Tue-Af-Po2.14-10 [10]

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Fatigue Behavior of No-Insulation Coils with and without Reinforcing Co-Wind

Iain R. Dixon, Mark Bird, Xinbo Hu, Kwangmin Kim, Kwang Lok Kim, Dylan Kolb-Bond, W. Scott Marshall, Thomas A. Painter, Hongyu Bai
National High Magnetic Field Laboratory, Tallahassee, FL

The National High Magnetic Field Laboratory is supported by the National Science Foundation through NSF DMR-1644779 and the state of Florida

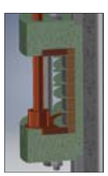
Abstract

The NHMFL has commenced with the development of an all-superconducting 40 T magnet that will be installed in its DC-Field User Facility. At present various high temperature superconductor technologies are being investigated as candidates for the magnet construction. It is the objective of this early development stage to address questions regarding the application of a type of superconductor to magnet technology through model coil testing and properties measurements. No-insulation (NI) REBCO is a viable conductor and coil configuration for the 40 T magnet but needs further studies to reduce risk and to better understand its ability to perform reliably through long term user operations. The research presented here is focused on the fatigue effects of small NI test coils (~ 4 kJ) with and without reinforcing stainless steel co-wind. The coils contain six double pancakes with an inner diameter of 100 mm and will be operated to strain levels up to 0.45 % in a background field of 6.9 T. The impact of electromagnetic cycling on the REBCO is evaluated using Yatestar which is a device that provides a full-length image of the REBCO's superconducting state via magnetization and transport measurements. The contact resistivity is measured periodically and is observed to decrease with load cycling.

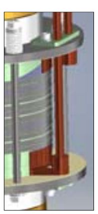
Test Coil and Test Bed Configurations

- Objectives
  - Observe effects of cycling on REBCO coils with electromagnetic loads, including screening currents, up to ~ 0.4 % - 0.45 % azimuthal strain
- Test Bed: NbTi magnet, 170 mm cold bore, 6.9 T
- Insert Coils:
  - IR = 50 mm
  - OR = 55 mm
  - Six Double Pancakes (4 mm wide)
- Test Coil #1
  - REBCO: 94 μm thick (50 μm substrate), 53 turns per pancake
  - REBCO oxidized via Ebonol-C
  - No co-wind, no reinforcement
  - Inductance = 32 mH
  - Termination: stiff ring
- Test Coil #2
  - REBCO: 51 μm thick (30 μm substrate), 61 turns per pancake
  - 30 μm thick stainless co-wind
  - Inductance = 39.1 mH
  - Termination: stiff ring
- Test Coil #3
  - REBCO: 94 μm thick (50 μm substrate), 40 turns per pancake
  - 30 μm thick stainless co-wind
  - Inductance = 24.8 mH
  - Termination: flexible

Test Coil (Left) and Assembled in NbTi Test Bed (right)



Stiff Ring Terminal



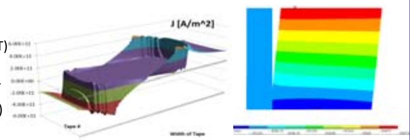
Flexible Terminal

Assembly of Test Coil #2

- All conductor is scanned through Yatestar before and after cycling for damage comparison and location identification
- Screening currents computed using a T-A formulation [1] in COMSOL and input into an ANSYS structural finite element model which utilizes contact elements between neighboring conductor turns [2]
- Characteristic resistivity, R_C, measured before and after cycling

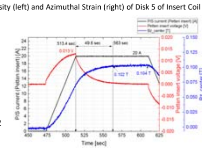
Test Coil #1

- Test Conditions
  - Current cycle: 0 A – 230 A (0 T – 1.4 T)
  - Background Field: 6.3 T
  - Max / Min Central Field: 6.3 T – 7.7 T
  - Peak Strain: 0.59 % (0.54 % with ε_{bend})



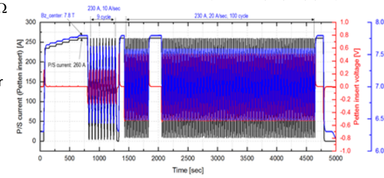
Current Density (left) and Azimuthal Strain (right) of Disk 5 of Insert Coil #1

- Test Results
  - The conductor was oxidized to increase the turn resistivity. At room temperature and 77 K the measured resistivity was 120 mΩ·cm^2 and 80 mΩ·cm^2 respectively
  - At 4.2 K the resistivity dropped significantly to < 0.1 mΩ·cm^2



Insert Coil #1 Ramp Detail Showing Long Charging Delay

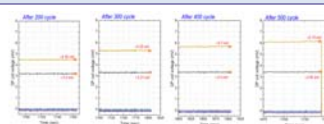
  - Prior to cycling the NbTi quenched at 6.4 T – causing damage to DP3 (1.2 mΩ at 330 A, SF)
  - 110 ramp cycles were applied to the coil, primarily at 20 A/s
  - No additional degradation to DP3 after cycling
  - Yatestar scan shows no damage on REBCO
  - R_{ct} = 62.5 $\mu\Omega$·cm^2 / 77.5 $\mu\Omega$·cm^2 (before / after cycling)



Multiple Charging-Discharging Operation of the Insert Coil #1 with 6.3 T Background Field

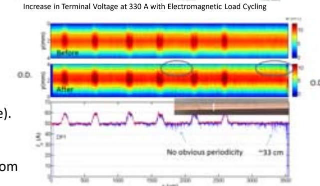
Test Coil #2

- Test Conditions
  - Current cycle: 130 A – 330 A (1.1 T – 2.1 T)
  - Background Field: 6.9 T
  - Max / Min Central Field: 8 T – 9 T
  - Peak Strain: 0.50 % (0.45 % with ε_{bend})

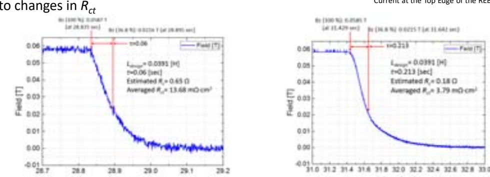


Increase in Terminal Voltage at 330 A with Electromagnetic Load Cycling

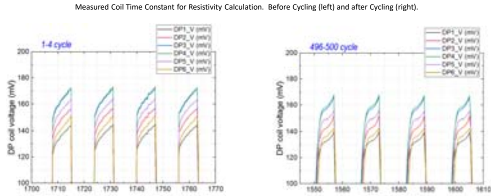
- Test Results
  - The Insert coil #2 was cycled 500 times
  - Voltage of REBCO to terminal joint continually increased during cycling until quench occurred in 501[st] cycle
  - A quench initiated in DP6 (termination joint failure). The quench propagation damaged DP1. All other pancakes appear normal.
  - The contact resistivity reduced with load cycles, from 13.7 mΩ·cm^2 to 3.8 mΩ·cm^2
  - The inductive voltage changed with cycles, possibly due to changes in R_{ct}



Yatestar Scan of DP1 Showing Some Local Reduction of Critical Current at the Top Edge of the REBCO



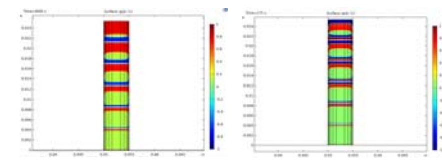
Measured Coil Time Constant for Resistivity Calculation. Before Cycling (left) and after Cycling (right).



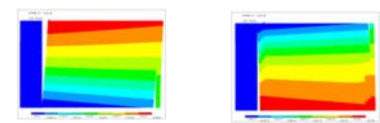
Inductive Voltage Pattern of each Double Pancake. Before Cycling (left) and after Cycling (right).

Test Coil #3

- Test Conditions
  - Current cycle: 110 A – 350 A (0 T – 1.65 T)
  - Background Field: 6.9 T
  - Max / Min Central Field: 6.3 T – 7.7 T
  - Peak Strain: 0.50 % (0.45 % with ε_{bend})
- Screening Current Strain
  - Strain from transport and screening currents were evaluated at 350 A and 110 A
  - During ramp down screening current reverses direction, as indicated in the current density contour plots
  - This creates hoop compression on the upper end of the pancakes (end three pancakes)

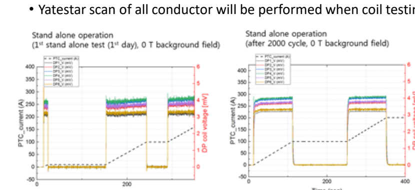


Current Density of Upper Six Pancakes at 350 A (left) and Ramping Down to 110 A (center)



Azimuthal Strain in End Pancake at 350 A (left) and after Ramp Down to 110 A (right)

- Test Results
  - A total of 2002 electromagnetic load cycles have been applied to the test coil
  - After ~ 1000 cylces, the NbTi coil quenched while at 6.9 T (test coil holding at 200 A)
    - 300 nΩ resistance developed in termination joint.
    - Resistance of all other pancakes and joints did not change
    - Restricted test bed to 6.5 T and increased test coil current to 370 A
  - The effective coil resistivity, R_{ct}, dropped significantly with E-M cycling
  - Resistance of termination joint increased to 1.3 $\mu\Omega$ after 2002 cycles. Testing has paused to repair the termination joint. E-M cycling will resume in mid-October.
  - Yatestar scan of all conductor will be performed when coil testing is completed



Test Coil Ramps of First Cycle (left) and 2000[th] Cycle (right) Showing Increased Charging Delay / Decreased Contact Resistivity

Contact Resistivity with E-M Load Cycles

R_{ct} Test #	E-M Cycles Applied	τ (ms)	R_{ct} (mΩ·cm^2)
1	0	3	193
2	0	5	109
3	1000	356	1.62
4	1000	325	1.78
5	2000	456	1.27
6	2000	484	1.19

Conclusions

- REBCO has been shown to withstand at least 2000 cycles to strains in the range of 0.4 % - 0.45 % and with a high gradient (electro-magnetic load cycling to be continued on test coil #3)
- Strain direction reversal occurs because of screening current
  - It is probably that joint damage was caused on test coils 1 & 2 by the stiff termination ring
- The contact resistivity reduces with load cycling

References

1. E. Berrospe-Juarez, V. M. R. Zermeno, F. Trillaud, F. Grilli, "Real-time simulation of large-scale HTS system: multi-scale and homogeneous models using the T-A formulation," *SuST*, vol 32, 065003, 2019.
2. D. Kolb-Bond, M. Bird, H. Weijers, F. Trillaud, F. Grilli, V. Zermeno, I. Dixon, E. Berrospe-Juarez, "Computing Strains due to Screening Currents in REBCO Magnets," Presented the 26[th] International Conference on Magnet Technology, Mon-Af-Po1.11-05 [5], to be published in *IEEE Transactions on Applied Superconductivity*, 2020.