Future Upgrade of the Superconducting High Field Facility HOMER II to 25 T

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***Abstract*—In 2006, the superconducting high field facility HOMER II of the Karlsruhe Institute of Technology was commissioned. It provides a magnetic field of 20 T in a large bore of 185-mm diameter, using a coil system with sections made of NbTi and $(NbX)_3Sn$ wires. With regard to the increasing availability of high-quality second-generation high temperature superconductors (2G-HTS) in longer lengths, in 2014, the project for an intended upgrade of HOMER II to a total field of 25 T has been started. The objective is to build up a 5-T insert made of REBCO HTS to be operated routinely in the background of 20 T produced by the basic magnet configuration of HOMER II. In this paper, we report on the schedule of the project, the preliminary design of the HTS-insert, and the requirements for the HTS wire. Furthermore, the results of the preparatory operation of small solenoid HTS coils in the 20-T background field are presented.**

***Index Terms*—Double pancake coil, high field magnets, high-temperature superconductors (HTSs), insert coils, solenoids, superconducting magnets.**

I. Introduction

MAGNETS are certainly the most important application for technical superconductors with a considerable wide scope: experimental superconducting magnet facilities, magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), accelerators, future fusion machines, etc. Superconducting magnets are the basis of these technologies and therefore the basis for the outstanding results in fundamental and applied research achieved by them.

Until now, low-temperature superconductors (LTS) have been used to build superconducting magnets for routinely operated facilities. Regarding superconducting high field and NMR magnets, the physical limit of LTS, given by their upper critical field, B_{c2}, has been reached: fields above approximately 25 T cannot be achieved by LTS materials—high temperature superconductors (HTS) have to be used [1]–[6].

For more than 30 years the high magnetic field laboratory of the Institute for Technical Physics (ITEP) at Karlsruhe Institute of Technology (KIT) has been developing superconducting high field magnets for high resolution NMR spectrometers and for the experimental facilities of the high field laboratory. Currently, we are working on the first stage upgrade of the experimental facility HOMER II from 20 T to 25 T. To obtain this high field, it is intended to use an insert coil made of 2G-HTS.

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In this paper, we report on the upgrade of HOMER II. After a short presentation of the facility, the experience gained from a first prototype of a 5-T insert constructed of 1G-HTS is summarized. Subsequently the preliminary design, schedule and requirements for the 2G-HTS of the new projected insert will be discussed. Finally, the results of the operation of a 1-T 2G-HTS solenoid in a background field of 20 T are presented.

II. Superconducting High Field Facility HOMER II

HOMER II is the most advanced facility in the high field laboratory of the ITEP. Its basic magnet configuration consists of two coil sections made of NbTi and three inner sections consisting of ternary/quaternary $(NbX)_3Sn$. The magnet is bath-cooled in liquid helium and can be operated at 1.8 K, i.e., in superfluid helium (He II). The nominal field provided by this basic configuration is 20 T at 1.8 K in a large bore of 185-mm diameter. The problem-free commissioning of HOMER II succeeded in 2006. Further details of HOMER II can be found in [7]. A cross sectional view of the cryostat and the basic magnet configuration of HOMER II is shown in Fig. 1.

III. Upgrade of HOMER II to 25 T

From the beginning of the design phase of HOMER II it was an objective to upgrade the basic LTS magnet configuration with its large bore by adding an HTS insert at a future point to get a total field of 25 T. The intention of this upgrade is explicitly not to achieve a magnetic field as high as possible, but to build up a reliable facility for stable regular operation—like the other high field facilities in our laboratory [7]—with a useful bore of 50-mm diameter.

A. *First Prototype 5-T HTS Insert*

In parallel with the construction of HOMER II, a prototype of a 5-T HTS insert was developed. As 2G-HTS were not commercially available at that time, Bi-2223 1G-HTS tapes were used for the insert. Due to the limited HTS piece length deliverable, a stack of 16 double pancakes with a bore of 50-mm diameter was chosen as the layout. The insert was tested in our superconducting high field facility HOMER I and produced a field contribution of 5.4 T in a background of 11.5 T, i.e., a total field of 16.9 T was achieved. In conditions corresponding to those in HOMER II, the test was carried out in a He II-bath temperature of 1.8 K. No problems occurred

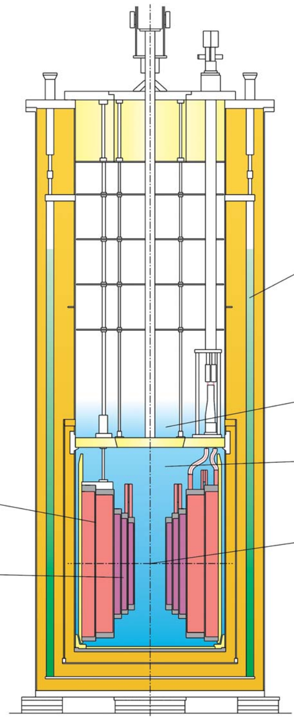

Fig. 1. Cross-sectional view of HOMER II illustrating the cryostat and the basic magnet configuration made of LTS.

during the operation of the insert. But after warming up and dismounting of the insert, ballooning of the HTS in several double pancakes was observed caused by the penetration of the superfluid helium into the voids of the Bi-2223 filaments. More information about the insert and the testing can be found in [8] and [9].

B. Design for 5-T HTS Insert Made of 2G-HTS

Based on the experience gained by the manufacture and operation of the first prototype HTS insert, the second 5-T coil for the upgrade of HOMER II is currently under construction. Due to their increasing availability and gradually improved low-temperature high field properties, 2G-HTS REBCO-tapes were selected as the superconducting material. As the maximum deliverable piece length of 2G-HTS without splices is still limited and the price for longer lengths of the wire rises disproportionately with piece length, a double pancake layout similar to the first prototype was chosen for the insert—this time with two nested coil sections as an improvement.

Overall, the insert consists of two electrically series connected stacks of 17 inner and 24 outer double pancakes with equal construction but different dimensions. The double pancakes of each stack are piled up on reception tubes made of stainless steel. The two windings of each double pancake as well as within the doubles pancakes themselves are separated by disks of G10. Based on the positive experience gained by our prototype insert, solid joints made of copper which are able to sustain the Lorentz forces arising are used for the electrical connection of adjacent double pancakes. For monitoring during operation and for quench detection, voltage taps will be soldered at each double pancake and at the terminals of each stack.

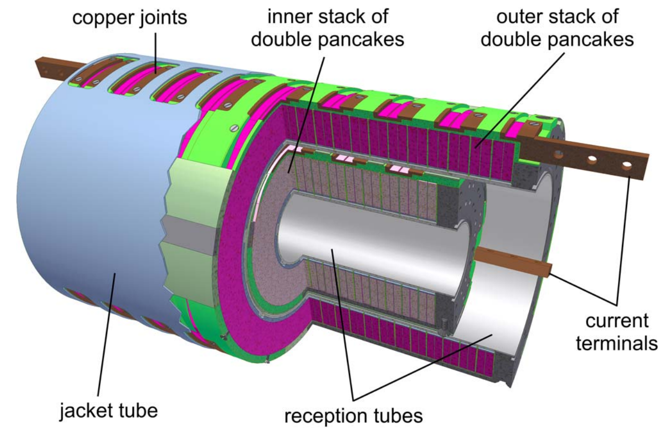

Fig. 2. Schematic drawing of the 2G-HTS insert for HOMER II, showing the two nested stacks of double pancakes, the current terminals, the jacket tube (left), and some of the copper joints located at the openings of the jacket tube.

TABLE I
PROPERTIES OF THE 2G-HTS 5-T HOMER II INSERT

design	2 nested stacks of double pancakes made of 4-5 mm wide 2G-HTS
inner double pancake stack	17 double pancakes total no. of turns: 17 x 2 x 91 = 3094 total HTS length: 802 m free bore diameter: 50 mm total outer diameter: 119 mm height incl. flanges: 215 mm field contribution: 2.7 T
outer double pancake stack	24 double pancakes total no. of turns: 24 x 2 x 81 = 3888 total HTS length: 1840 m free bore diameter: 121 mm total outer diameter: 184 mm height incl. flanges: 294 mm field contribution: 2.3 T
rated current for 5 T	145 A

After assembling, each double pancake stack will be encased by a jacket tube made of G10 and potted. For better cooling, openings in the jacket tubes are envisaged at the locations of the joints. In Fig. 2 a schematic drawing of the structure of the insert magnet is shown.

The dimensions of the insert and the subdivision into two sections were optimized with respect to conductor costs, field angle relative to HTS surface at the coil ends and uniformity of the field. In total, the configured insert consists of 2642 m 2G-HTS. The nominal field contribution of 5 T will be provided at a rated current of 145 A. The properties of the insert design are summarized in Table I. Fig. 3 shows the self-field distribution of the coil. Together with the HOMER II basic configuration a total field of 25 T is envisaged in a free bore of 50 mm produced by a pure superconducting magnet system. The radial development of the maximum magnitude of the magnetic field, $|B|_{\max} = (B^2_{\text{radial}} + B^2_{\text{axial}})^{1/2}_{\max}$, is illustrated in Fig. 4.

In principle, the presented design for the insert is independent of the 2G-HTS. Of course, the wire has to provide a sufficiently high current carrying capacity at 25 T. With respect to high field applications, REBCO HTS with substrates made of Hastelloy or stainless steel are advantageous due to their high tensile strength. For this project commercially available wires

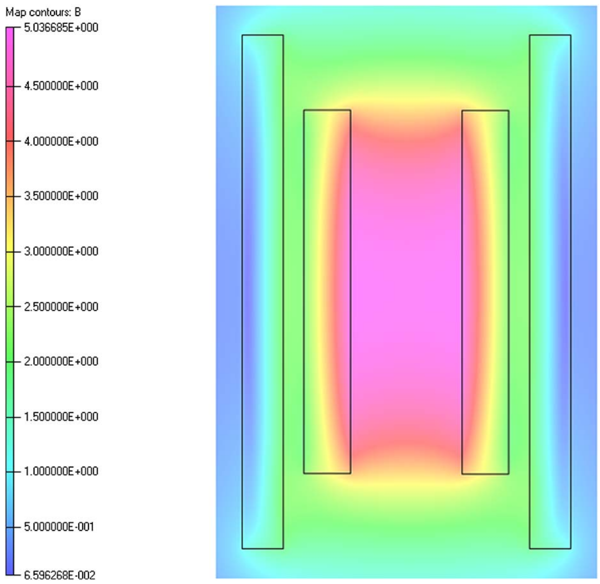

Fig. 3. Cross-sectional plane of the self-field distribution at nominal current of the 2G-HTS 5-T insert coil. The winding packs of the two nested stacks of double pancakes are indicated schematically.

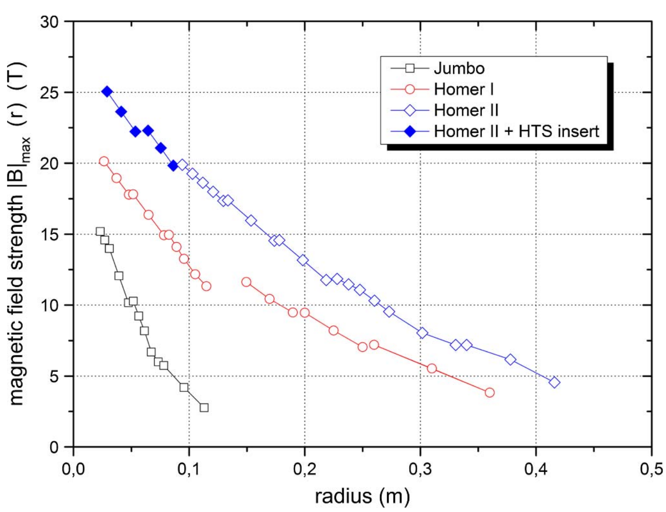

Fig. 4. Upper curve: Radial development of the maximum magnitude of the magnetic field, $|B|_{\max}$, of HOMER II. Superposition of the field produced by the basic LTS magnet configuration (open diamonds) and the contribution of the 2G-HTS insert (closed diamonds). In addition, the field data of the other superconducting high field facilities of the high field laboratory at KIT—JUMBO and HOMER I—are shown [7].

designed for in-field applications from all manufacturers were characterized in detail at 1.8 K/2.2 K/4.2 K in fields up to 20 T. In addition, the angular dependence of the critical current, $I_c(B, \Theta)$, of the wires was investigated at 4.2 K in fields up to 10 T. Parts of these results can be found in [10] and [11]. By extrapolation of the measurement data it turned out that the existing wire generations of all major manufacturers comply with the required current.

Due to the degradation of our first insert made of Bi-2223 1G-HTS after operation in superfluid helium, the compatibility of the 2G-wires with He II was investigated extensively by a comprehensive test procedure. The results showed that the 2G-wires are compatible with superfluid helium. No ballooning or other degradation was observed in the experiments.

After the final selection, the wire for the 5-T insert will be ordered before the end of this year. The delivery is expected by mid-2015. The construction of the insert is scheduled for mid-2015 to mid-2016 and commissioning by the end of 2016.

It is well known that magnetization effects caused by induced screening currents can play an important role for 2G-HTS magnets due to the tape shape of the superconducting layer of the wire. As consequence, the real magnetic field of a magnet may differ from the calculated nominal field. Depending on coil geometry, a possible reduction of up to 18% of the central magnetic field of YBCO solenoids due to screening currents is reported in [12]. Therefore the insert itself is an object of investigation. The quantity of the field deviation, its development in time and its dependence on process of magnet charging are important issues to be addressed for the magnet.

IV. Manufacture and Test of a 1-T 2G-HTS Solenoid in 20-T Background Field

A. Design and Objectives

In order to gain experience in their manufacture and high field operation, several multilayered 2G-HTS solenoid coils have been wound and tested at $\leq$4.2 K in a 20-T background. The main interest of the investigations was the behavior of longer 2G-HTS lengths in high fields and the stability of the winding against Lorentz forces. In addition, the compatibility of the coils with He II was also examined.

The results for the largest coil of this series are presented in this paper. This coil was designed to produce 1 T in a background of 20 T. It consists of 92 turns overall wound in 11 layers on a bobbin made of G10 with an outer diameter of 48 mm. Due to its comparatively small dimensions, the coil was manufactured in a layer winding technique—and not using double pancakes. After winding, the coil was bandaged by glass silk tape and potted with epoxy resin. To control the operation, voltage taps were soldered to the current leads. For field measuring a Hall probe was placed in the center of the coil. In Fig. 5 a photograph of the 1-T 2G-HTS coil is shown.

B. Results of the 20-T High Field Test

After cooling down the helium bath—and thus the coil—to 1.8 K the background field was increased in steps from 5 T to 20 T. At each field, the current of the 1-T coil was increased stepwise to 525 A with a ramp rate of 1 A/s. This current corresponds to a field contribution of 1 T. After dwell times of approximately 30 s the coil was discharged at the same rate. The complete procedure was carried out without any problems; no quenches, etc. occurred. Fig. 6 shows the results measured for the highest background field of 20 T where a total field of 21 T was reached as confirmed by the Hall probe data.

As stated above, the high field testing was performed while cooling the coil in superfluid helium. After the test the coil was warmed up to $\approx$20 K and cooled down to 1.8 K again in order to check if substantial damage of the coil package occurred due to the Lorentz forces, or a ballooning of the wire due to the operation in superfluid helium. The curves obtained for currents up to 300 A showed no evidence for such fundamental

Fig. 5. Bandaged and potted 2G-HTS layer wound solenoid coil designed to produce 1 T in a background field of 20 T.

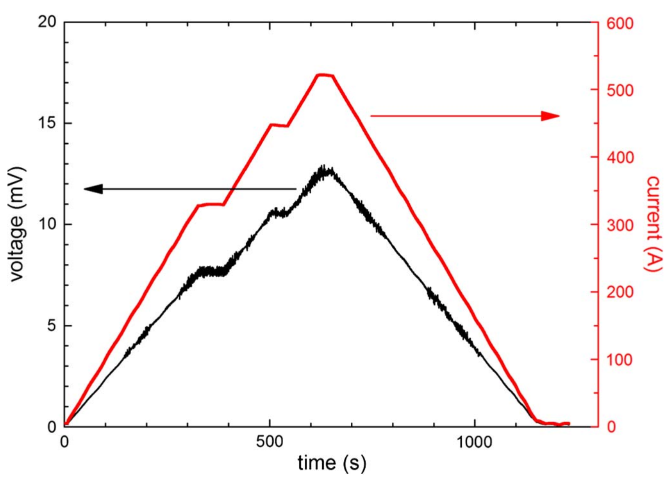

Fig. 6. Coil current (right) and voltage at the copper current leads (left) measured for the 1-T 2G-HTS coil in a background field of 20 T at 1.8 K. The maximum current of 525 A corresponds to a field contribution of 1 T, i.e., a total field of 21 T was reached without any problems.

damage of the coil. The crucial question of whether the critical current of the wire was affected as a result of the testing will be addressed in the following section.

C. Results of Self Field Test

After the high field testing, high current tests in self-field were performed at 1.8 K. At the maximum, the coil current was ramped up with a rate of 3 A/s to 993 A where the quench detection system of the coil switched off the current without degradation of the coil. 993 A corresponds to a center field of 1.9 T produced by the coil. Due to the angular dependence of the critical current of 2G-HTS, the current carrying capacity is limited by the coil ends where the largest angle between the self-field and the tape surface occurs. For our coil the calculated self-field angle at the coil ends is 82° and the corresponding radial field component on the tape at the switch off current is 1.6 T. On the other hand, short sample measurements of the used wire at 4.2 K in perpendicular field versus tape surface show critical currents of approximately 1100 A at 1.6 T with a variation of ±100 A for different samples due to the inhomogeneity of the HTS. At field angles near 90° the critical current is only weakly dependent on the angle [10], [11], thus the switch off current and the short sample value for perpendicular field at 1.6 T can be compared. In conclusion, the switch off current of 993 A reaches in effect the short sample value of the wire proving that the tape was not degraded by the superfluid helium or by the high field testing.

V. Conclusion

The upgrade of the superconducting high field facility HOMER II from 20 T to 25 T by a HTS insert coil is one of the major projects of the high field laboratory at KIT. Based on the positive experience gained from a first prototype, a double pancake design consisting of two nested stacks with 17 inner and 24 outer double pancakes is chosen for the insert. The characterization of commercially available 2G-HTS shows that state of the art wires from all major manufacturers comply with the required current density. After the delivery of the wire, the construction of the insert is scheduled for mid-2015 to mid-2016 and the commissioning for the end of 2016. Within the test of a multilayered 2G-HTS solenoid coil at 1.8 K an add-on field of 1 T in 20 T background was produced without any problems. In self-field operation at 1.8 K the coil generated 1.9 T at a current of 993 A, i.e., the short sample value of the wire was virtually reached.

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