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Construction and Test Results of Coil 2 of a Three-Coil 800-MHz REBCO Insert for the 1.3-GHz High-Resolution NMR Magnet

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Abstract

This paper focuses on the construction and test results of Coil 2 that is part of a trio of nested coils composing the REBCO 800 MHz insert. Upon its completion, the REBCO 800 MHz insert will be placed in the bore of a 500 MHz low temperature superconducting (LTS) NMR magnet (L500) to form the MIT 1.3 GHz high-resolution NMR magnet. Coil 2 is a stack of 32 double pancake (DP) coils wound with 6-mm wide REBCO tape using the no-insulation (NI) technique. Each pancake is wound on a stainless steel inner supporting ring to prevent the collapsing of its crossover due to the external pressure exerted by the winding pack. Coil 2 will be constructed in the following sequence: 1) after winding each DP will be individually tested in a bath of liquid nitrogen at atmospheric pressure to determine its current carrying capabilities; 2) DPs will be then assembled as a stack with interconnecting joints, and 3) as in Coil 1, each pancake will be overbanded with a stainless steel tape, this time to a thickness of 5 mm, thickness determined by a stress analysis previously performed. Finally the fully assembled Coil 2 will be tested in liquid nitrogen at 77 K and then in liquid helium at 4.2 K. We present here details of the stress analysis leading to the sizing of the DP inner supporting stainless steel ring and of the overbanding thickness required. Test results include coil index, critical current, charging time constant.

Index Terms

Double Pancake coils; NMR; superconducting magnet; NMR; REBCO

I. Introduction

At the MIT Francis Bitter Magnet Laboratory/Plasma Science Fusion Center, the Magnet Technology Division is in the final stage of completing Coil 2 of the trio composing the all high temperature superconducting (HTS) 800-MHz insert (H800) for the 1.3 GHz/54-mm LTS/HTS high resolution NMR magnet system. A general overview of the magnet system has been published elsewhere [1]. To date, Coil 1 the innermost coil has been fabricated and fully tested with and without its overbanding. A brief summary is presented here for completeness. Complete test results are presented elsewhere (ASC2016-2LPo2F-01, this conference).

II. General Aspects of the H800

Coils 1 and 2 are wound, and also eventually Coil 3, using the standard double pancake (DP) technique, technique that allows having both terminals of the DP on the outside with just an internal crossover (see Fig. 1). Coils are wound, making use of the no-insulation (NI) technique [2–4], with the 6-mm wide type SCS6050-AP conductor from SuperPower, a REBCO based conductor 75- μm thick with a 50- μm thick Hastelloy substrate. A 178- μm thick G-10 insulation is placed between each pancake and also between each double pancake.

All coils are wound with a 50-N winding tension; also all three coils incorporate an inner supporting stainless steel ring to prevent the collapsing of their innermost turn/crossover.

III. Coil 1 Summary

As stated above, full test results of Coil 1 are presented elsewhere (this conference). Coil 1 consisted of 26 DPs including 6 with an inside notch. In order to contain the hoop stresses and hoop strains developed during operation of the H800-L500, Coil 1 was overbanded, with stainless steel tape 76- μm thick, 6 mm wide, to a 7-mm thick build wound at 50-N winding tension.

The assembled coil without overbanding, is shown at the top of Fig. 2, while at the bottom the coil is shown overbanded and ready for test. Coil 1 was tested at 77 K and at 4.2 K. Field mapping at different values of operating current, I_{op} , and at 77 K and 4.2 K are presented in Fig. 3. The coil successfully generated, in liquid helium, a center field of 8.65 T at 253 A.

Coil reached the design field at the first run with no training sequence. For the test the coil was energized by an Oxford Instruments IPS 125-9 power supply manually controlled; the magnetic field was measured with a Lakeshore HGCA-3020 Hall sensor.

IV. DPs Inner Supporting Stainless Steel Ring

At the start of winding the DPs of Coil 1, it was found that the innermost turn of the coil would collapse upon its removal from the winding mandrel.

Assuming the innermost turn to be a short cylinder under uniform radial external pressure, its collapsing pressure can be determined by means of the following equation [5]:

$$p_c = \frac{2.42ED_o}{(1-\nu^2)^{0.75}(L-0.45(tD_o)^{0.5})} \left(\frac{t}{D_o}\right)^{2.5} \quad (1)$$

Where E = Young's modulus, ν = Poisson ratio, D_o = cylinder inner diameter, L = cylinder length and t = cylinder thickness. For Coil 2 the innermost turn has a diameter of 150.75 mm, a length of 6 mm and a thickness of 0.075 mm. With $E = 140$ GPa and $\nu = 0.3$, the estimated collapsing pressure of its innermost turn is $P_c = 0.067$ MPa.

As can be seen from Fig. 4, the computed value of radial stresses [6] for the innermost turn of Coil 2 is ~ 0.75 MPa, a value 11 times greater than the previously calculated collapsing pressure of that turn.

Based on the above results it was decided to add, to each coil an inner non-magnetic stainless steel ring, thick enough to provide the support required by the innermost turn not only during winding and overbanding, but also during cooldown. Appropriated ring thicknesses for the three coils were determined using Eq. 1. For Coil 2, the required thickness of the ring was 1 mm. A photo of one of the DPs with its inner supporting ring is presented in Fig. 5

V. Coil 2

A. General

The key parameters of Coil 2 are presented in Table I. Values shown are as designed at 4.2 K, $I_{op} = 251.3$ A operating in conjunction with Coils 1 and 3 and in the background of the LTS 500 MHz magnet, that is, as part of the 1.3 GHz magnet system.

B. Coil 2 Status

Of the 32 DPs composing Coil 2, to date 22 have been wound and individually tested in liquid nitrogen at 77 K, thus characterizing each DP for its critical current and charging delay time constant. All coils were tested at a ramping rate of 2 A/min.

A typical coil voltage versus current trace for one of the non-notched DPs is shown in Fig. 6.

From the tests the critical current, I_c , time constant, τ , characteristic resistance and n -values for the NI coils were determined. Representative values are presented in Table II.

Magnet time constants, α = center field/current, versus power supply current for representative DPs are presented in Fig. 7. The Fig. also shows the design value $\alpha = 1.885$ mT/A for Coil 2. The drops in α shown in Fig. 7, as the power supply current approaches each coil's critical current (I_c), is a typical no-insulation charging behavior due to the current leaking through the turn-to-turn shorts. The drop starts at different current values mainly owing to the coil-to-coil I_c variation.

The voltages of the same double pancakes, as obtained during current steps in steady state, are presented in Fig. 8. The results show the coil-to-coil I_c variation; after all the DP coils

are completed and tested in LN₂, their stacking order will be established positioning a pair of DPs having the largest I_c at the top and bottom of the DP stack. The next step will be to join a DP to its neighboring DP by splicing them together with 12 mm wide REBCO tape from the same manufacturer. Splices will be done in the same manner as was done for Coil 1, a process already described in a previous publication [7].

VI. Conclusions

- The 1.3 GHz High Resolution NMR magnet program proceeds at a good pace. The REBCO H800 MHz insert is expected to be assembled and operated at 77 K and 4.2 K in 2018.
- Coil 1 has been fabricated and fully tested, performing as expected, reaching 8.65 T at 253 A in a bath of liquid helium at 4.2 K.
- For Coil 2, all no-notch DPs have been wound and individually tested. Only the 10 notched DPs remain to be wound.
- Coil 2 is expected to be fully assembled and tested during the first quarter of 2017.

Acknowledgments

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Fig. 1.
Graphic depiction of a double pancake (DP) showing its crossover, C, and terminals, A and B.

Fig. 2.
Coil 1 shown fully assembled, top: without overbanding, bottom: overbanded.

Fig. 3.
Plots of central field vs. operating currents at 77 K (top) and 4.2 K (bottom) of Coil 1.

Fig. 4.
Radial stresses due only to winding tension of coils with overbanding

Fig. 5.
A DP for Coil 2 showing the inner stainless steel supporting ring.

Fig. 6.
Coil voltage vs. current trace for continuous up-ramp of current and stepped current down ramp back to zero.

Fig. 7. Measured magnet time constants, α , vs. power supply current of representative DPs of Coil 2, at 77 K and self-field.

Fig. 8.
DPs voltage versus current plots, obtained at 77 K, self-field and in steady state during current steps.

TABLE ICoil 2 Key parameters As Designed @ 4.2 K, $I_{op} = 251.3$ A

Parameter	Units	Value
Frequency	[MHz]	242
Field contribution	[T]	5.68
$B_{\perp}$	[T]	4.6
$I_c(B_{\perp}, 4.2 \text{ K})/I_c(77 \text{ K, sf})$		>2.3
Overall current density	[MA/m ²]	546.9
Total # DP coils		32
# Notched DP coils		10
# turns/pancake		121
# turns/notched pancake		118
Inner diameter (ID)	[mm]	150.75
ID (notch)	[mm]	151.20
OD (without overband)	[mm]	168.90
Overall height	[mm]	392.13
Notched section height	[mm]	122.54
SS overband radial build	[mm]	5
REBCO length/DP coil	[m]	121.5
REBCO length/notch DP	[m]	118.7
Total length/coil	[km]	3.84
Inductance	[H]	3.08
Peak bending strain	[%]	0.0364
Peak magnetic hoop strain	[%]	0.35
Peak total hoop strain	[%]	0.39

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TABLE II

Measured Coil 2 Parameters

DP #	I _c [A]	L [mH]	τ [s]	R _c [$\mu\Omega$]	n-value
11	60.8	17.55	25.9	677.61	16.7
12	60.0	16.50	27.3	604.40	13.7
13	58.4	17.93	25.6	701.43	22.2
14	58.9	17.20	26.4	651.51	19.9
15	59.8	17.23	31.1	550.59	18.5
16	58.8	18.80	26.2	717.56	20.3
19	63.4	18.36	40.0	459.17	16.8
23	65.0	17.20	38.6	445.98	16.6
24	63.7	19.10	40.0	477.50	13.2