Tue-Af-Po2.05-02

Construction and Test Results of Coils 2 and 3 of 800 MHZ REBCO Insert for MIT 1.3 GHZ LTS/HTS NMR Magnet

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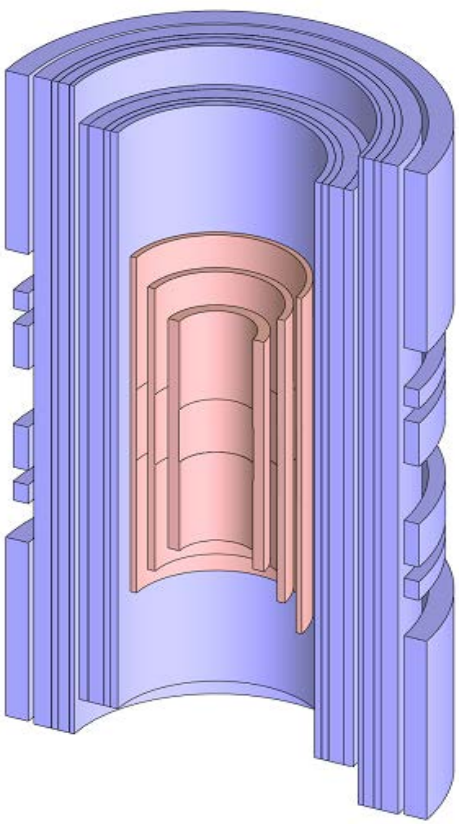
Background – MIT 1.3G

2012 – 2014 Post-theft Phase 3A by NIBIB-NIGMS

2015 – 2018 Phase 3B1 by NIGMS: H800 completed

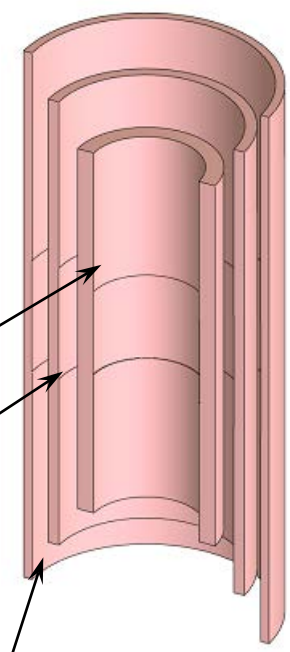
2018 – 2020 Phase 3B2

L500/H800



H800 (Operated at 4.2 K in LHe)

- 3-nested-coil formation
- **No-insulation (NI) winding**
- REBCO tape, 6-mm wide, 75-μm thick, made by SuperPower Inc.



Coil 1: 26 DP; 8.67 T (369 MHz)

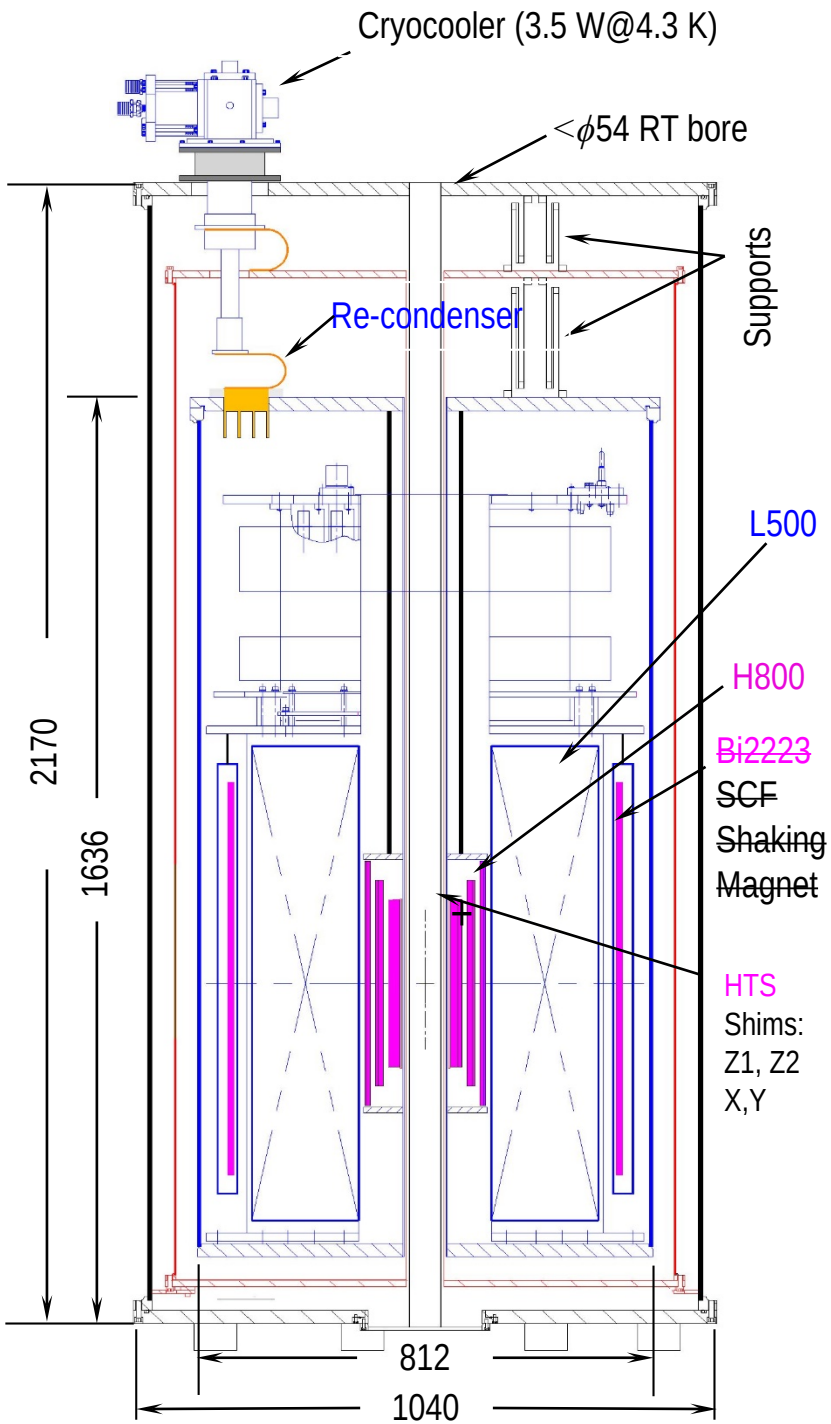
Coil 2: 32 DP; 5.64 T (240 MHz)

Coil 3: 38 double-pancakes; 4.44 T (189 MHz)

Background – MIT 1.3G

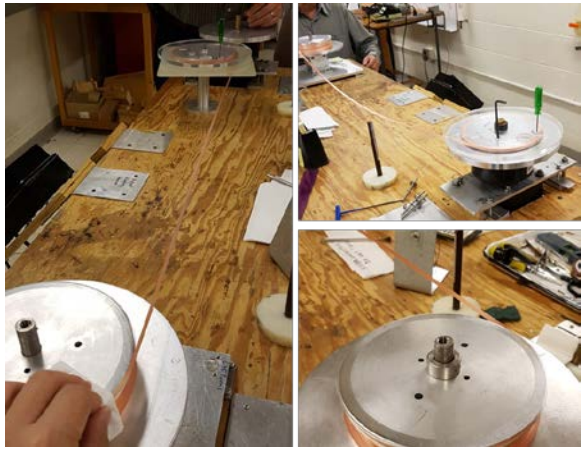
Noteworthy Features

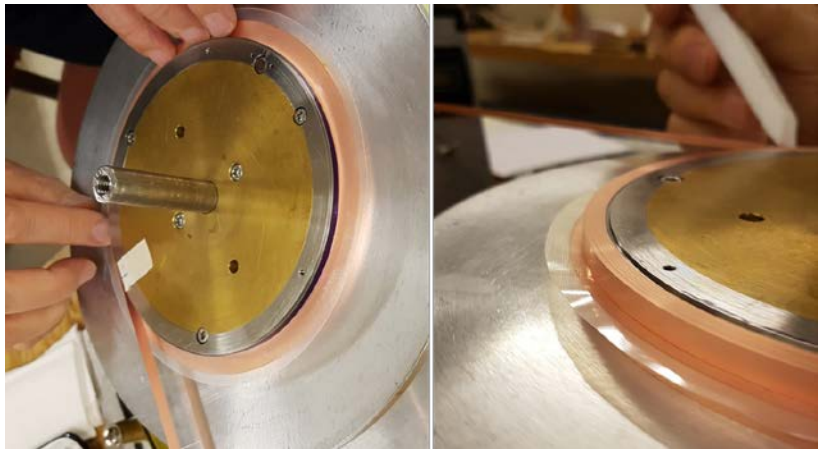
- H800 field contribution: 61.3%
- NI winding technique for All HTS
- Inside-notched Coil Design
  → Short but homogeneous
- Persistent-mode HTS shims:
  → Z1, Z2, (X, Y)
- SCF shaking magnet
  → Not practical
  → May use L500
- LHe re-condensation

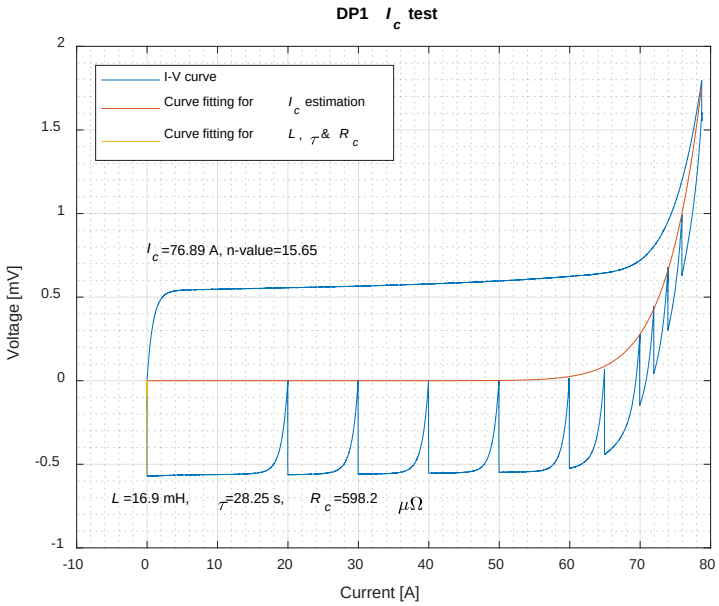


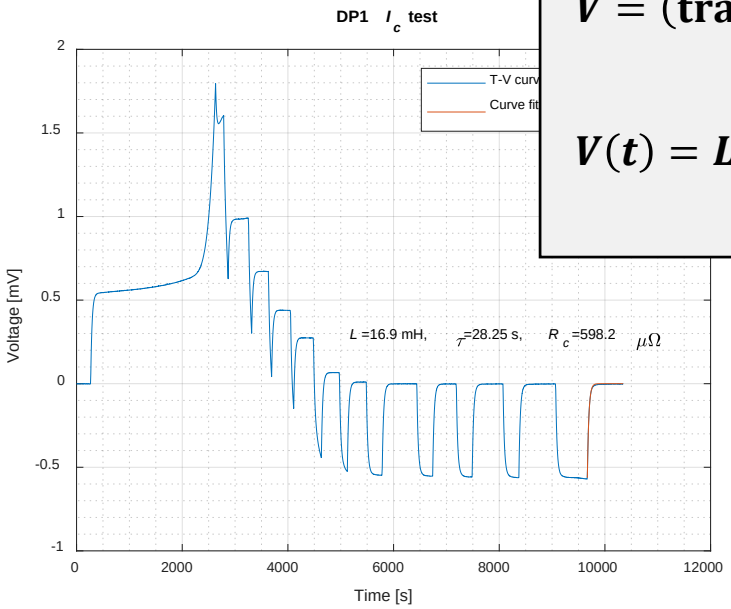
DP Winding & Individual Tests

- Conductor: 6-mm wide, 75-µm thick REBCO conductor from SuperPower
- Winding Tension: 50 N









$$V = (\text{transition criterion})\left(\frac{I}{I_c}\right)^n + I \cdot R_s$$

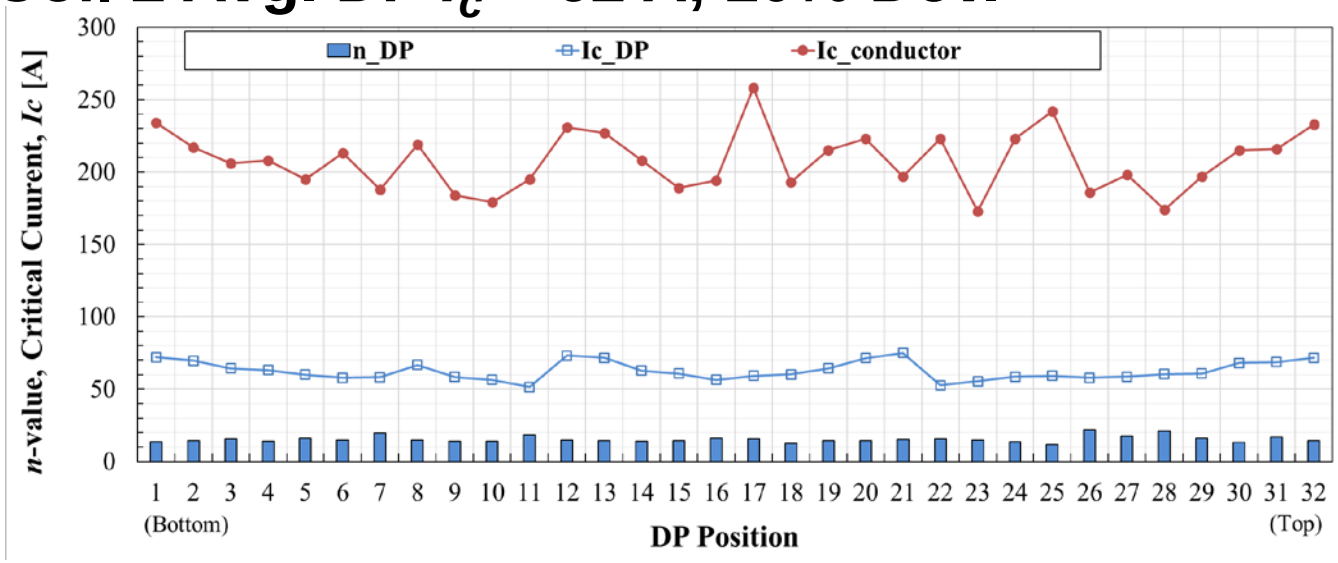
$$V(t) = L\frac{di}{dt}\left(1 - exp\left(\frac{-(t - t_o)}{\tau}\right)\right)$$

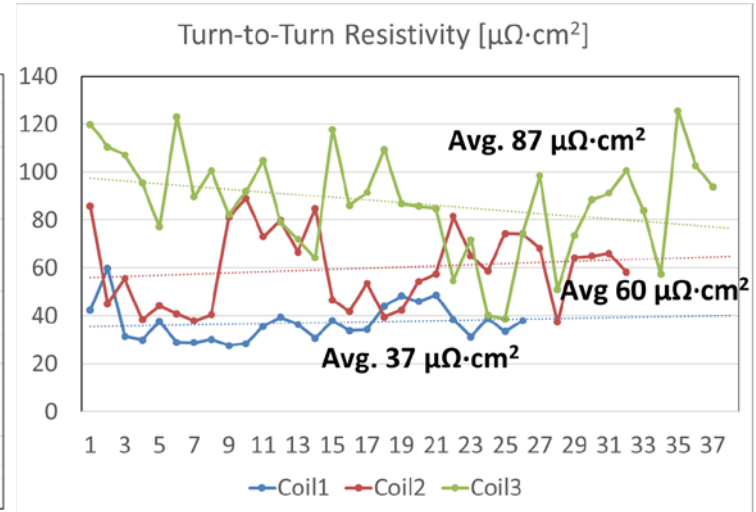
Derived Parameters

I_c, n, L, τ, R_c

Individual DP Test Results

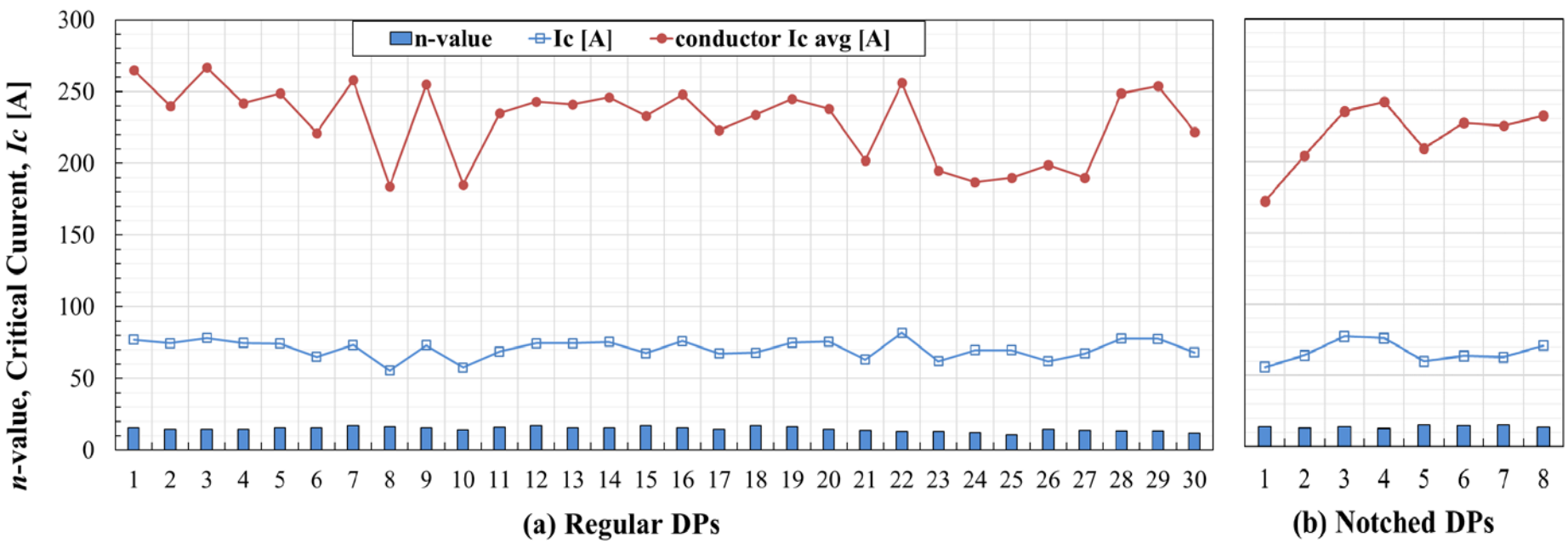
Coil 2 Avg. DP I_c = 62 A, 10% Dev.





$\rho_c \propto 1/\sigma_r$, $\sigma_r \propto$ *Tension/radius*
$\rightarrow \rho_c \propto$ *radius* of coils

Coil 3 Avg. DP I_c = 70 A, 10% Dev.

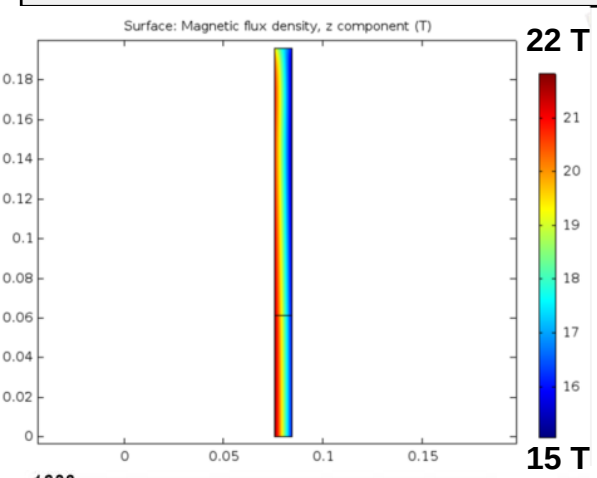


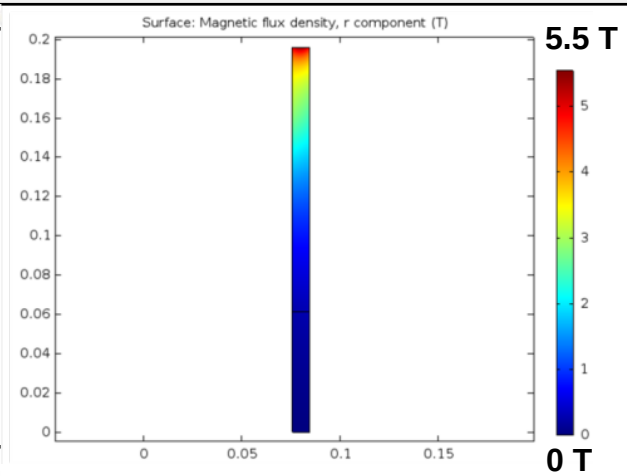
Stacking Order

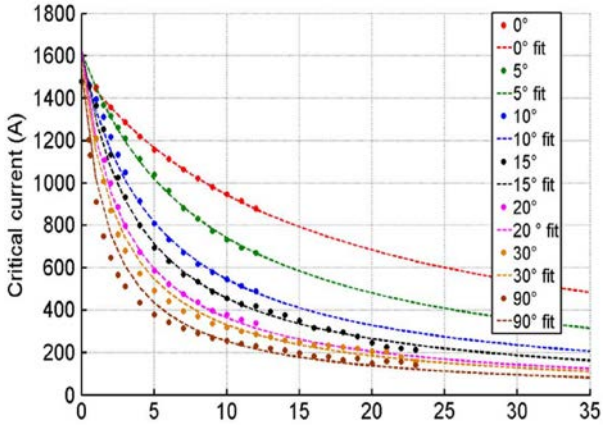
Objectives:

1) Achieve the maximum critical current margin
2) Match as closely as possible the OD for low joint resistance

Coil 2 Ic estimation at 4.2 K, 30.5 T operation
: Consider angular dependent Ic properties of REBCO
: FEM result → In regular DPs 15.3 T ~ 21.6 T within 15.6°

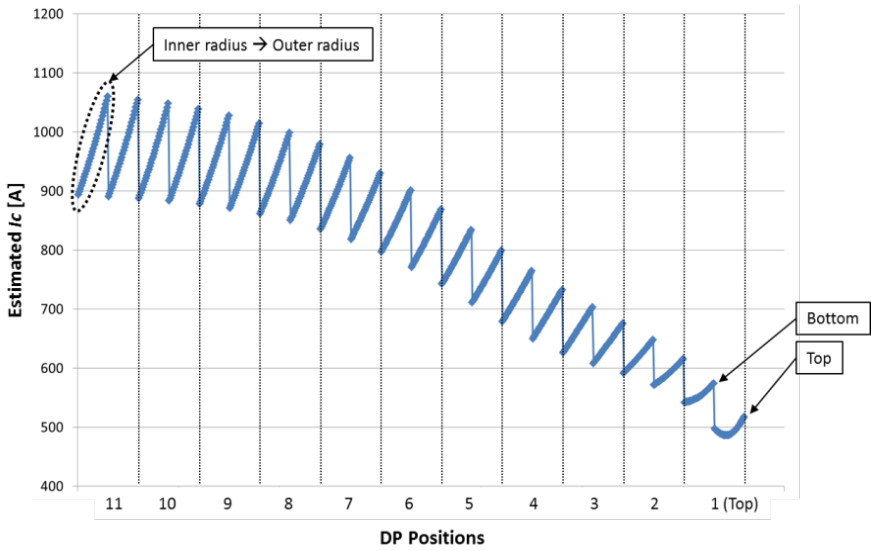






$$I_c(B_\parallel, B_\perp) = \frac{I_{c0}}{\left(1 + \frac{\sqrt{(kB_\parallel)^2 + B_\perp^2}}{B_c}\right)^b}$$

* Ref. Tara Benkel et al, 'REBCO Performance at High Field with Low Incident Angle and Preliminary Tests for a 10-T Insert,' IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 3, APRIL 2016

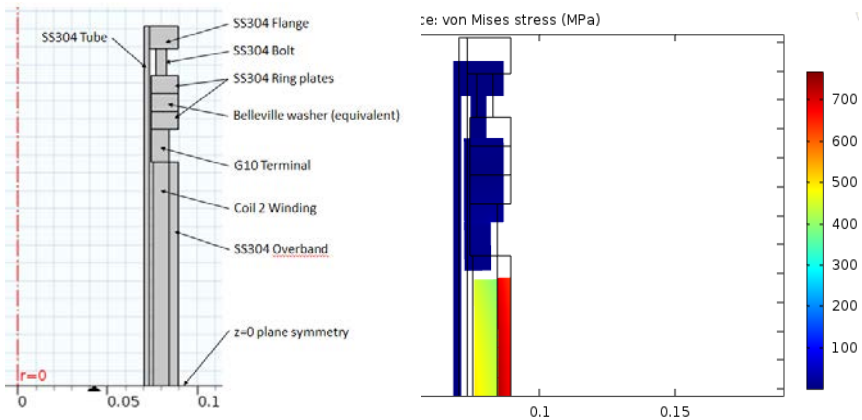


DPs with higher I_c were placed further away from the center

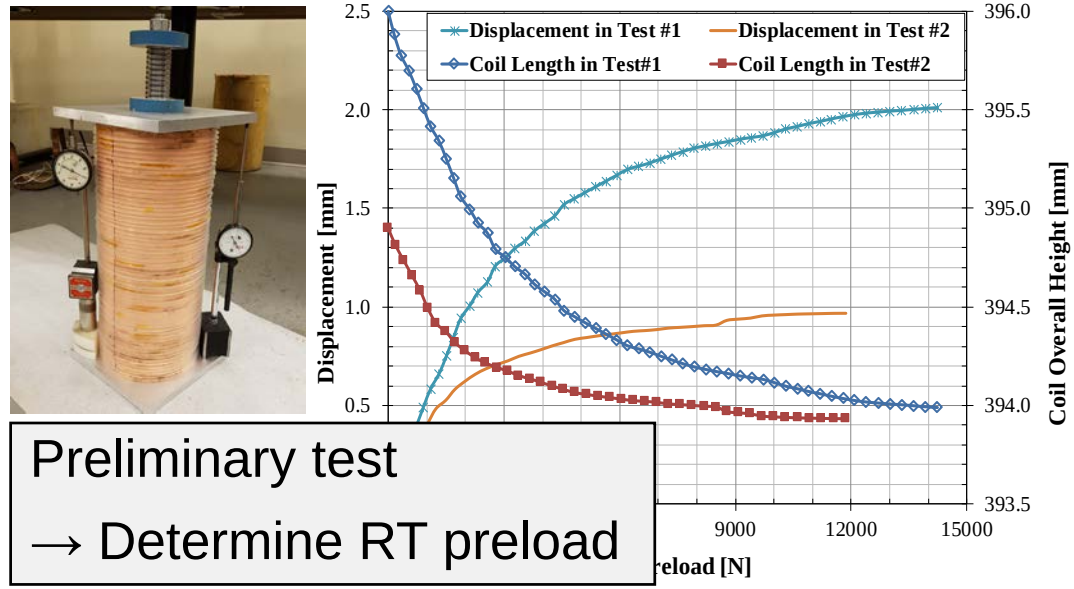
Preloading

Objectives:

Prevent any motions in the DP stacked coil during cool-down and energization, while the coil maintains its elastic behavior



FEM analysis (Thermal + EM)
→ possible gap in the coil structure



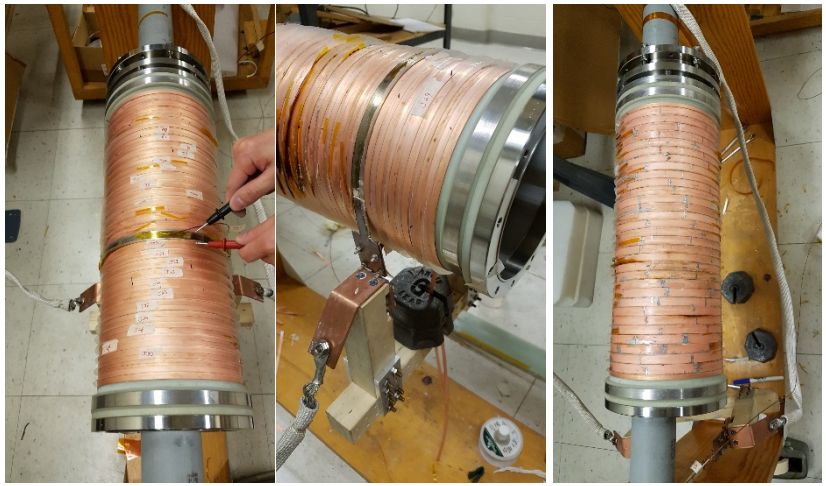
Preliminary test
→ Determine RT preload

16.3 kN was pre-loaded by
6 Belleville washer sets, each
consist of 8 Belleville in series

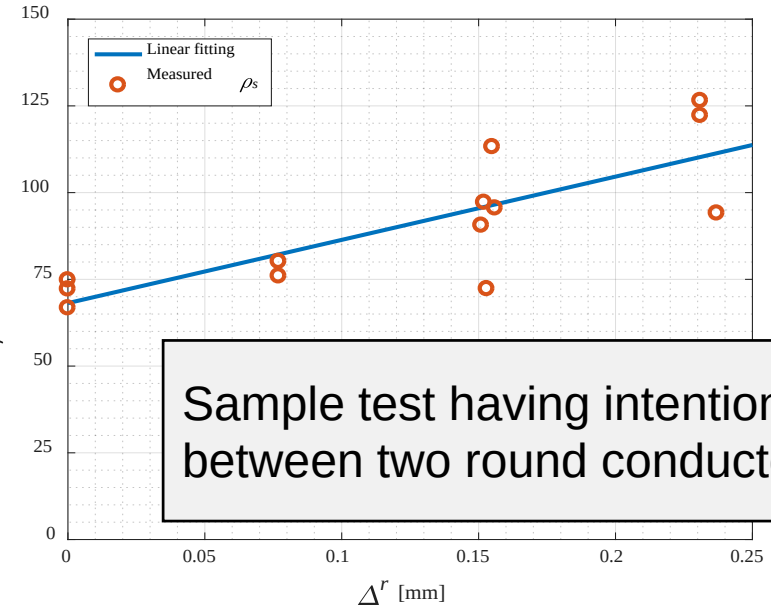
Splicing “Bridge” Joints

Objectives:

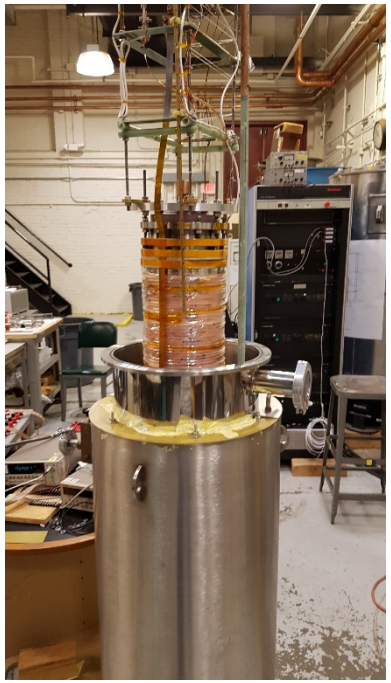
Minimize splice resistance for less Joule heating at 4.2 K operation

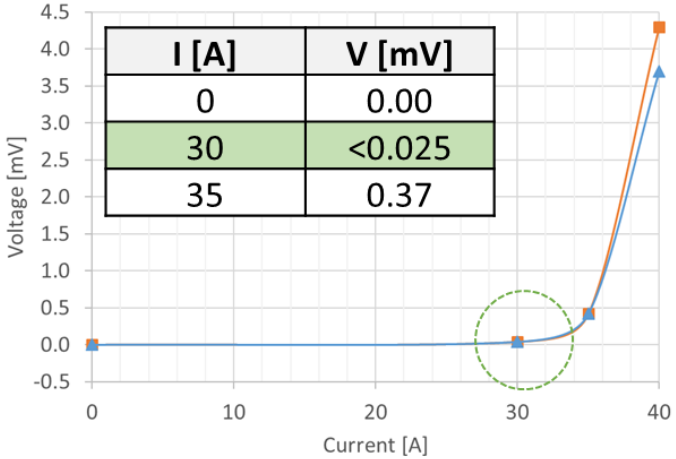


“Bridge” joint requires:
- 12-mm wide REBCO from SuperPower
- $In_{80}Pb_{15}Ag_5$ foils (melt point: 152°C)



Sample test having intentional gap between two round conductors





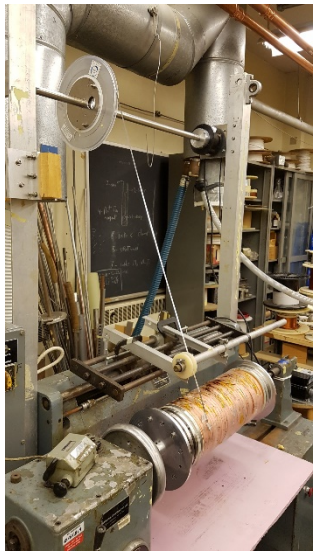
I [A]	V [mV]
0	0.00
30	<0.025
35	0.37

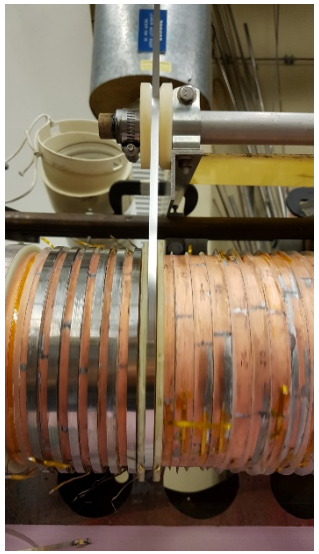
77-K testing before over-banding shows Joint resistance are okay <30 nΩ per each splice

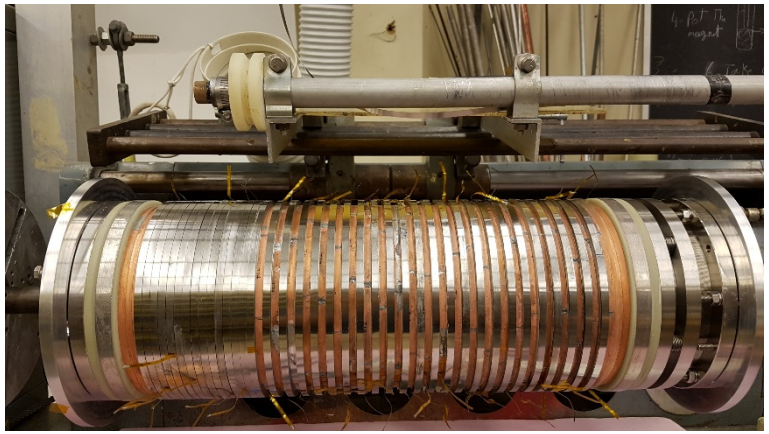
Over-banding & Test setup

Objectives:

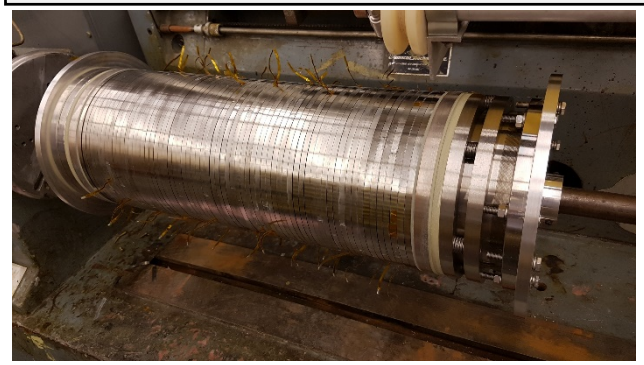
Mechanical reinforcement against radial direction expansion during energization → Limit the hoop strain under criterion, <0.4%







Solder SS304 tape to a REBCO tail and wind with 50 N tension along the guide rail



4.2 K Test Setup after over-banding completed




Coil 2 Test @ 77 K

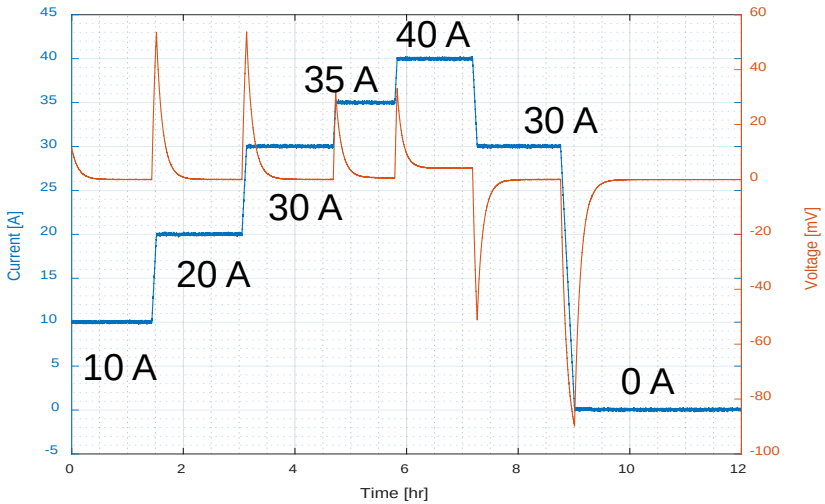
Overall test procedures:

- 77-K Test → (RT) over-banded → 77-K Test → 4.2-K Test

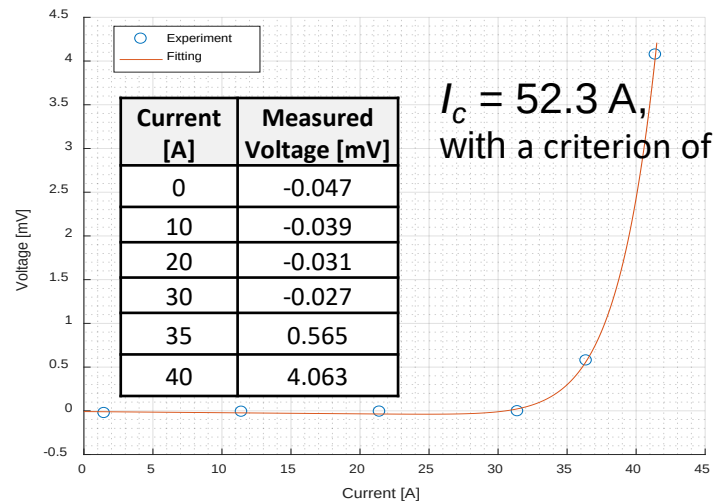
** No significant changes were observed after Coil 2 was over-banded*

77-K test procedures:

- 0→ 10→ 20→ 30→ 35→ 40→ 30→ 0 A @ 2 A/min and settle >1 hr at every step



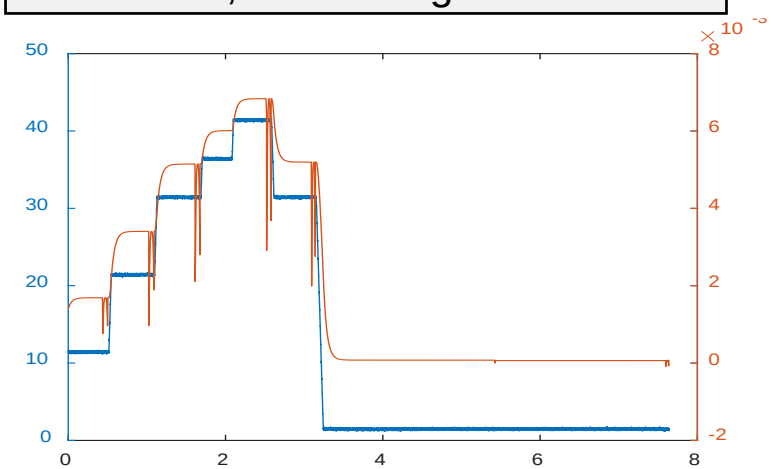
Current, Coil Voltage vs. Time



Current [A]	Measured Voltage [mV]
0	-0.047
10	-0.039
20	-0.031
30	-0.027
35	0.565
40	4.063

I_c = 52.3 A,
with a criterion of 0.1 μV/cm

Coil Voltage vs. Current



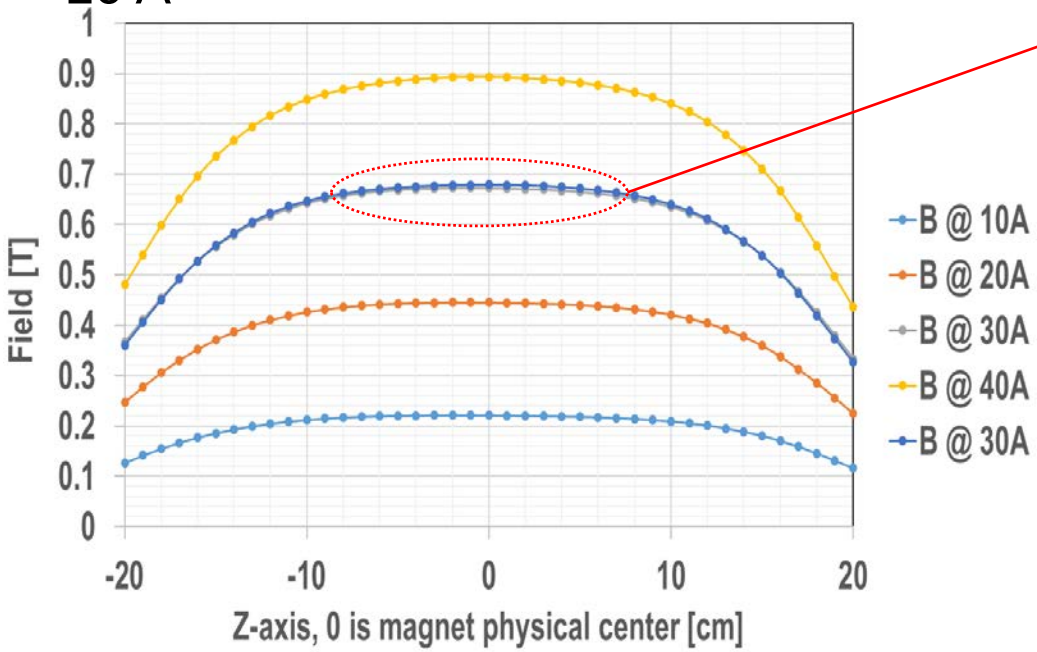
Center Field, Current vs. Time

Time Constant	After over-banding			Before over-banding		
	Rm [mΩ]	L [H]	Tau [sec]	Rm [mΩ]	L [H]	Tau [sec]
0 → 10 A	7.13	3.08	432	6.57	3.08	469
10 → 20 A	7.03		438	6.48		475
20 → 30 A	6.91		446	6.43		479
30 → 0 A	6.97		442	6.68		461

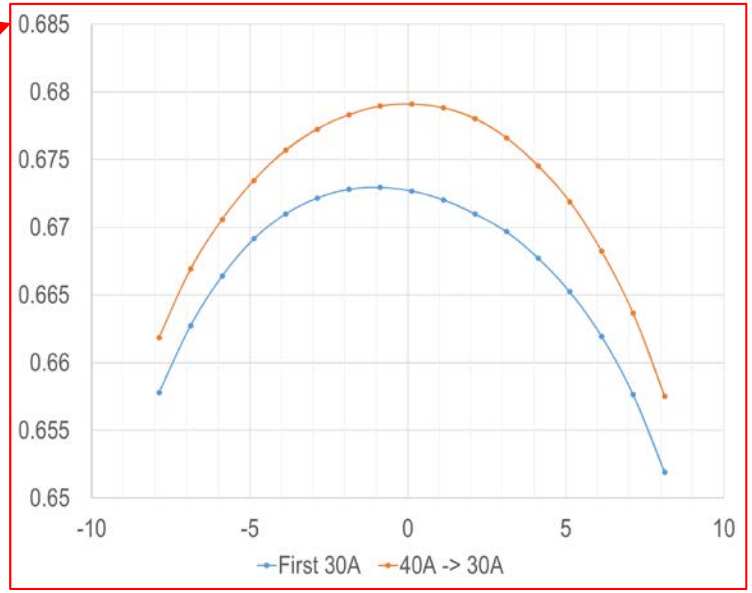
Coil 2 Test @ 77 K

Testing Procedure:

- 0 → 10 A



Field mapping @ 10, 20, 30, 40, back to 30 A



Field Comparison @ 30 A

HC	Unit	Calculation (As Wound)	Measured (0→@30 A)	Measured (40→@30 A)
Z1	ppm/cm^1	-7.4	-605.1	-13.5
Z2	ppm/cm^2	-368.3	-279.6	-355.8
Z3	ppm/cm^3	0.9	6.2	-5.5
Z4	ppm/cm^4	-1.4	-1.8	-0.6
Z5	ppm/cm^5	0.0	0.0	0.0
Z6	ppm/cm^6	0.0	0.0	0.0

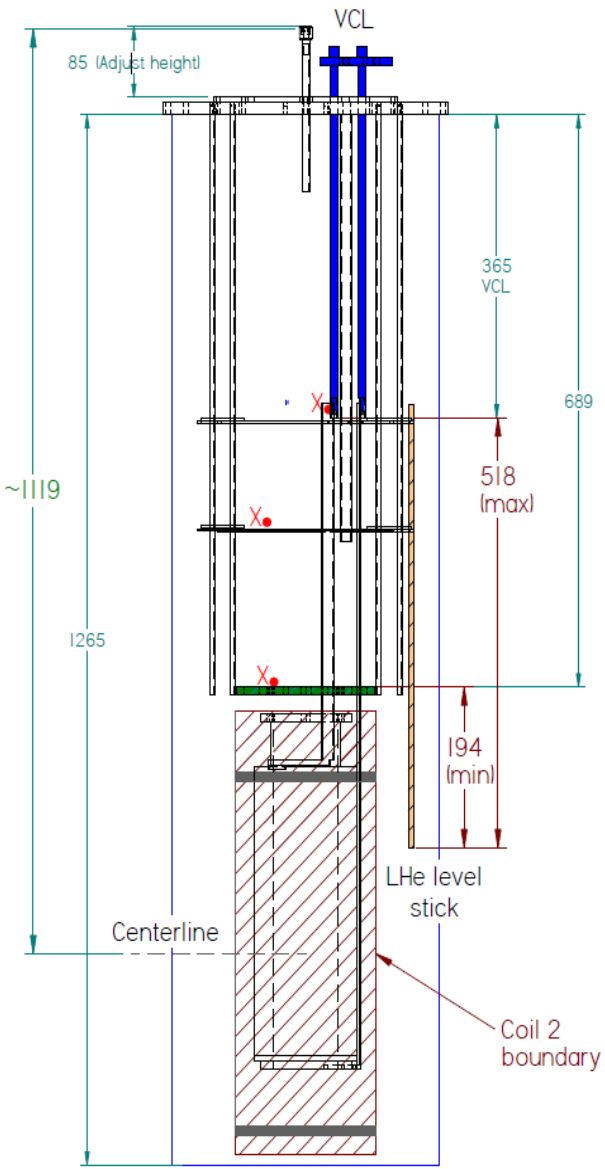
- Z1 Term was reduced significantly
- Z2 Term was consistent with calculation after over-current to 40 A
- Induced SCF in the first ramp seems to be erased by over-current of 40 A

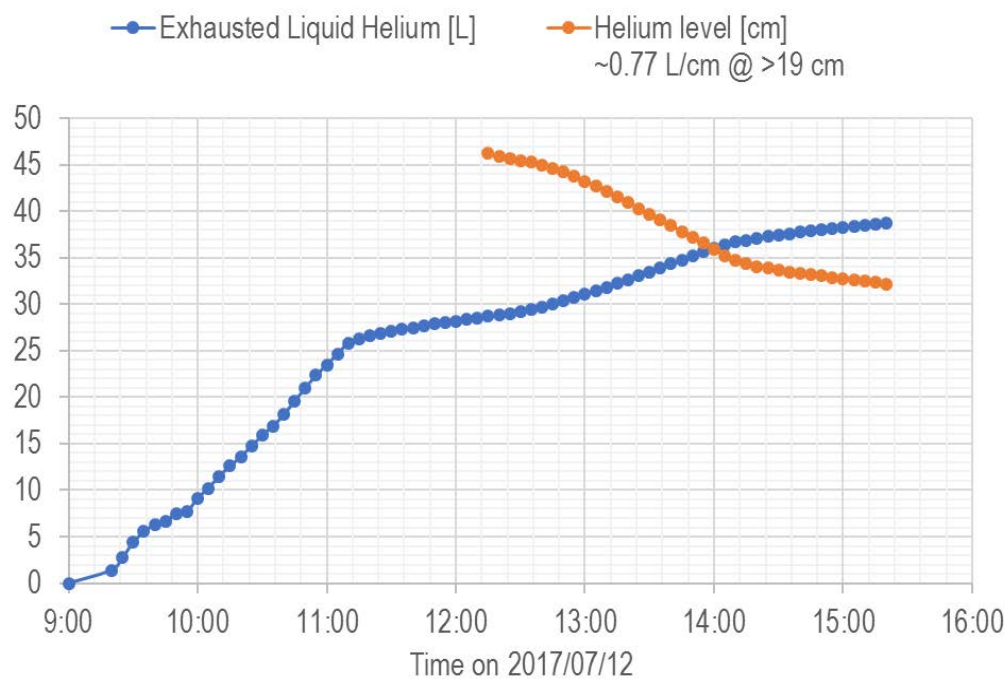
Coil 2 Test-1 @ 4.2 K

Cooling and 4.2-K Test Procedure:

- Purge LN2 completely → Connect flow meter →Transfer LHe with <1 psig
- Set current (1st test) 0 → 204 A → P/S cut → 0 A
  (2nd test) 0 → 204 A →251.3 A →260 A → 251.3 A → 0 A

** Settled >1 hr at each step*





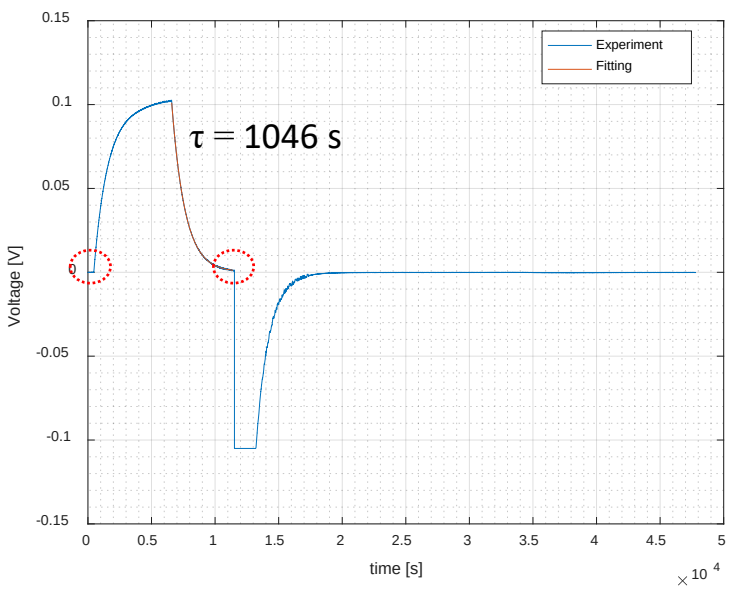
Exhausted LHe was measured by gas flow meter and LHe level meter

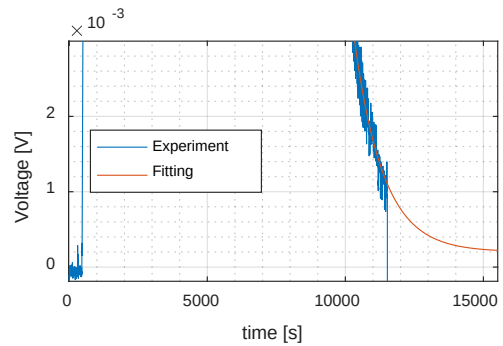
A single process of 'cooling down to 4.2 K and charging to /settling at 204 A' consumes ~60 Liter of LHe

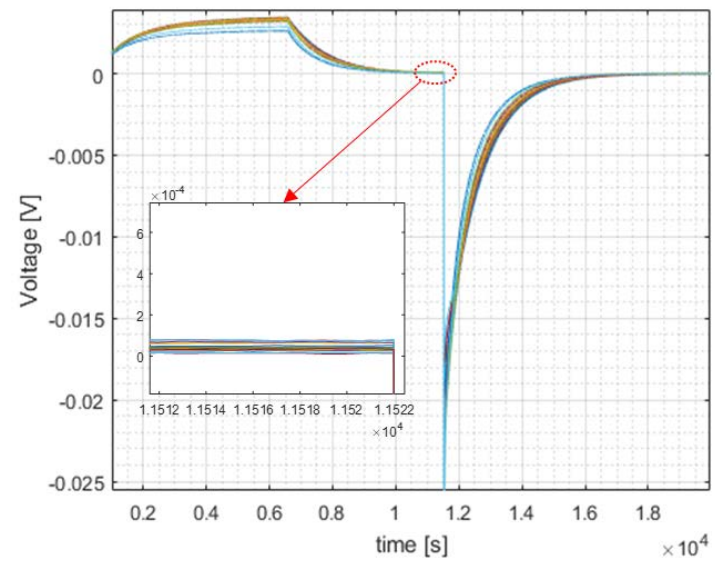
Coil 2 Test-1 @ 4.2 K

Power supply current cut out by low flow rate of cooling water:

- At least in Coil 2 stand-alone test at 4.2 K, 204 A, Coil 2 was self-protected
- During the re-tests, we checked Coil 2 reproduced same field, voltage performance

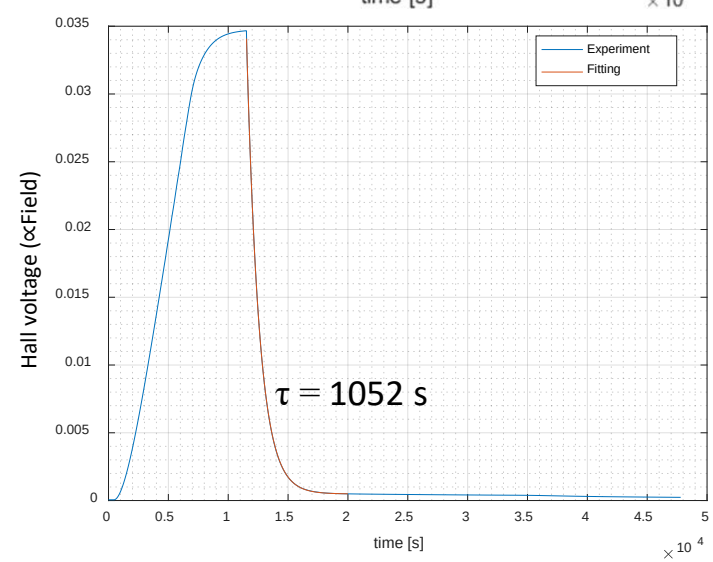






Coil Voltage vs. Time

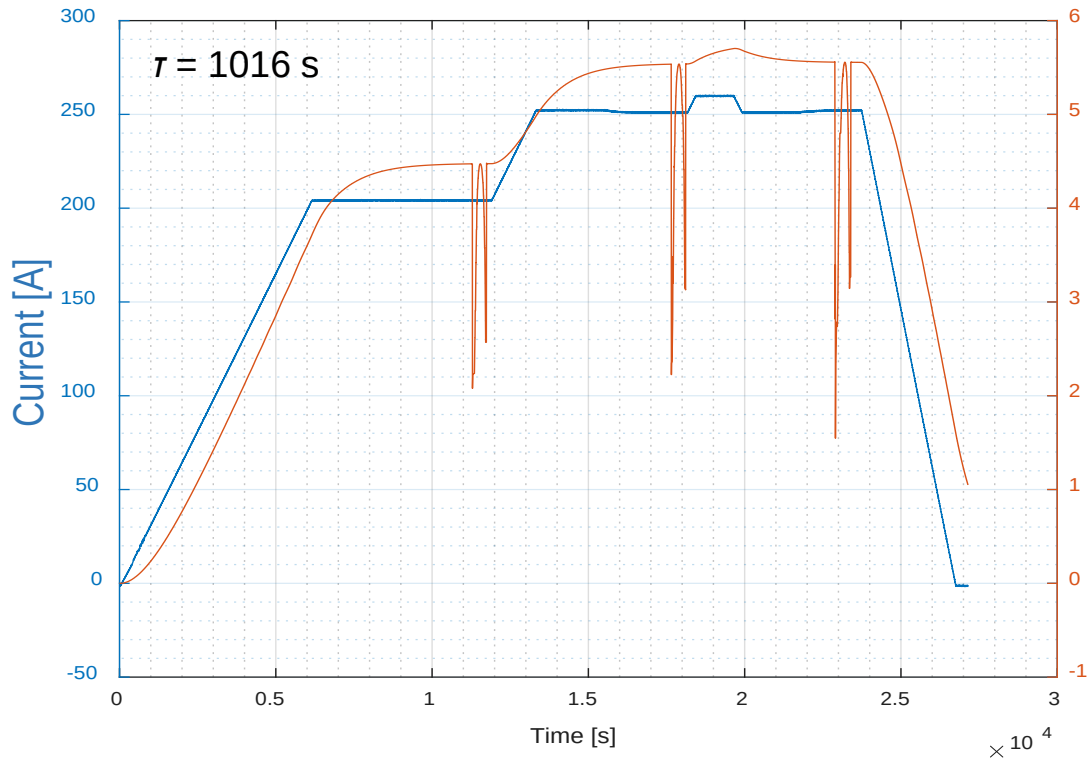
- Time constant : 1050 s (×2.4 of τ at 77 K)
- Overall coil voltage at 204 A after fully settled: 0.25 mV
  : Total resistance, R=0.25 mV / 204 A = 1.23 μV
  ➔ ~100 nΩcm^2
- Coil 2 has no damage after sudden power supply cut out
  ➔ NI coil's self-protection behavior



Coil voltage, Field (hall voltage) vs time

Coil 2 Test-2 @ 4.2 K

After attaching the water boost pump, the power supply problem was cleared



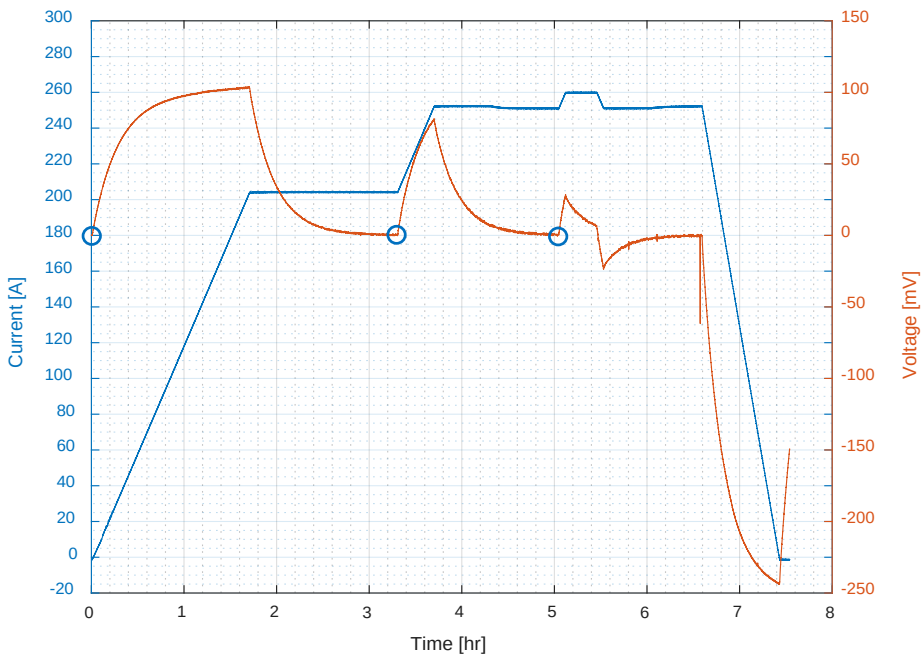
Center field, current vs. Time

Center field mapping along z-axis

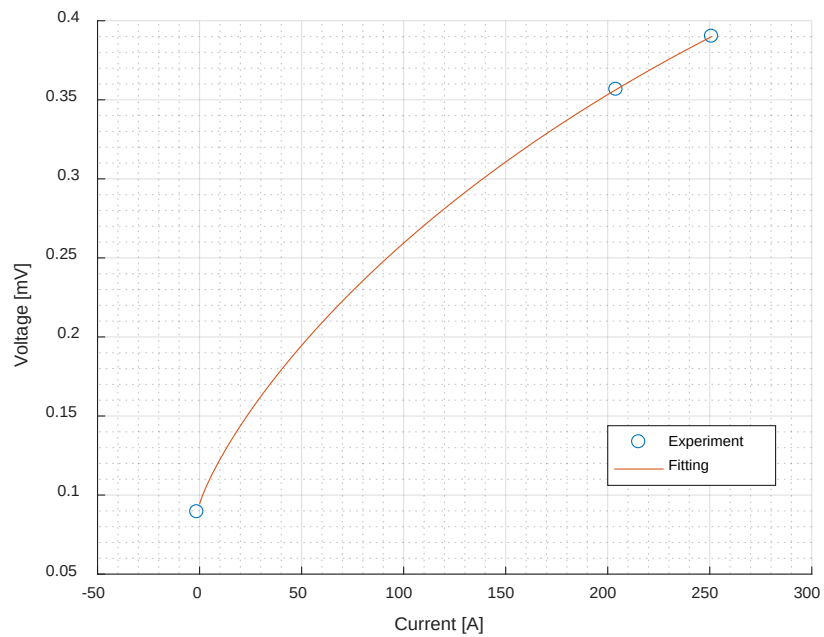
- Coil 2 ramped up to 251.3 A, I_{op}, and beyond, 260 A.
- Field distribution at 4.2 K is more symmetric than 77 K REBCO has more symmetrical field angular dependence characteristics at 4.2 K than 77 K
- It seems SCF generating Z2 error term was not erased by over current (O.C.) since 260 A is still far lower than I_c

HC	Unit	Calculation (As Wound)	Before O.C. @ 251.3 A	After O.C. @ 251.3 A
Z1	ppm/cm^1	-7.4	-3.6	-14.4
Z2	ppm/cm^2	-368.3	-379.2	-395.9
Z3	ppm/cm^3	0.9	3.6	5.4
Z4	ppm/cm^4	-1.4	-1.3	-1.3
Z5	ppm/cm^5	0.0	0.0	0.0
Z6	ppm/cm^6	0.0	0.0	0.0

Coil 2 Test-2 @ 4.2 K



Coil voltage, current vs. Time



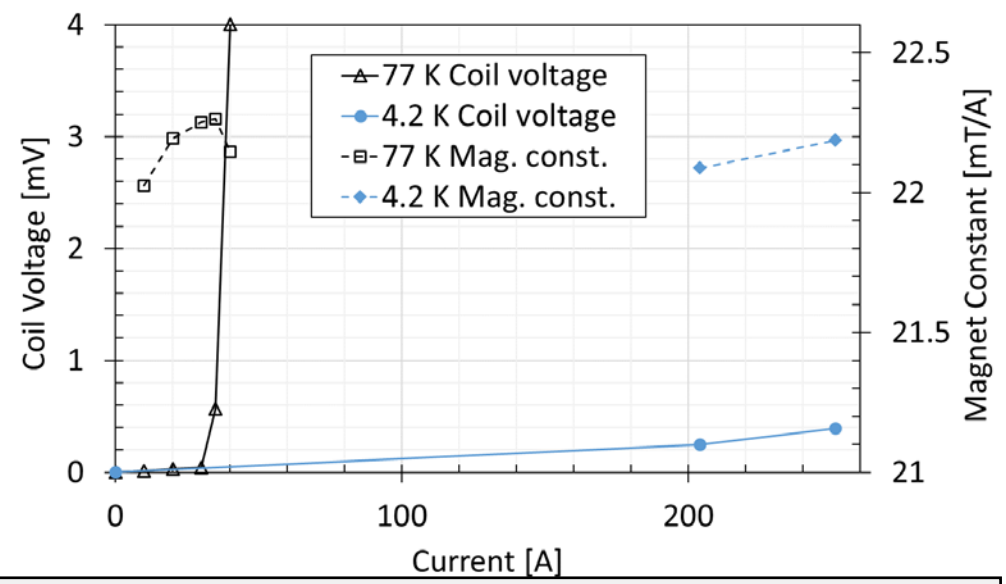
Coil voltage, current vs. Time

- Coil overall voltage @ 204 A: 0.26 mV

  (similar with 1st 4.2-K test result)

  : 100~105 nΩcm2

- No discernible resistive voltage was observed

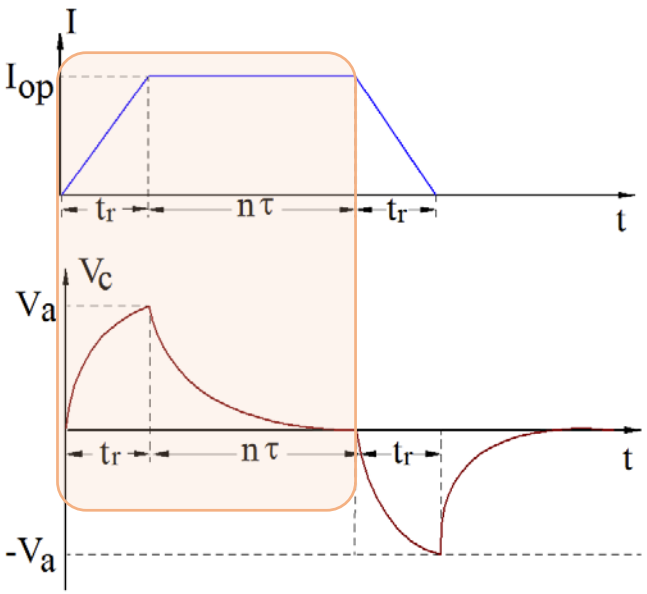


Coil voltage, magnet constant summary for Coil 2

Coil 2 Tests @ 4.2 K

Helium consumption during charging of NI coils:

- Analytical approach
- Experimental measurement by both flow meter and LHe level meter



$$Q_t(t) = Q_s + I^2(t)\,R_j + \frac{V_c^2(t)}{R_m}$$

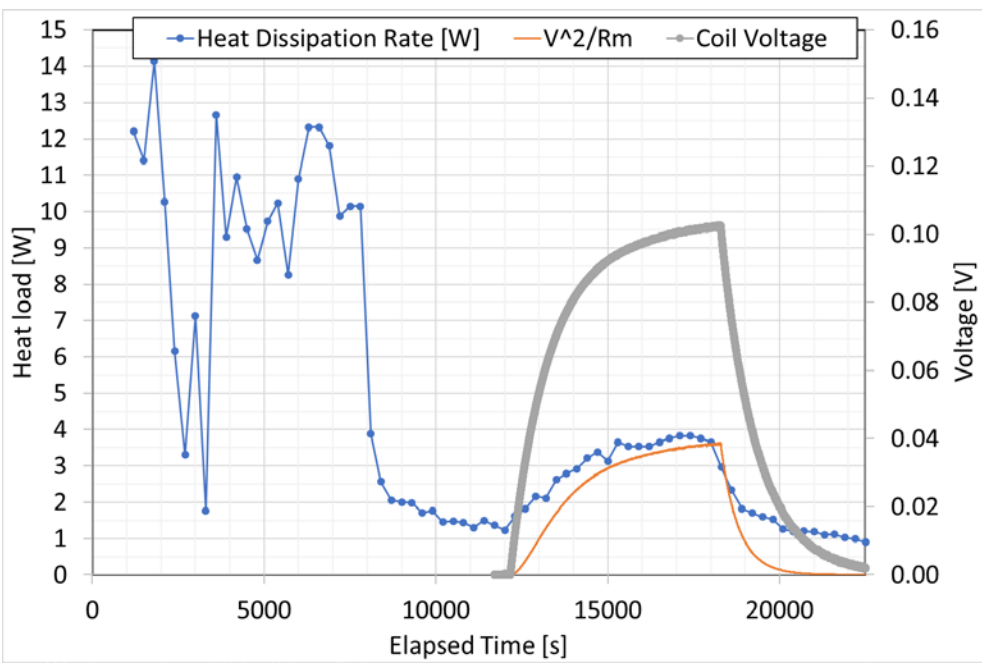
E_c: unique term in NI coils

$$E_c = \frac{L_m\,\tau\,I_{op}^2}{t_r^2}\left[t_r + \tau\,exp\left(\frac{-t_r}{\tau}\right) - \tau\right]$$

with L_m = 3.04 [H], I_{op} = 204 [A], t_r = 6120 [s], τ = 1050 [s]

➔ **E_c = 18 kJ**,

Dissipated during charging only by turn-to-turn resistance



- Heat dissipation rate was measured by gas flow meter. Integrated heat dissipation during charging and settling was **26.4 kJ**

  c.f.) 18 kJ (analytical & numerical, $\int \frac{V(t)^2}{R_m} dt$, way)
- Standing loss + Joule heating from current leads/joints = (26.4-18) kJ / 11,300 s = 0.72 W

Summary

Phase 3B of **MIT 1.3-GHz LTS/HTS NMR** magnet project is in good progress

- ✓ Coil 2 of 3-nested-coil H800 was completed

  - Assembled, DP-DP jointed, over-banded, and most importantly, successfully tested at 4.2 K to its design current of 251.3 A and beyond up to 260 A without discernible resistive voltage

  - The center field was 5.6 T (<1% discrepancy by SCF)

- ✓ Coil 3, the outermost stack of 38 DPs, we have wound all DPs and tested at 77 K

- ✓ We plan to assemble all 3 coils into H800 and operate it at 77 K and 4.2 K in early 2018.

As-Wound H800 Key Parameters @ 4.2 K, I_{op} = 251.3 A (Appendix.)

Parameter		Coil 1	Coil 2	Coil 3
Frequency	[MHz]	369	240	189
Field contribution	[T]	8.67	5.64	4.44
$B_{\perp, Max}$ at 1.3 GHz	[T]	4.8	4.6	3.8
$I_c(B_\perp, 4.2\ K)/I_c(77\ K, sf)$		>2.3	>2.3	>2.7
Total # DP coils		26	32	38
# Inside-Notched DP coils		6	10	8
# turns/pancake		185	120	96
# turns/notched pancake		177	118	92
ID average of regular DPs	[mm]	91.0	150.79	196.90
ID average of notched DPs	[mm]	92.35	151.41	197.20
OD average (before over-band)	[mm]	119.12	169.23	211.30
Overall height	[mm]	323.65	393.93	465.65
SS over-band radial build	[mm]	7	5	3
Inductance	[H]	2.43	3.04	3.77
Charging delay time constant	[s]	570	1030	1400[1]
Average turn-to-turn resistivity, ρ_c	[$\mu\Omega\cdot cm^2$]	37	60	86
Axial force on mid-plane	[kN]	363	613	772
Peak total hoop strain	[%]	0.47	0.39	0.35
Field error at 1-cm / 3-cm DSV	[ppm]	1.1 / 34 (peak-to-peak)		