Manufacture and Test of a 5 T Bi-2223 Insert Coil

M. Beckenbach, F. Hornung, M. Kläser, P. Leys, B. Lott, and Th. Schneider

***Abstract*—With the goal of obtaining a magnetic field of 25 T in our facility HOMER II with a superconducting LTS-HTS hybrid magnet, a first prototype 5 T high temperature superconducting (HTS) insert coil has been constructed and tested. The HTS insert consists of 16 double pancakes made of stainless steel reinforced Bi-2223 tapes manufactured by American Superconductor. The HTS coil was operated at 1.8 K and produced 5.4 T at a current of 151.2 A. In a background field of 11.5 T provided by our facility HOMER I, a total field of 16.9 T was obtained several times. No training or quench of the coil was observed during the test, but after warming up a defect in the winding of one double pancake was detected, presumably due to a ballooning of the tape. The design of the coil and the results of the test are presented and discussed.**

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

I. INTRODUCTION

HE generation of high magnetic fields is one of the most important applications of superconductors. Magnetic fields above 20 T can be obtained by superconducting magnets without the massive heat production occurring in magnets made of normal conducting materials, 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 excellent temporal stability of the magnetic field can be obtained. Therefore superconducting magnets have a wide range of applications: From accelerators, detectors, fusion magnets, high field experimental facilities, etc. to magnetic resonance imaging (MRI), and nuclear magnetic resonance spectroscopy (NMR).

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 experimental high field facility HOMER II. Details of the design, manufacture, and test run of the insert are presented and discussed.

II. THE FACILITY HOMER II

The latest experimental facility of the High Field Laboratory of the Institute for Technical Physics is HOMER II. Its basic magnet configuration is made of low temperature superconductors (LTS)—NbTi as well as ternary/quaternary $\mathrm{Nb_3Sn}$—and is designed to produce a magnetic field of 20 T in a bore of 180 mm at a helium bath temperature of 1.8 K. After reworking the high-voltage stability of the magnet and the cryostat, the basic configuration is now ready to be tested.

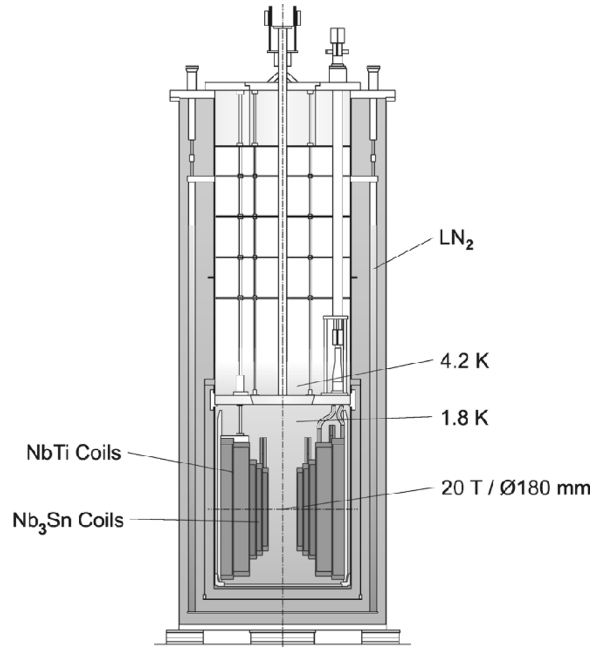

Fig. 1. Schematic drawing of the cryostat and the basic magnet configuration of the HOMER II test facility.

More details about HOMER II is found in [1] and [2]. A cross sectional view of the cryostat and the basic configuration of HOMER II is given in Fig. 1.

In a second stage, it is planned to upgrade the magnet system of HOMER II by adding an insert coil to reach fields up to 24/25 T in a bore of 50 mm at 1.8 K. From a materials point of view, this field can be reached by both superconductor types, LTS and HTS. As it can be seen e.g. in [3] and [4] advanced $\mathrm{Nb_3Sn}$ is able to produce 24 T and HTS 25 T, respectively. Considering the promising perspective of HTS for future projects to reach fields even above 25 T, our first prototype was manufactured using Bi-2223 tapes.

III. 5 T HTS INSERT COIL

A. *Bi-2223 Tapes Used for HOMER II Insert Coil*

To build up an HTS insert coil consisting of stacked double pancakes, 16 Bi-2223 tapes were purchased from American Superconductor (AMSC). Due to the reinforcement by two layers of stainless steel soldered on both sides, the AMSC tapes used provide a unique combination of properties: High critical currents and high n-values associated with a high tensile strength to withstand the hoop stress occurring in a magnet without degradation of the superconducting properties. A detailed study of the physical properties and the suitability of the AMSC tapes for high field insert magnets is given in [5]. More information

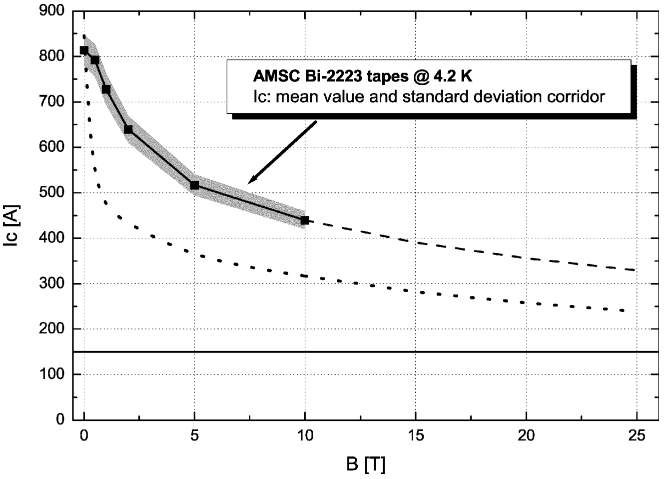

Fig. 2. Upper curve: mean value and standard deviation corridor of $I_c(B)$ measured at 4.2 K for the 16 AMSC Bi-2223 tapes used for the HTS insert coil. The extrapolation of the data up to 25 T is indicated by the dashed line. Lower curve: extrapolated $I_c(B)$ data measured for a comparable AMSC tape in perpendicular field orientation [5]. Both curves lie well above the rated current of 150 A for the HTS insert.

about the specifications of the wire is found in [6]. In the following we report on the acceptance tests carried out for the 16 purchased tapes.

From each tape reel, a one layer test coil of 90 mm diameter was constructed and tested in our facility JUMBO [1]. For different values of the external magnetic field, B, up to 10 T, the voltage-current characteristics were measured at 4.2 K under steady-state conditions for all 16 samples using a high resolution four-point measurement technique. As occurs in a magnet, the tests were performed under hoop stress, i.e. in parallel orientation of self-field and background field. For details concerning the measurements and their analysis, see [7].

As a result of the acceptance tests, the mean value and the standard deviation of the obtained 16 $I_c(B)$ curves are shown in Fig. 2. Using a power law fit for the voltage-current relation the exponent n as a measure for the steepness of the superconducting/normalconducting transition is also obtained. Fig. 3 shows the mean value and standard deviation of the 16 $n(B)$ curves.

In conjunction with our results obtained in earlier investigations of the AMSC wire (see [2], [5], and [7]) following can be stated.

- The critical current of all 16 tapes is high enough to reach the aimed field. The extrapolation of the flat running $I_c(B)$ curves to the desired field of 25 T yields critical currents well above the rated current of 150 A for our stacked double pancake configuration (see Fig. 2).
- The anisotropic $I_c(B)$-behavior with respect to the magnetic field direction of the Bi-2223 tapes in conjunction with the occurring radial field component oriented perpendicular to the tape does not limit the aimed field (Fig. 2).
- There is no degradation of the superconducting properties of the reinforced AMSC tape at winding diameters of 60 mm as required by the double pancake insert.

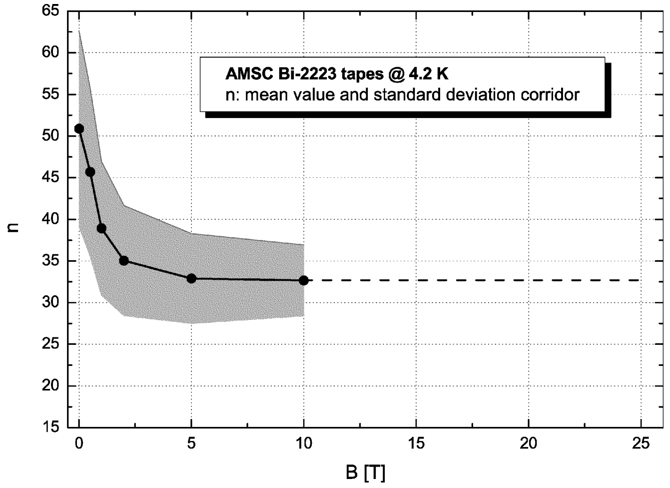

Fig. 3. Mean value and standard deviation corridor of $n(B)$ measured at 4.2 K for the 16 AMSC Bi-2223 tapes used for the HTS insert coil. The extrapolation of the data up to 25 T is indicated by the dashed line.

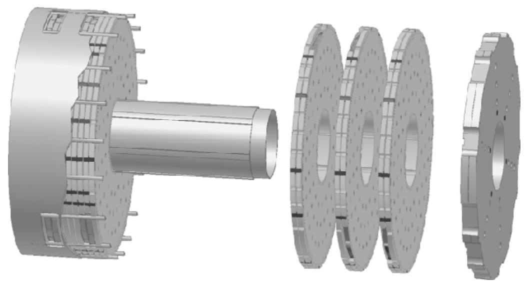

Fig. 4. Schematic drawing of the stacking of the double pancakes showing the core retainer, some of the double pancakes, the flange (on the right), the jacket tube (on the left), and some of the copper joints (at the openings of the jacket tube).

- The specification by AMSC of 265 MPa for the maximum stress applicable to the tape without degradation is well above the hoop stress that occurs in the stacked double pancake insert.
- The measured n-values above 30 reflect the good quality and homogeneity of the tapes.

B. Design of the Insert Coil

With regard 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 the reinforced AMSC Bi-2223 tapes. A Kapton foil was co-wound as electrical insulation. The two windings of each double pancake and the double pancakes among themselves were electrically separated by disks of G10. After construction, the double pancakes were stacked up on a core retainer made of stainless steel and connected by joints made of copper as sketched in Fig. 4. The double pancakes wound with the tapes with the lowest $n(B)$ values were arranged at the ends of the coil, where the field is lower. Compared with a single pancake layout, the number of normal conducting joints is halved by using double pancakes, thus reducing the dissipation of the insert coil. To control the operation of the insert magnet and for quench detection, voltage taps were soldered on each double pancake and on the terminals of the

TABLE I
SPECIFICATIONS OF THE FABRICATED HTS INSERT COIL

HTS material	reinforced Bi-2223 tape by AMSC
design	16 double pancakes
technique	react & wind
height incl. flanges	177 mm
free bore	50 mm
outer diameter incl. jacket tube	185 mm
number of turns	5402
coil constant	35.41 mT/A

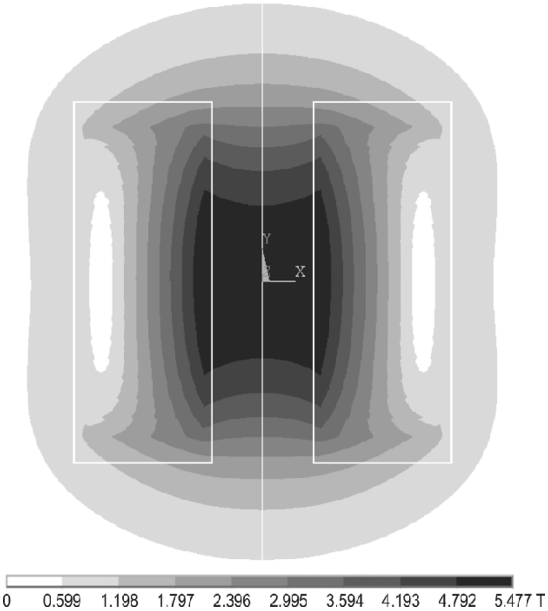

Fig. 5. Norm of the magnetic field distribution of the HTS insert calculated for a current of 151.2 A. The maximum field on the symmetry axis is 5.4 T; the overall maximum 5.5 T. The total dimensions of the magnet are indicated by white outlines.

magnet. After the assembly, the insert magnet was grouted and enclosed by a jacket tube made of G10. To optimize the cooling, openings were placed in the jacket tube at the positions of the copper joints.

Table I summarizes the main specifications and geometric parameters of the fabricated insert coil. The calculated field distribution of the magnet is given in Fig. 5. A photograph of the HTS insert directly before its test is shown in Fig. 6.

IV. RESULTS AND DISCUSSION

The test of the fabricated insert coil was carried out in our superconducting magnet facility HOMER I which is described in detail in [1]. By removing the $\mathrm{Nb_3Sn}$ sections from the inner cryostat, a sufficiently large bore of 259 mm diameter was provided to house the HTS magnet as shown in Fig. 7. The remaining NbTi sections of HOMER I are able to produce a background field of up to 11.5 T at a helium bath temperature of 1.8 K. During the test the voltage drops of all double pancakes as well as of the whole insert magnet were measured and recorded to control the operation of the magnet and for quench detection. Additionally several temperature probes were installed. The magnetic field in the bore of the HTS insert was detected independently by a pick-up coil and a Hall probe. All measurements were performed at a temperature of 1.8 K of the helium baths of the NbTi section and the HTS coil in the inner cryostat.

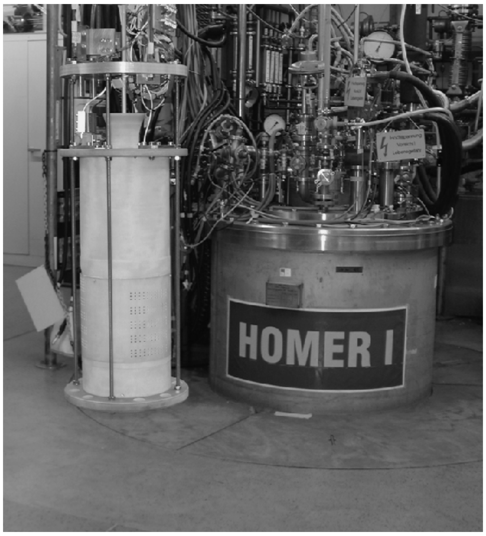

Fig. 6. Insert carrying the HTS coil before being tested in HOMER I.

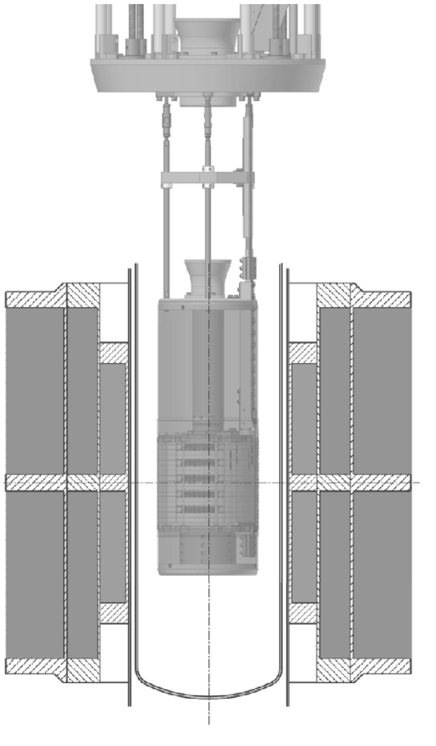

Fig. 7. Schematic drawing of the NbTi magnet section and the inner cryostat of HOMER I together with the insert carrying the HTS coil.

- *1st test run*: In the first test run the HTS insert was operated without background field, i.e. the coil was only exposed to its self-field. After cooling down the insert to 1.8 K the coil current was increased by steps of 30 A from 0 A up to 150 A. After each current step a dwell time of several minutes was waited. The voltage drops across the double pancakes and the temperatures of the coil showed no irregularities.

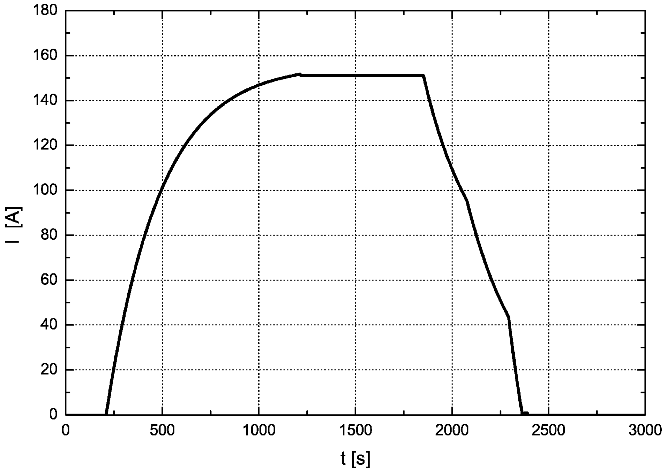

Fig. 8. Excitation of the HTS insert at the highest applied background field of 11.5 T. The maximum of 151.2 A was held nearly 700 seconds and leads to an additional field contribution of 5.4 T.

- *2nd test run*: In the second test run, after cooling down to 1.8 K the procedure of the first test run was repeated in background fields provided by HOMER I. The field was increased stepwise to 1, 3, 5, 7, 9, and 11.5 T. For each specified background field the coil current was increased from 0 A to 150 A, usually in steps of 30 A with dwell times of several minutes. After reaching and holding the maximal value, the coil current was decreased to 0 A. Subsequently the background field was increased to the next value. The highest total field and the highest Lorentz forces were reached several times in the background field of 11.5 T at a precise coil current of 151.2 A. This current is correlated with a contribution to the field of 5.4 T in the center of the HTS insert (see Fig. 5) leading to a total field of 16.9 T. The longest dwell time at this maximum field was nearly 700 seconds (see Fig. 8). Again, no irregularities, training, quenches, or degradation of the insert coil were observed during the whole test.
- *3rd test run*: In the third test run, the long-term stability of the HTS insert was checked. At 1.8 K and a background field of 11.5 T the current of the insert was increased stepwise up to 142.2 A corresponding to a field contribution of 5.0 T. The resulting total field of 16.5 T was held for one hour. Again, no quench, degradation or any other incidents occurred.

After warming up and demounting of the HTS insert irregularities in the jacket tube made of G10 were visible. At some positions the surface of the tube was uneven. To confirm the operating capability of the coil, another test run was made in HOMER I. It appeared, that one double pancake was defective due to a short circuit. The disassembling of the HTS insert showed that there was a ballooning of the tape in several double pancakes probably caused by the penetration of helium into the tape. As this problem has never been observed before in our tests of the tape at 4.2 K, the superfluidity of the helium at the operating temperature of the HTS insert of 1.8 K might be the reason for the penetration. Currently this explanation is under investigation.

Meanwhile for possible future projects for an HTS insert coil a promising variant of the Bi-2223 tape offered by AMSC exists: the so-called ‘Hermetic Wire’ [6]. In addition to its reinforcement by the two layers of stainless steel, the Hermetic Wire is 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 and with it the ballooning will be investigated before a possible second project for developing an HTS insert is begun.

V. CONCLUSION

In order to raise the magnetic field of our facility HOMER II from 20 T to 25 T, a first prototype of an HTS insert coil consisting of 16 stacked double pancakes was designed, constructed, and tested. Combining high tensile strength with high critical currents and high n-values, reinforced Bi-2223 HTS tapes manufactured by AMSC were used for winding the double pancakes in react-and-wind technique. The HTS 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 magnet field of 16.9 T. All test runs were carried out without any incidents—no quenches or degradation of the magnet occurred. After warming up, ballooning of the tape was observed in several double pancakes, presumably due to the penetration of superfluid helium. To cope with this problem, the applicability of the sealed ‘Hermetic Wire’ fabricated by AMSC for future HTS inserts will be investigated.

REFERENCES

[1] A. Rimikis, F. Hornung, and T. Schneider, *IEEE Trans. Appl. Supercond.*, vol. 10, pp. 1542–1545, 2000.
[2] F. Hornung, A. Rimikis, R. Kimmich, and T. Schneider, *IEEE Trans. Appl. Supercond.*, vol. 11, pp. 2304–2307, 2001.
[3] J. A. Parrell, Y. Zhang, M. B. Field, P. Cisek, and S. Hong, *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 3470–3473, 2003.
[4] H. W. Weijers, B. ten Haken, H. H. J. ten Kate, and J. Schwartz, *IEEE Trans. Appl. Supercond.*, vol. 11, pp. 3956–3959, 2001.
[5] F. Hornung, M. Kläser, and T. Schneider, *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 1102–1105, 2004.
[6] American Superconductor. (2004). [Online]. Available: www.amsuper.com
[7] F. Hornung, M. Kläser, H. Leibrock, H. Müller, and T. Schneider, *Physica C*, vol. 401, pp. 218–221, 2004.