of the HTS insert in HOMER I was consequently performed at the same temperature, i.e. in superfluid helium (He II). The insert produced a magnetic field of

5.4 T at a current of 151.2 A in a background of 11.5 T provided by our facility HOMER I, resulting in a total magnetic field of 16.9 T. All test runs were carried out without any incidents—no quenches or degradation of the magnet occurred. But after warming up, ballooning of the tape was observed in several double pancakes, in all probability due to the penetration of superfluid helium. Details of the manufactured HTS insert and the test runs can be found in [5] and [6].

III. Stability of Bi-2223 in Superfluid Helium Near T_λ

A. *Introductory Remarks*

As we have never observed ballooning of the AMSC Bi- 2223 tape before in our tests at 4.2 K, the superfluidity of the helium at the operating temperature of the HTS insert of 1.8 K is most likely the reason for the penetration of the tape. In literature there is no information regarding the behavior of state-of-the-art Bi-2223 tapes when cooled in superfluid helium. In addition, there is no information provided by the manufacturers. There are, however, several papers dealing with the microstructure of the filaments. It is shown that there are many voids between the Bi-2223 grains (e.g. [7]). It is easy to image that superfluids can penetrate this porous structure, remaining confined when becoming normal fluid and leading to ballooning of the tape at the liquid-gas transition.

It is far beyond of the scope of this paper to report on the manifold properties of superfluids, but there are three issues we would like to readdress briefly:

- *Critical velocity:* For superfluids there exists a critical velocity v_{sc} which is necessary to create turbulence. Experimental data for He II indicate that for flows in porous media v_{sc} follows a $d^{-1/4}$ law with d as dimension of a channel. For a pore of e.g. 1 μm in diameter v_{sc} is about 0.1 m/s as shown in Fig. 2 [8].
- *Fountain effect:* In superfluids changes in temperature are connected with changes in pressure. A local temperature increase in He II of e.g. 0.4 K (e.g. from 1.8 K to the lambda-point, $T_\lambda = 2.2$ K, of helium) leads to a pressure increase of 3.2×10^4 Pa [8].
- *Fluctuation effects:* Closely above the superfluid transition temperature T_λ there exist long range and long-living fluctuations of the order parameter with locally ordered regions of the size of the coherence length ξ and the lifetime τ. ξ and τ follow power laws which diverge at T_λ:

$$\xi \sim t^{-\nu} \quad \text{and} \quad \tau \sim t^{-\nu z} \tag{1}$$

  with the reduced relative temperature, $t = (T - T_\lambda)/T_\lambda$, and the critical exponents $\nu = 2/3$ and $z = 3/2$. Due to the small coherence length of superfluid helium, fluctuations are important well above T_λ in a temperature interval of about 0.5 K [9], [10].

From these points it follows that He II can penetrate even longer lengths of open-porous media in minutes, that destructive pressure can occur even below T_λ and that penetration of He II can even be an issue above T_λ.

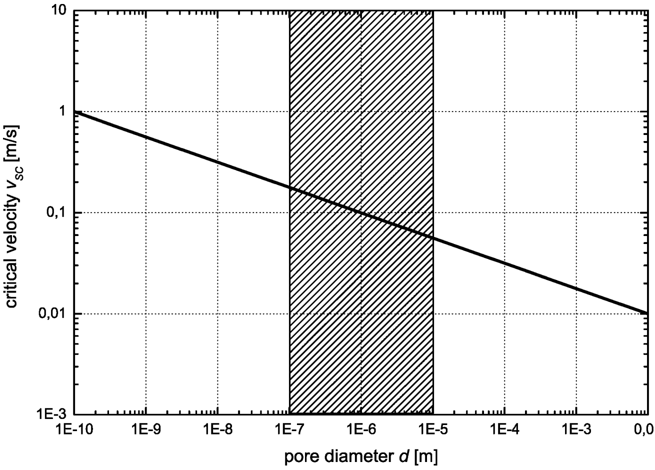

Fig. 2. Critical velocity v_{sc} for flow of He II in porous media [8]. For a typical pore diameter d in the range of 1 $\mu\mathrm{m}$ v_{sc} is about 0.1 m/s.

B. *Experimental*

The only way to clarify the influence of He II on the stability of specific Bi-2223 tapes are appropriate experiments in He II as it is nearly impossible to predict the stability visually or by other indirect means. For future projects there are two promising Bi-2223 tapes which could withstand the penetration of superfluid helium and with it the ballooning: the so-called "Hermetic Wire" manufactured by AMSC and the CT-OP wire from Sumitomo Electric. In addition to its reinforcement by two layers of stainless steel, the Hermetic Wire is completely sealed to avoid the penetration of cryogenic liquids. Originally, the Hermetic Wire was developed to withstand high pressure liquid nitrogen. The capability to avoid the penetration of superfluid helium is not guaranteed by AMSC. Another attempt to improve the Bi-2223 wire is the "controlled overpressure" (CT-OP) technique adopted by Sumitomo. High pressure is applied during the heat treatment to densify the Bi-2223 grain structure and to reduce the void fraction substantially. Again, only the impermeability against liquid nitrogen is guaranteed by the manufacturer.

To investigate the stability of the AMSC Hermetic Wire and the Sumitomo CT-OP wire in He II a long-term test was carried out in our facility MTA I. Detailed information on MTA I can be found in [1]. Due to its higher critical tensile strength—which is advantageous for the application in magnets—the "High strength" variant of the CT-OP wire was used in the test. From each tape a pair of one layer test coils of 90 mm diameter was prepared. As a reference, one test coil of the pairs was characterized before the test in self-field at 4.2 K in our facility JUMBO (see [1]). Afterwards the four samples were mounted in MTA I, cooled down in a controlled way, stored in a superfluid helium bath at temperatures near T_λ for about 150 hours, and finally warmed up in a well-defined process. The temperature was controlled by several probes. The dwell time of the samples in the helium bath was chosen preferably long to allow the potential penetration of superfluid helium. After the test the four samples were characterized in JUMBO in external fields, B, up to 10 T, by measuring the voltage-current characteristics, $U(I)$, at 4.2 K under steady-state conditions using a high resolution four-point measurement technique.

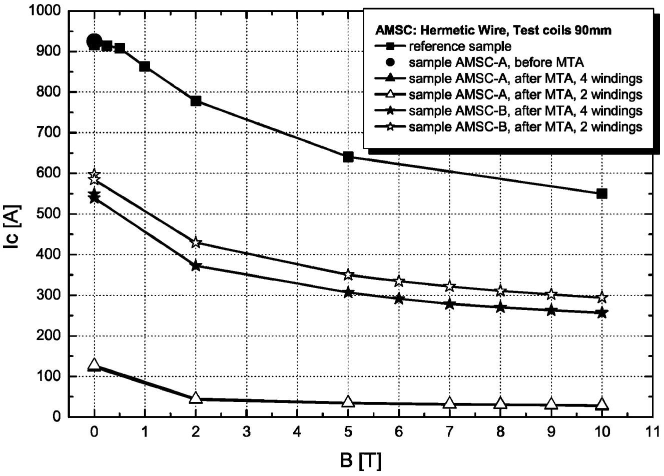

Fig. 3. Reference sample of AMSC Hermetic Wire not exposed to He II (■) and test coils before (●) and after (▲, ⋆) long-term storage in He II near T_λ for 150 hours. I_c of the Hermetic Wire degrades when stored in superfluid helium.

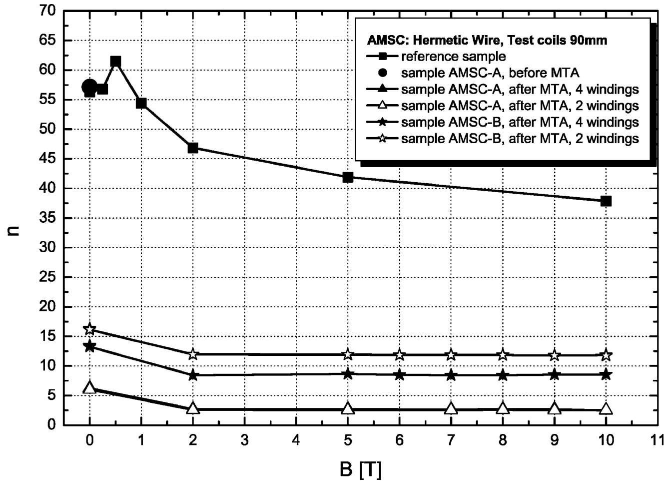

Fig. 4. Reference sample of AMSC Hermetic Wire not exposed to He II(■) and test coils before (●) and after (▲, ⋆) long-term storage in He II near T_λ for 150 hours. The n-value of the Hermetic Wire degrades when stored in superfluid helium.

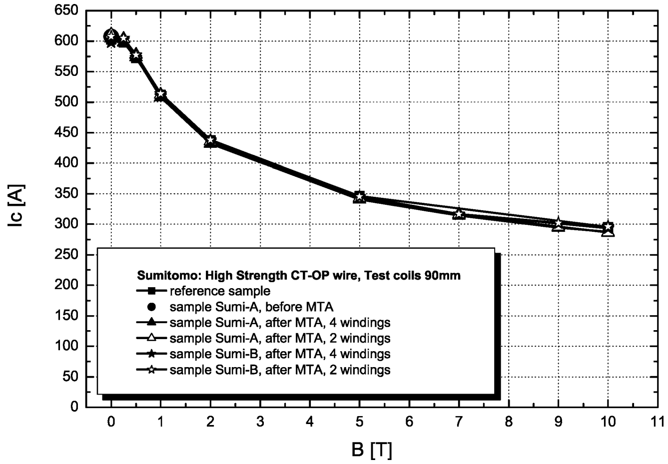

Fig. 5. The investigated samples of the Sumitomo High Strength CT-OP wire show no degradation after storing for 150 hours in superfluid helium near T_λ as the critical current data measured for the reference sample not exposed to He II (■) and the test coils before (●) and after (▲, ⋆) the long-term test in MTA I are identical.

As occurs in a magnet, the characterization was performed under hoop stress, i.e. in parallel orientation of self-field and background field. For details concerning the measurements and their analysis, see [11].

C. Results

As a result of the characterization in JUMBO one gets the voltage-current relation $U(I)$. To compare different samples with different measuring lengths, l, one has to build the quotient $\bar{E}(I) = U(I)/l$. As samples may degrade inhomogeneously, the calculated electrical field, $\bar{E}$, is an average value as indicated by the bar. Fitting the power law $\bar{E}(I) = E_c(I/I_c)^n$ to the experimental data gives the critical current I_c and the n-value for a given E_c-criterion. In this paper we define $E_c \equiv 10^{-7}\ \mathrm{V/cm}$.

Fig. 3 shows the critical current data measured for the two test coils made of AMSC Hermetic Wire after the long-term test in MTA I (▲: sample AMSC-A, ⋆: sample AMSCB). The closed symbols indicate the voltage drop along the four innermost windings; the open symbols along the two innermost windings. For comparison the data for a AMSC test coil not exposed to He II is shown (■). In addition, the reference value measured for sample AMSC-A in self- field before the test in MTA I is included (●). The data show a strong degradation of the AMSC Hermetic Wire after the storage in superfluid helium near T_λ for 150 hours. In detail, the drop of I_c for sample AMSC-A is larger than that for the sample AMSC-B, while the latter shows an inhomogeneous degradation—in contrast to the first (▲ and △ are identical). As the I_c-value in self-field of sample AMSC-A is identical to that for the reference sample one can conclude that the sample was intact before the test in MTA I. The n-values shown in Fig. 4 confirm these results.

In contrast to the Hermetic Wire from AMSC, the investigated samples of the High Strength CT-OP wire of Sumitomo were not affected by superfluid helium near T_λ in our 150 hour long-term test. As shown in Fig. 5, the critical current data for the two samples Sumi-A (▲) and Sumi-B (⋆) stored in superfluid helium is identical to the values measured for a reference sample (■) not exposed to He II. The n-values of the three samples—which are in the range of ≈45 at 10 T to ≈75 in self-field (not shown)—confirm these results as they are identical, too. Apparently, the densification of the grain structure in the Bi-2223 filaments due to the CT-OP process seems to be an appropriate way to avoid the degradation of the tapes when stored in superfluid helium near T_λ.

IV. ANALYSIS OF $\bar{E}(I)$-CURVES

When analyzing a $\bar{E}(I)$-curve, the characteristic data I_c and n are usually derived. The critical current I_c is defined by a given E_c-criterion (e.g. $10^{-7}\ \mathrm{V/cm}$) and the n-value is evaluated as slope of the straight line fitted to the log-log-plot of the experimental data for a given interval (e.g. $10^{-8}\ \mathrm{V/cm}$ to $10^{-7}\ \mathrm{V/cm}$). As already mentioned, $\bar{E}(I)$ is in general an average value disregarding local effects. When interpreting the $\bar{E}(I)$-curves of (degraded) Bi-2223 tapes the question arises of

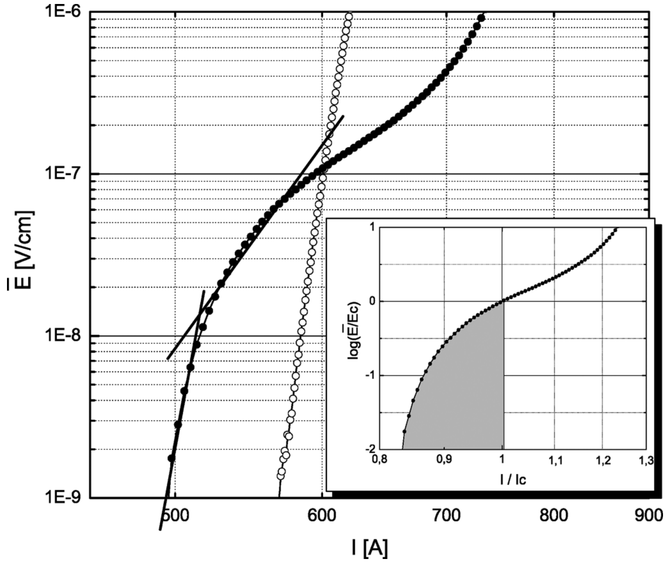

Fig. 6. Log-log-plot of the $\bar{E}(I)$-curve of a degraded Bi-2223 wire (•). The slope of the fitted straight lines as a measure for the n-value depends crucial on the fitting interval. The inset shows the double-normalized "$\log(\bar{E}(I)/E_c)$ versus logarithmical scaled (I/I_c)"-curve used for the calculation of the Q-value. For comparison, the $\bar{E}(I)$-curve of a non-degraded Bi-2223 wire is included (o).

whether I_c and especially the n-value are appropriate variables to cover the behavior of the wires.

Fig. 6 shows as example the log-log-plot of the $\bar{E}(I)$-curve of a degraded Bi-HTS wire (•). Obviously, a straight line does not describe the behavior of the wire. Nevertheless, if one fits a straight line to the data, it depends crucial on the fitting interval which slope (i.e. n-value) one gets. The resulting n-values differ by more than a factor of 2. Therefore, the n-value is an inadequate variable to describe this $\bar{E}(I)$-curve. In consequence, we suggest applying an integral method to evaluate $\bar{E}(I)$-curves in addition to the differential variable n. In detail, we suggest evaluating the area, Q, under the $\bar{E}(I)$-curve.

With Q given as

$$Q \sim \int \bar{E}(I)\mathrm{d}I, \qquad (2)$$

Q is a measure for the power dissipation and therefore a useful classification for superconducting transitions. In principle, the sharper the transition the lower the Q-value and with it the dissipated power. Regarding the application of a wire for NMR-magnets, low dissipation is equivalent to a small drift of a magnet.

To get standardized Q-values, the area under the double-normalized "$\log(\bar{E}(I)/E_c)$ versus logarithmical scaled (I/I_c)"-curve is evaluated, as shown in the inset of Fig. 6. The integration limits are defined implicitly by given $\log(\bar{E}(I)/E_c)$-values (here: -2 to 0). Due to the normalization, data of different wires with different I_c-values are comparable.

For a perfect power law behavior of the $\bar{E}(I)$-curve there exists a correlation between Q and n. It can be easily shown that the triangle area under the log-log-plot is proportional to the reciprocal value of n : $Q \propto 1/n$.

With the introduced integral variable, Q, the development of a wide (or the whole) range of the $\bar{E}(I)$-curve is taken into account, improving the significance compared with the n-value. As a result, future experiments will be analysed by evaluating the Q-value in addition to I_c and n.

V. CONCLUSION

In order to raise the magnetic field of the high field facility HOMER II up to 25 T, a first prototype of an HTS insert coil consisting of 16 stacked double pancakes was designed, constructed and tested. The HTS insert produced a magnetic field of 5.4 T in a background of 11.5 T provided by our facility HOMER I, resulting in a total magnetic field of 16.9 T. All test runs were carried out without any incidents but after warming up, ballooning of the tape was observed in several double pancakes, due to the penetration of superfluid helium. This cause was confirmed by a long-term test exposing AMSC Hermetic Wire to superfluid helium near T_λ for 150 hours. In contrast, by showing no degradation, the investigated samples of Sumitomo high strength CT-OP wire were not affected by He II in the long-term test. Future experiments have to confirm the resistivity of the CT-OP wire against He II. It was shown, that the n-value, which is a differential variable, is not adequate to describe in general degraded $\bar{E}(I)$-curves. In consequence, we suggest in addition an integral method. With the introduced integral variable, Q, the development of a wide (or the whole) range of the $\bar{E}(I)$-curve is taken into account improving the significance compared with the n-value.

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