From Double-Pancake Coils to a Layer Wound 5 T *RE*BCO-HTS High Field Insert Coil Design

Frank Hornung, Matthias Eisele, Marion Klaeser, Pauline Leys, Claudia Ruf, and Theo Schneider

***Abstract*—The superconducting high field facility HOMER II of the Karlsruhe Institute of Technology (KIT) provides a magnetic field of 20 T in a large bore of 185 mm using solenoid magnet sections made of NbTi and $(NbX)_3Sn$ wires. One of the major goals of the high field laboratory at KIT is to upgrade this basic magnet configuration of HOMER II to achieve a total field of 25 T. Recently, a design for a 5 T insert has been proposed using *RE*BCO-HTS. The envisaged layout consists of two series-connected nested stacks of double pancakes. Meanwhile, the increased long-length availability of *RE*BCO-HTS makes a 5 T insert composed of layer wound solenoid sections an attractive option. In this paper, a design for such a layer wound 5 T insert for the HOMER II upgrade is presented. Furthermore, the manufacture and test of a prototype layer wound HTS section made of a 170 m length of *RE*BCO coated conductor tape is reported.**

***Index Terms*—High field magnets, high-temperature superconductors, insert coils, layer wound coils, superconducting magnets.**

I. Introduction

DESPITE the constantly increasing efforts and progress in areas such as energy applications, superconducting magnets are still by far the most important utilisation of superconducting materials. Energy efficient high field magnets for basic research, dipole magnets for accelerators, magnets for fusion machines, and - using superconducting joints - persistent mode operated solenoids delivering excellent field quality for magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) represent only a selection of the prominent achievements.

Naturally, the evolution of superconducting magnets is strongly linked to progress in the development of *technical* superconductors, i.e., strands and cables ready to be used for winding. For the metallic low temperature superconductors (LTS) the development is far advanced. The 1 GHz NMR-magnet is still a benchmark close to the limits of the LTS. It has been developed in a joint cooperation between our laboratory at the Karlsruhe Institute of Technology (KIT) and BRUKER BioSpin GmbH and produces a magnetic field of 23.5 T using sections made of NbTi and $(NbX)_3Sn$ [1]. In contrast, regarding the high temperature superconductors (HTS), it is still a challenge to provide HTS insert magnet sections to raise the field strength to the range of 25 T and above for routinely operated fully superconducting magnets. Some of the major ongoing and finished projects within that scope can be found in [2]–[5].

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In the high field laboratory of KIT the experimental superconducting high field facility HOMER II is able to generate 20 T in a large bore of 185 mm using a basic magnet configuration made of LTS [6]. The declared objective is to upgrade HOMER II for regular operation — in a first step — to at least 25 T provided in a cold free bore of 50 mm minimum. In this paper we summarize the efforts made in the past and present a design for a 5 T multi-sectional layer wound *RE*BCO-HTS insert magnet as well as the results of the testing of a prototype layer wound *RE*BCO-HTS section.

II. Retrospection: History of Efforts For THE HOMER II Upgrade

It was already intended in the design phase of HOMER II to upgrade the basic magnet configuration with its large bore of 185 mm in future by adding insert coils. The history of considered upgrades for HOMER II is longer than the period since commissioning the facility in 2006, and reflects the protracted evolution of technical HTS in the last one and a half decades.

A. 2004: Design, Construction and Test of a First 5 T 1G-HTS Double-Pancake Insert

In 2004, parallel to the construction of HOMER II, a first 5 T insert was designed and manufactured. As *RE*BCO 2nd generation (2G) HTS were not available on the market at that time, 1st generation (1G) Bi-2223 tapes were used. These multifilamentary and optionally twisted tapes with a stabilizing Ag or Ag-alloy matrix/sheath are produced in powder-in-tube technique and were already well advanced in 2004. Due to the limited available piece-length of the wires (at least at that time), a stack of 16 double-pancakes with a free bore of 50 mm was chosen as the design for the insert. As HOMER II was not commissioned in 2004, the test of the insert was carried out in the superconducting high field facility HOMER I of KIT [6] in superfluid helium (He II) bath. At a background field of 11.5 T an additional contribution of 5.4 T generated by the HTS insert could be obtained. The testing was successful without training of the insert, but after warming up ballooning of the tape due to the penetration of He II was observed [7], [8].

B. 2014: Design of a 5 T 2G-HTS Double Pancake Insert

Ten years after the testing of the Bi-2223 insert, the overall quality and low-temperature high-field performance of the

*RE*BCO coated conductors (CC) reached a sufficient level so that in 2014 a design for a 5 T insert for HOMER II using 2G-HTS was proposed [9]. In particular, the high tensile strength (for Hastelloy and stainless steel substrates) and the high overall critical current density make the 2G tapes attractive for high field applications. As the availability of long piece lengths ($>$ several 100 m) of 2G-HTS without splices is still limited, a double-pancake design with a free bore of 50 mm was considered in 2014–in accordance with the Bi-2223 insert. However, to optimize field uniformity for a given conductor budget, a subdivision into two nested stacks of double-pancakes was suggested as an improvement [9].

C. 2014: Construction and Test of Small Layer Wound 2G-HTS Solenoids

In view of the NMR application, layer wound high field insert coils are preferred over pancake windings. There are two main reasons: (1) A nearly perfect coil geometry is required to fulfill the spatial homogeneity specifications for NMR, and (2) the series of joints connecting the double pancakes in the high field region on the outer winding diameter is not acceptable. Therefore, to gain experience in the layer winding technique of 2G-HTS tapes, several multilayer 2G-HTS solenoids wound with Fujikura FYSC-SC05 tape were already constructed and tested in 2014. The tests were performed in HOMER I in superfluid helium bath and background fields of up to 20 T. Add-on fields of up to 1 T at 20 T were obtained without training or degradation of the 2G-HTS due to He II or other causes [9].

III. Design of a 5 T Layer Wound 2G-HTS Insert

Based on the successful operation of the small layer wound solenoids, the initial proposed double-pancake layout for the HOMER II insert was rethought and a layer wound design considered instead, dependent on the long length availability of 2G HTS on the market.

A. Procurement of 2G-HTS for Layer Wound Insert

For the selection of suitable conductors, commercially available 2G-HTS tapes from nearly all manufacturers were acquired and characterised in detail regarding:

1) In-field $I_c(B)$ measurements up to 20 T at 4.2 K and He II temperature ($<$ 2.2 K).
2) Investigation of the angular dependence of the critical current, $I_c(B, \theta)$, at 4.2 K up to 10 T as well as interpolation and extrapolation of the data up to 30 T.
3) Comprehensive examination of the compatibility of the 2G-HTS tapes with He II bath cooling regarding degradation and ballooning.

Part of the results obtained has been published in [10] and [11]. It turned out that the 2G-HTS of several major manufacturers fulfill the requirements with respect to critical current density and compatibility with superfluid helium. However only Fujikura was able to deliver the required total wire length and single piece lengths without any normal conducting splices.

In total, 2380 m of insulated FYSC-SC05 wire was ordered in nine pieces with piece lengths of up to 460 m. The wire was delivered by the end of 2014 just before the major revision of the production process at the Fujikura factory in Japan accompanied by a switch to a new wire architecture. The main data of this no longer available wire is given in Table I.

TABLE I
Fujikura Specifications of Delivered 2G-HTS FYSC-SC05 Tapes

Subject	Material	Dimension
total delivery	FYSC-SC05 2G-HTS	2380 m in 9 pieces w/o splices (160 m ≤ piece length ≤ 460 m)
tape width		5.0 mm w/o insulation ≤ 5.25 mm insulated
tape thickness		0.22 mm w/o insulation ≤ 0.29 mm insulated
insulation	polyimide tape	12.5 μm ×4
substrate	Hastelloy	100 μm
superconductor	GdBaCuO	2.4 μm–2.9 μm (variation over the pieces)
stabilisation	single-sided Cu lamination	100 μm
I_c @ 1 μV/ cm, 77 K, s.f.		minimum 255 A–352 A (variation over the pieces)

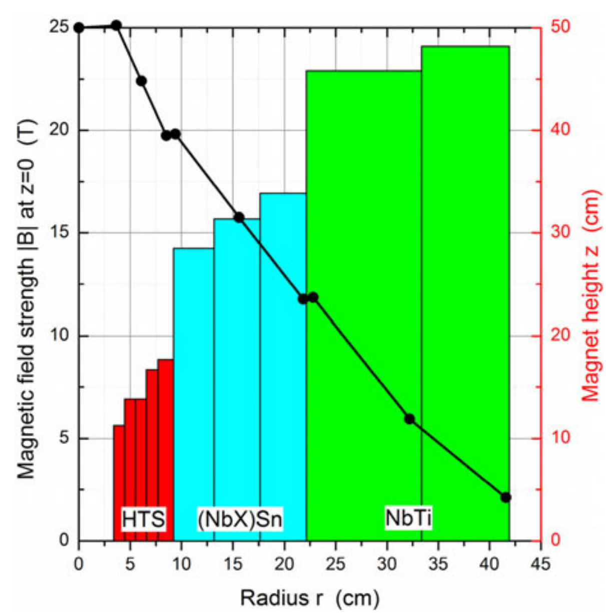

Fig. 1. Design for a 5 T insert coil composed of five nested electrically series connected layer wound coil sections (red) together with the basic magnet configuration of HOMER II consisting of three (NbX)Sn (cyan) and two NbTi sections (green) (illustration of one quadrant only). In total 25 T are provided (black line) in a free bore of 68 mm when cooling at 1.8 K.

B. Insert Consisting of 5 Nested Layer Wound 2G-HTS Sections

The design presented here for a layer wound 5 T insert is the result of an iterative optimization process considering the field homogeneity, the maximum available 2G-HTS piece lengths without splices, the total wire length, the utilization (I/I_c) of the tapes, and their price per meter — which approximately doubles for the longest available piece lengths.

On this basis, an insert design consisting of five nested layer wound sections is identified as shown in Fig. 1 and Table II. Six of the acquired 2G-HTS pieces will be used for winding; for the

TABLE II
2G-HTS 5 T INSERT: DOUBLE PANCAKE VS. LAYER WOUND DESIGN

Subject	Double Pancake Design [9]	Layer Wound Design
design	2 series connected nested stacks of 17 inner and 24 outer double pancakes	5 series connected nested layer wound coil sections
total outer diameter	184 mm	184 mm
cold free bore	50 mm	68 mm
total height	294 mm	364 mm
total no. of turns	6982	4125
total 2G-HTS length	2642 m	1670 m
rated current for 5 T	145 A	232 A
max. hoop stress ($B_z \times J \times r$)	228 MPa	365 MPa

outermost section two 320 m lengths will be jointed. In total, the insert will consist of 1670 m *RE*BCO wire. With a cold free bore of 68 mm an appreciable 25 T volume will be provided.

The nominal field contribution of 5 T is achieved at a rated current of 232 A. With an inductance of 710 mH the stored energy at nominal current is 19.1 kJ. Due to the relatively tall background coils of HOMER II, the maximum occurring field angle at the insert — defined as the angle between field vector and tape (or coil) surface — is only 5°. Thus, the coil current is estimated to be below ≈76% of the angular depended critical current of the lowest performing tape at operating conditions. The maximum occurring hoop stress of 365 MPa is also well below the destructive tensile stress value of >600 MPa measured by the manufacturer; consequently no additional reinforcement is included in the design.

Without reinforcement, the strain of the tape caused by the Lorentz force is given by its stress-strain relationship and reaches a maximum value of approximately 0.30% at the outer winding diameter. In contrast, the maximum bending strain occurs at the innermost layer with a value of approximately ±0.31% at the tape surfaces. Due to the equal thickness of the copper and substrate layers of the Fujikura FYSC-SC05 2G-HTS, the *RE*BCO layer is close to the neutral axis of the tape. The linear superposition of both strain effects results in a nearly constant total strain of about 0.44% at the outer tape surface, independent of the winding radius.

C. Comparison of Layer Wound and Double Pancake 2G-HTS Insert Design

Compared to the previous double pancake layout, the aspired to layer wound design is more challenging. The add-on field of 5 T is intended to be achieved in a larger bore of 68 mm (instead of 50 mm) using approximately 37% less superconductor. Therefore, the insert current — and with it the maximum hoop stress — is increased by 60% as shown in Table II. These enhancements are possible due to improved performance of the acquired wire.

When comparing the two designs, the electrical connection of the coil sub-units has to be considered. The layer wound coil has five inner connections, whereas the double pancake design shows 40 joints. Therefore, the energy dissipation caused by the resistive connections—and thus the heat load into the superfluid helium bath—is considerably higher for the double pancake design.

To connect double pancakes, the parallel aligned HTS tapes of two adjacent disks are soldered to a copper joint in the high field region at the outer winding diameter. To estimate the energy dissipation, several joints with different geometries and joint areas of up to 8.2 cm^2 have been prepared in a manner applicable in coil manufacturing practice and investigated in a helium bath at 4.2 K in magnetic fields of up to 10 T. The extrapolation of the joint resistance data to 22.3 T, i.e. the field strength at the outer winding diameter of the inner pancake stack, lead to a dissipation in the range of 2.3 mW to 50 mW for the different geometries and the rated coil current of 145 A (see Table II). Assuming a mean dissipation of 25 mW, the total heat production caused by the joints connecting the 40 double pancakes can be estimated to approximately 1 W, which is, in view of a long-run operation, a considerable drawback for the double pancake design.

IV. TEST OF A PROTOTYPE LAYER WOUND 2G-HTS SECTION

To validate the layer winding technique as well as the design and construction of the coil sections, a full-size prototype 2G-HTS layer wound section has been manufactured and tested. For this, a 170 m length of the acquired Fujikura FYSC-SC05 wire was wound in 18 layers each with 21 turns on a bobbin made of GRP with 137 mm diameter and a total length of 206 mm. For quench detection, a compensation winding made of enameled copper wire was placed around the outermost 2G-HTS layer for cancelling out inductive voltage contributions during testing using a bridge circuit. To address the risk of delamination of the 2G-HTS tape at the brittle *RE*BCO interlayer due to the high Lorentz forces occurring in high magnetic fields, firstly, the tape was wound with the supporting substrate orientated at the outer winding diameter. Secondly, for impregnation of the winding, weak bonding wax was used instead of adhesive epoxy resin to prevent adjacent layers sticking together. After impregnation, the section was bandaged with glass silk tape and the outer surface sealed with epoxy resin. A photo of the prototype layer wound 2G-HTS section is shown in Fig. 2.

The test of the prototype section was carried out in the 15 T configuration of the superconducting high field facility HOMER I [6]. For stepwise increased background fields from 2 T to 14 T the coil current was increased with sweep rates of up to 4 A/s gradually to 500 A for each field value. After reaching the maximum current and a holding time of approximately 1 min., the current was ramped down using the same sweep rate as for powering up. During the experiment the voltage across the copper terminals of the coil was recorded as well as the signals of a Hall probe and a pick-up coil for field measurement. For quench detection, the compensated coil voltage was detected. The above described measurement procedure was executed at a helium bath temperature of 4.2 K at first, and re-run afterwards at 1.8 K to check the compatibility of the coil with superfluid He II. Fig. 3 shows the measured coil voltage at $T = 1.8$ K for the maximum field of 14 T and the maximum current of 500 A ramped with ±4 A/s. The graph shows two runs for these parameters resulting in identical *V*(*I*) curves proving

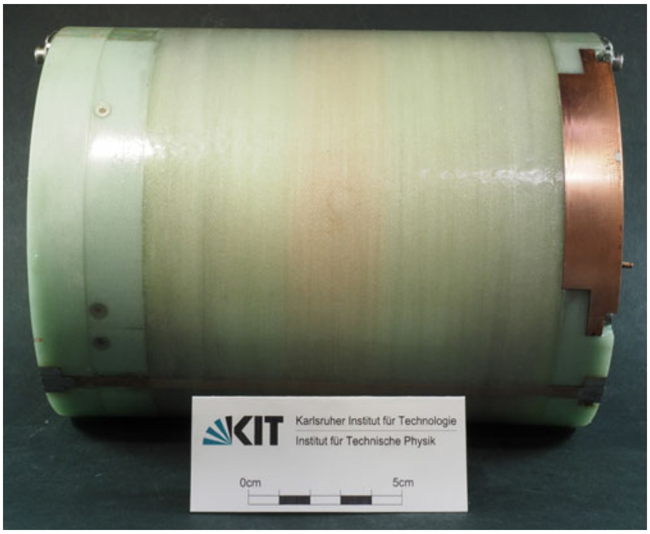

Fig. 2. Photo of the manufactured prototype layer wound 2G-HTS section after bandaging and sealing of the surface with epoxy resin.

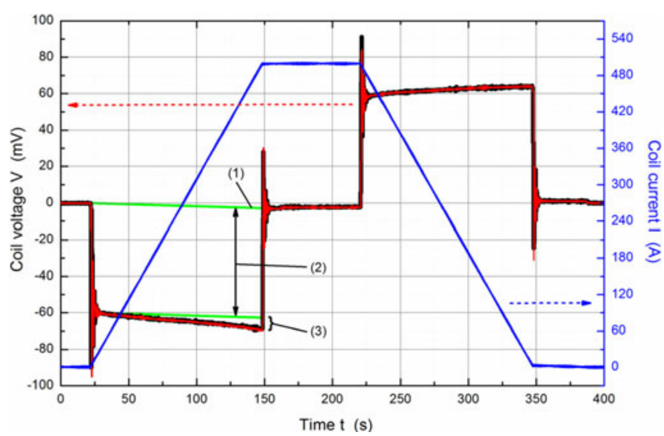

Fig. 3. Coil voltage measured for the prototype layer wound 2G-HTS section in 14 T background field at 1.8 K. The graph shows two experimental runs resulting in identical $V(I(t))$ curves (black and red) for ramping the coil current up to 500 A and back to 0 with a ramp rate of ± 4 A/s (blue curve). The coil voltage can be separated into a linear resistive (1), constant inductive (2), and a nonlinear contribution (3) which can be attributed to the magnetization of the coil. The polarity of the measured coil voltage was chosen arbitrarily.

the reproducibility and stability of the measurement process and the coil. The voltage signal during the current increase/decrease can be separated into three parts: (1) a linear resistive part due to the copper terminals, (2) a constant inductive part of approximately 60 mV which corresponds to a coil inductance of $\approx$15 mH – in good agreement with the calculated value of 15.4 mH – and (3) a nonlinear part which can be attributed to the dynamic magnetization of the coil during ramping [12]. For the plateau at constant current, $I = 500$ A, the resistive voltage part is residual and shows its maximum value of approximately 2.2 mV.

At maximum current, the field contribution of the 2G-HTS prototype section reaches 1.3 T and the hoop stress at 14 T background field 476 MPa. Thus, in the experiment the maximum stress value of 365 MPa calculated for the 5 T layer wound insert design (see Table II) is exceeded significantly.

In summary, the layer wound 2G-HTS section passed the complete testing without any quench or evidence for any degradation demonstrating the feasibility and reliability of this winding concept.

V. Conclusion

With the commercial availability of *RE*BCO 2G-HTS wires in piece lengths of several 100 m, larger layer wound coils are now becoming feasible. Therefore, the design of the HTS insert for the intended upgrade of the superconductive high field facility HOMER II from 20 T to 25 T was changed from the recently proposed double pancake to a layer wound layout. The design presented here consists of five nested layer wound sections using in total 1670 m of *RE*BCO HTS and produces 5 T at a rated current of 232 A. The wire has been already acquired from Fujikura. The layer winding technique as well as the design and construction of the coil sections has been validated by the manufacture and successful test of a full-size prototype 2G-HTS layer wound section consisting of 170 m of *RE*BCO tape. In background fields of up to 14 T maximum coil currents of 500 A were applied — corresponding to a hoop stress of 476 MPa — without any training or degradation of the coil section.

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