No Protection Device: No-Insulation HTS Magnets

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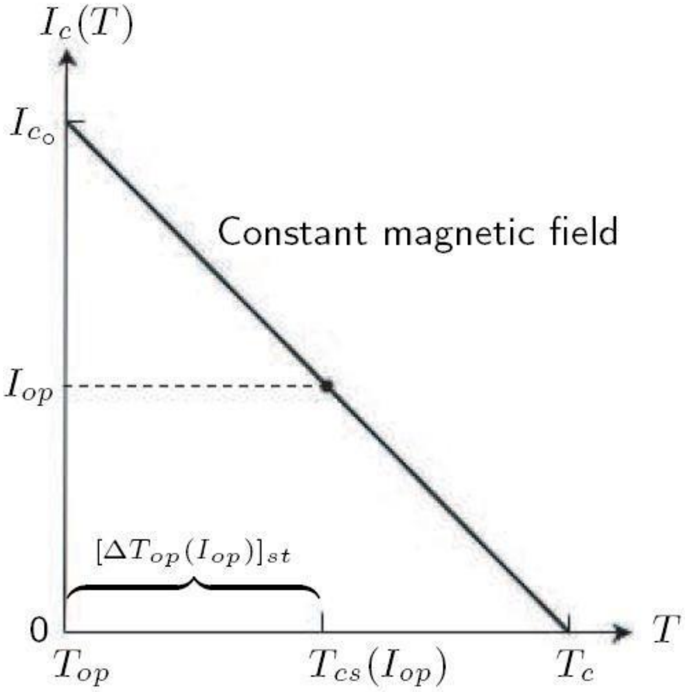
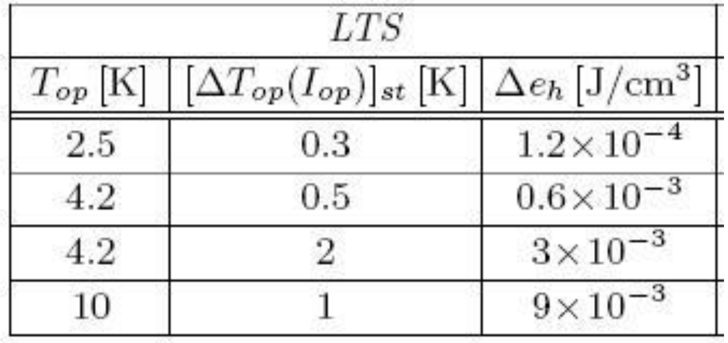
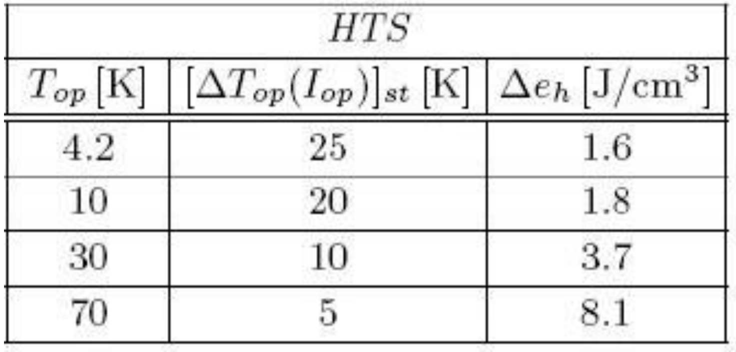
Stability Margin: LTS vs. HTS

- Stability Margin [J/m³]: $\Delta e_h = \int_{T_{op}}^{T_{cs}(I_{op})} C_{cd}(T)\,dT$





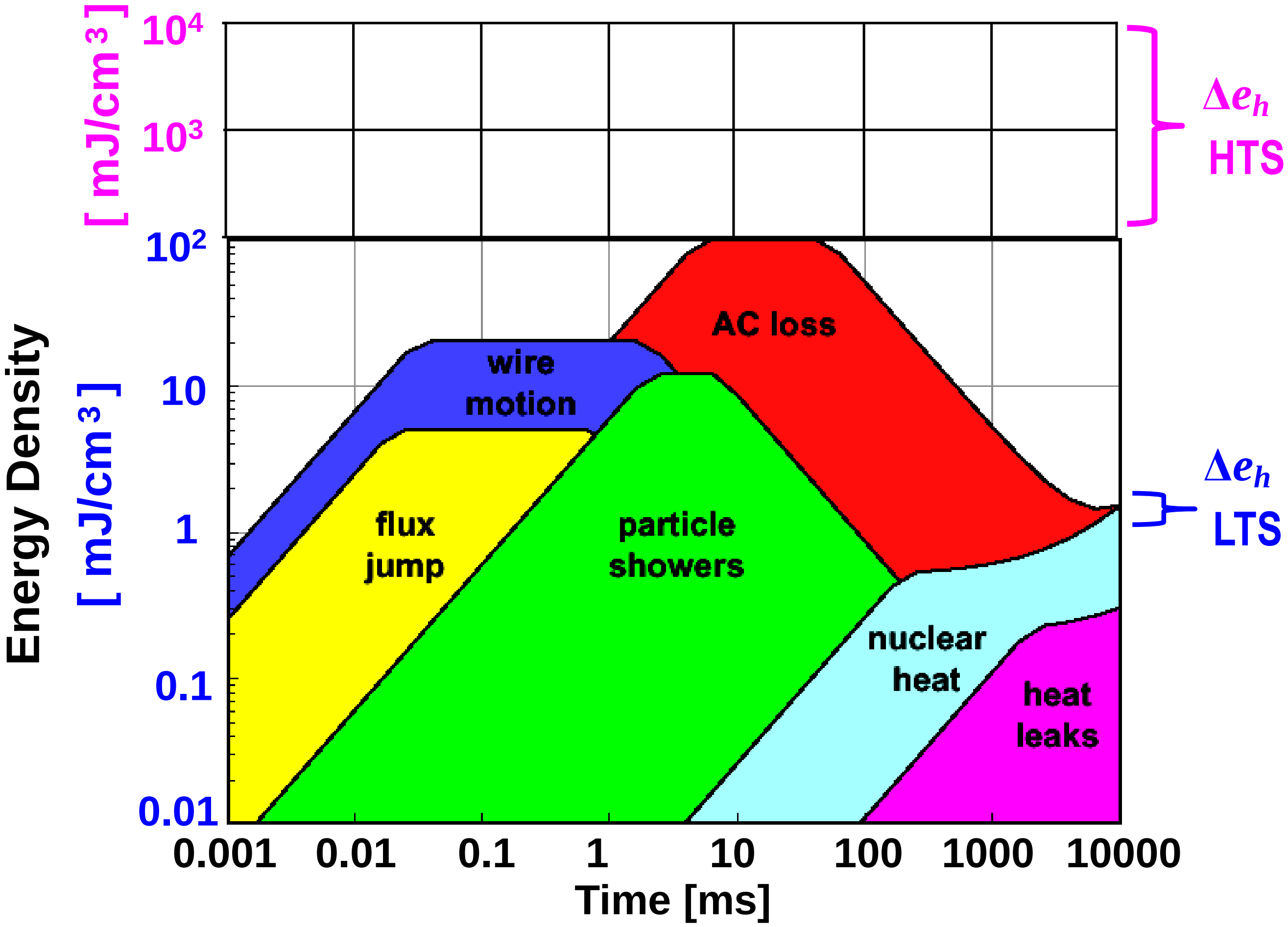
LTS		
T_{op} [K]	$[\Delta T_{op}(I_{op})]_{st}$ [K]	Δe_h [J/cm³]
2.5	0.3	1.2×10^{-4}
4.2	0.5	0.6×10^{-3}
4.2	2	3×10^{-3}
10	1	9×10^{-3}



HTS		
T_{op} [K]	$[\Delta T_{op}(I_{op})]_{st}$ [K]	Δe_h [J/cm³]
4.2	25	1.6
10	20	1.8
30	10	3.7
70	5	8.1

✓ > 100 times larger stability margin of HTS magnet than that of LTS

Disturbance Energy Spectra



- ✓ Low stability margin and consequent premature quench are major problems of NbTi magnets
- ✓ In contrast, HTS magnets having "large stability margin" rarely quench.

Major sources for HTS magnet quenches: 1) accidental failure; 2) unexpected "local" defect

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Protection Challenge of HTS Magnet and NI HTS Winding Technique

- Key Issues in Protection of Superconducting Magnets

Problem: concentration of the entire energy on a local hot spot

⇩

Solution: 1) fast energy dumping into the outside of a magnet
2) uniform energy dissipation within a magnet

No-Insulation

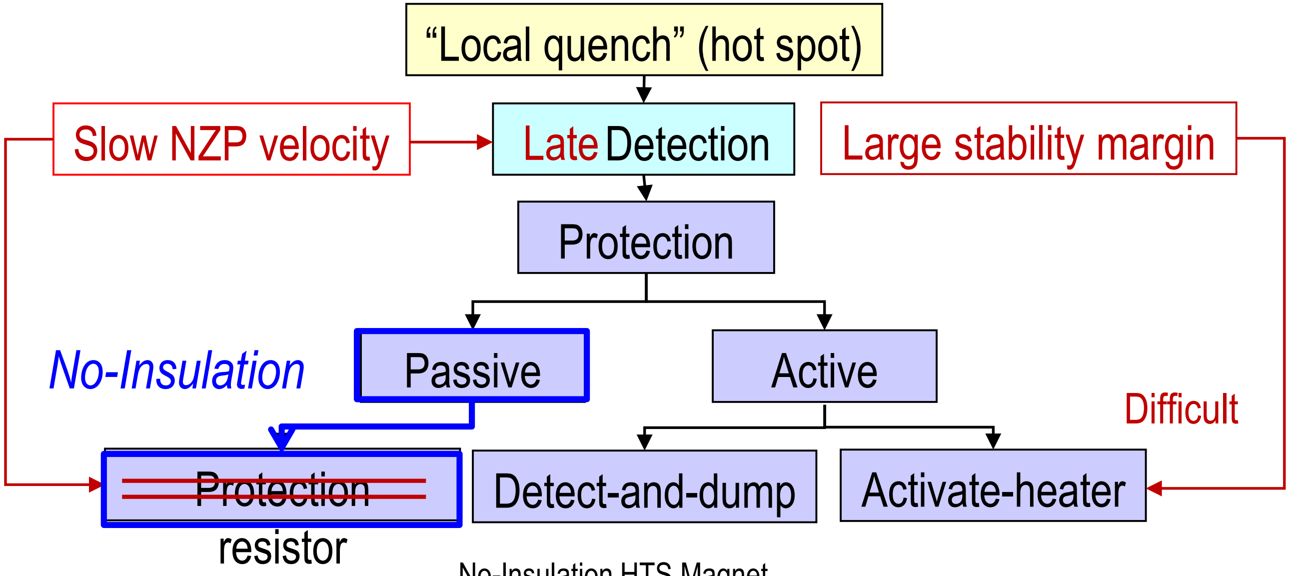
✓ Thermal issue: Overheating, T_{max}

✓ Mechanical issue: Overstrain, ε_{max}

✓ Cryogenic issue: Overpressure, P_{max}

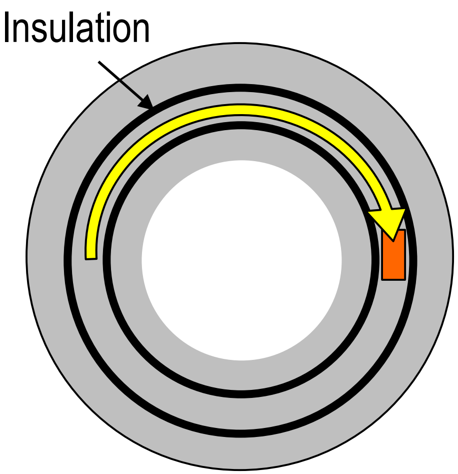
✓ Electrical issue: Breakdown, V_{max}

- Challenges in Protection of HTS Magnets
  - ✓ ~100 times larger stability margin of HTS than that of LTS
  - ✓ ~1000 times slower NZP of HTS than that of LTS



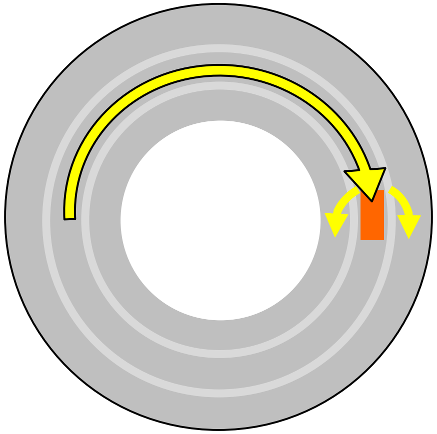
No-Insulation HTS Winding Technique

INS: Difficulty in Protection



- ☐ Slow normal zone propagation in HTS
  - ➔ Slow quench detection
- ☐ Larger enthalpy (stability margin) of HTS
  - ➔ Difficulty in “activate-heater” protection

NI: “Quench Current Bypass”

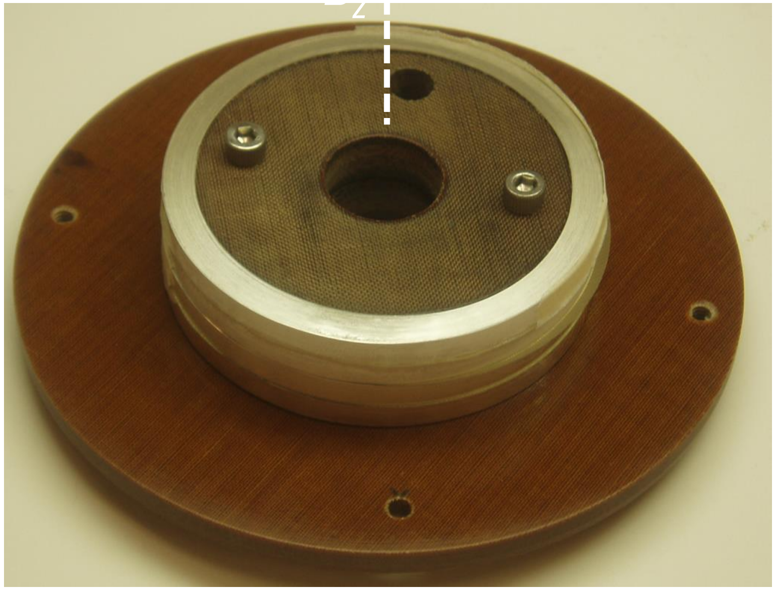


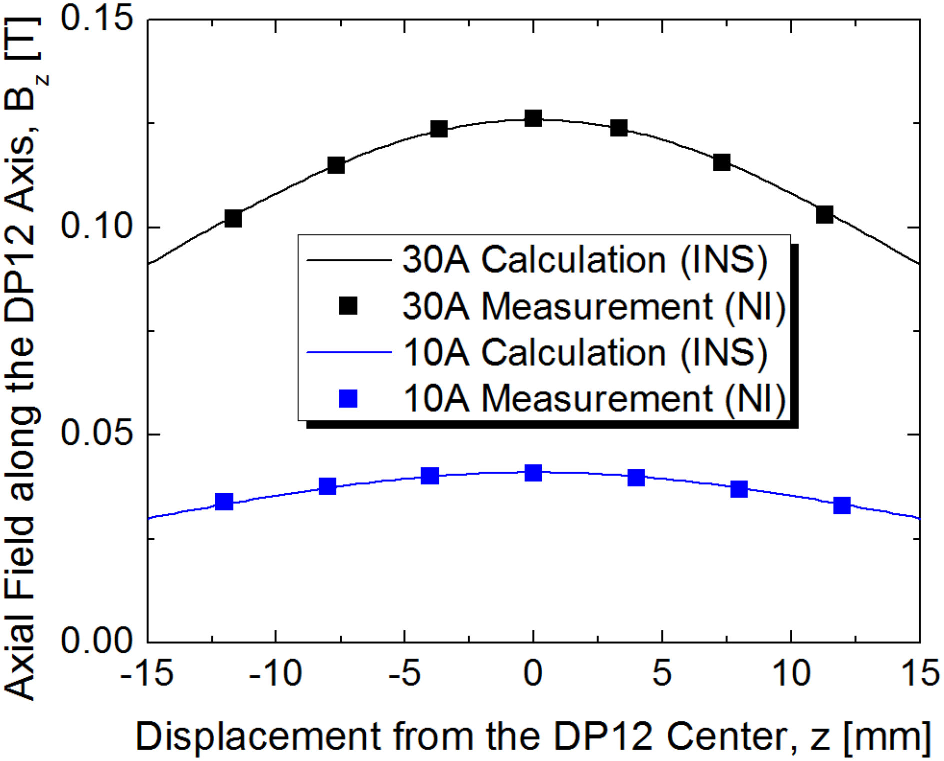
- ☐ “Automatic bypass” of quench current through turn-to-turn contacts

REF: S. Hahn, D. Park, J. Bascuñán, and Y. Iwasa, “HTS Pancake Coil without Turn-to-Turn Insulation,” *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 1592 – 1595, 2011.

Comparison of Spatial Field Distributions between NI and Insulated Coils

An REBCO NI Magnet (2012)
- Stack of 2 double pancake coils
- Wound with “no-stabilizer” tapes





- Axial fields measured along the magnet axis at operating currents of 10 A and 30 A.
- Barely discernible difference (by a Hall sensor) in spatial field distributions between an NI coil and its insulated counterpart (numerical simulation).
- Need for further investigation on the spatial field distributions for NMR applications

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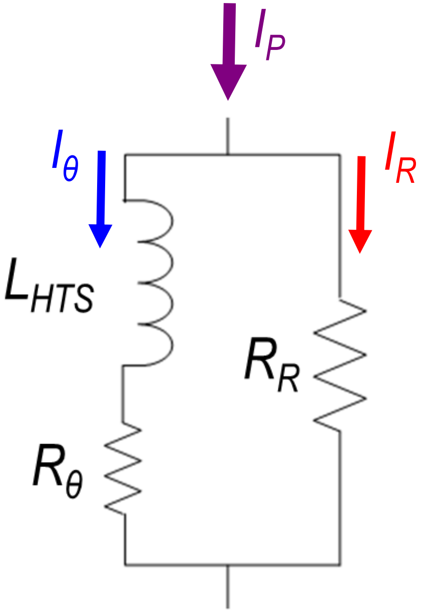
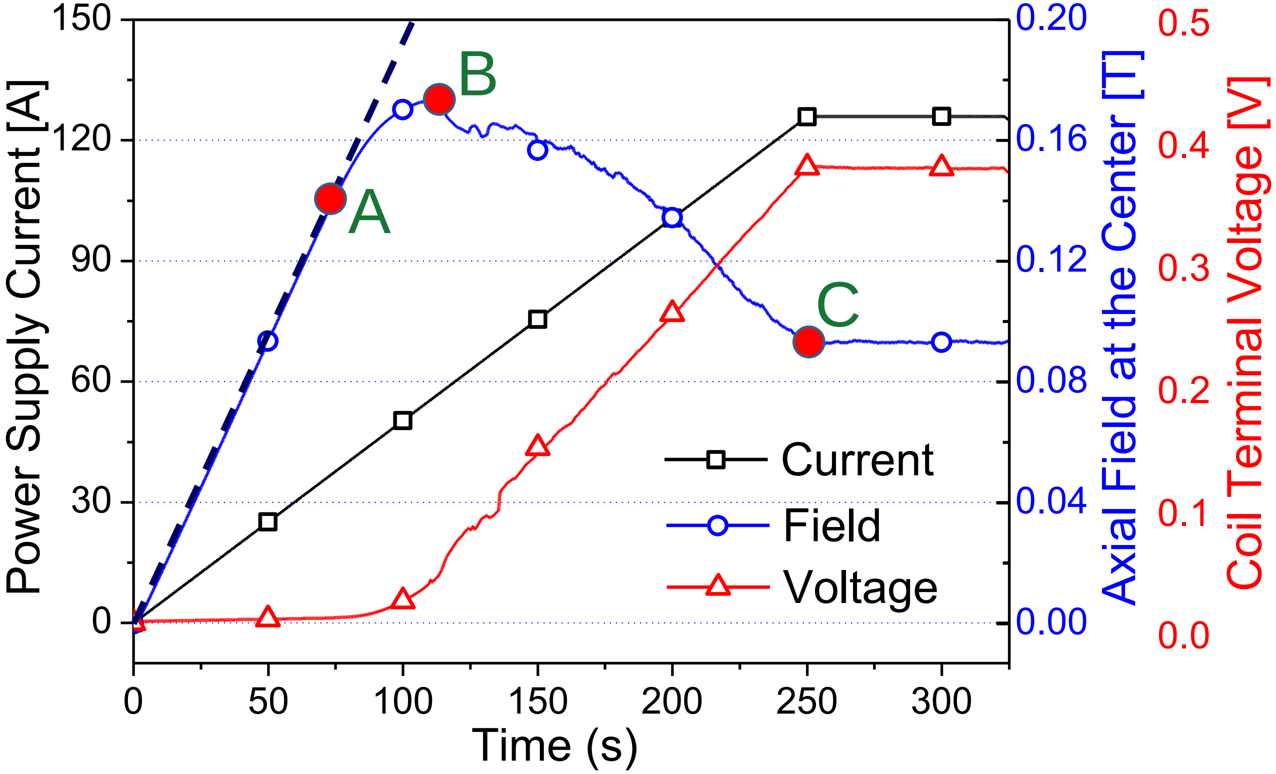
“Bypass” of Quench Current through Turn-to-Turn Contacts





- ☐ “A”: Initial local quench (R_θ > 0) at Ic; start of field saturation ($I_R \approx 0$; $I_p \approx I_\theta$)
- ☐ “B”: Full quench; no more field increase after this point
- ☐ “C”: I_p(125 A) >> I_c(38 A); (I_θ: 23 A, I_R: 102 A)
- ☐ Short sample burned at 61 A in liquid nitrogen

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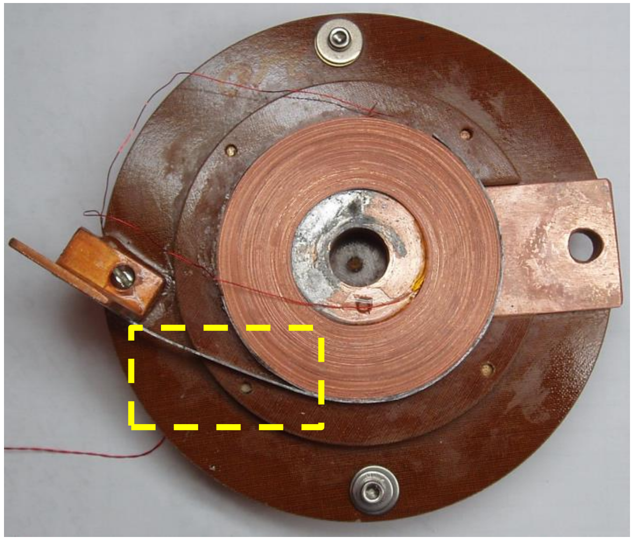
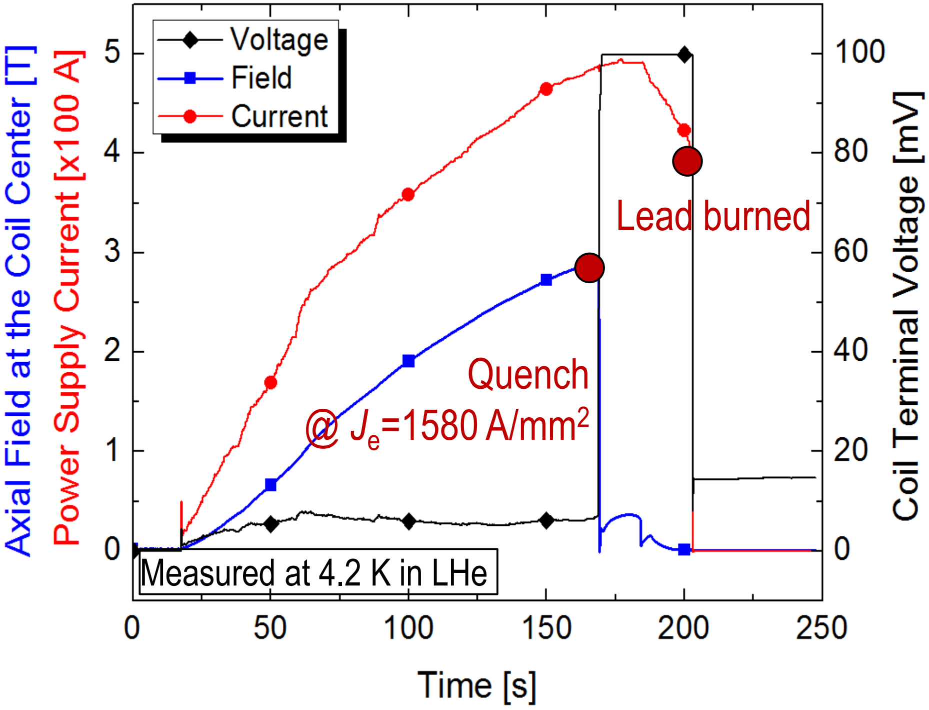
"Survival" of an NI REBCO Coil at 1580 A/mm^2

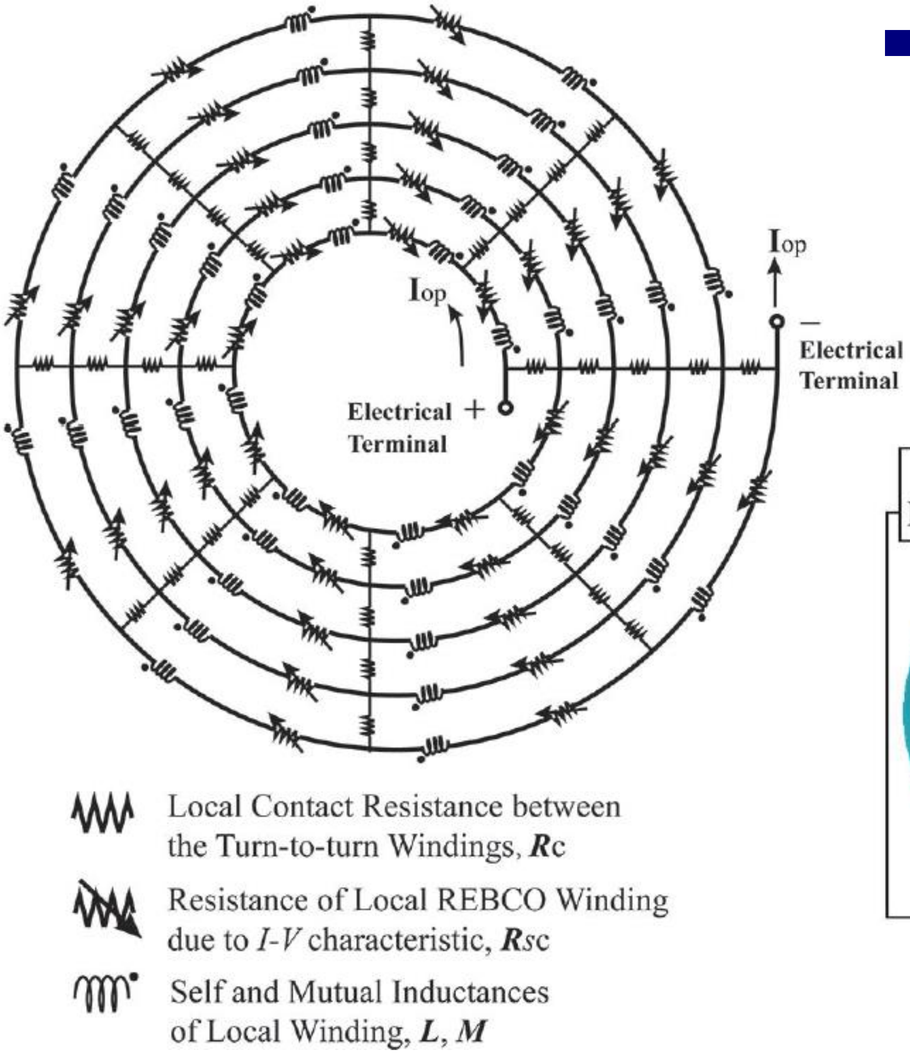


Parameters		**Values**
Conductor		
Overall width; thickness	[mm]	4.0; 0.065
Cu stabilizer thickness	[µm]	10 (5 per each side)
Coil		
i.d. (2a$_1$); o.d (2a$_2$).; height (h)	[mm]	25.4; 53.2; 4.0
Turns; layers		210; 1 (single pancake)
Inductance	[mH]	1.87
Magnet constant (B$_{zc}$ @ 1 A)	[mT]	6.97
Charging time constant	[s]	30

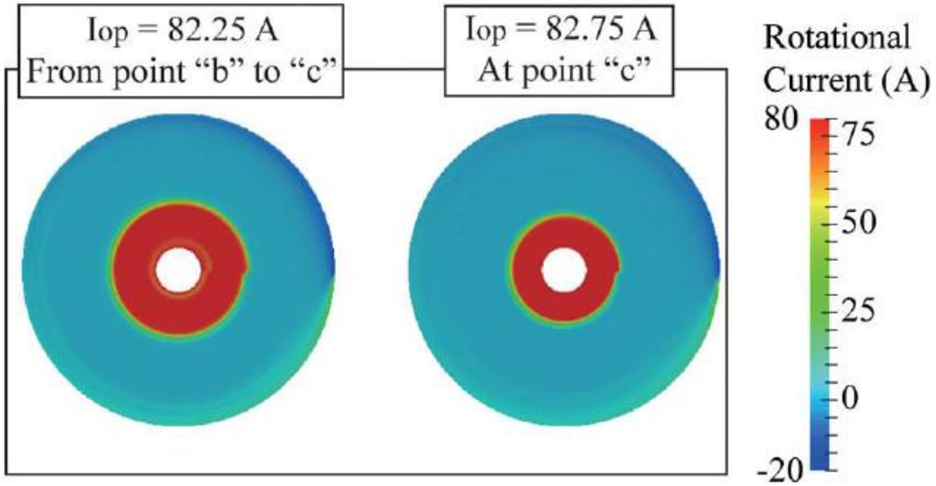


- ☐ Coil quench at 412 A (1580 A/mm^2)
- ☐ Short sample burned at 90 A in LN2

Comprehensive Numerical Analysis



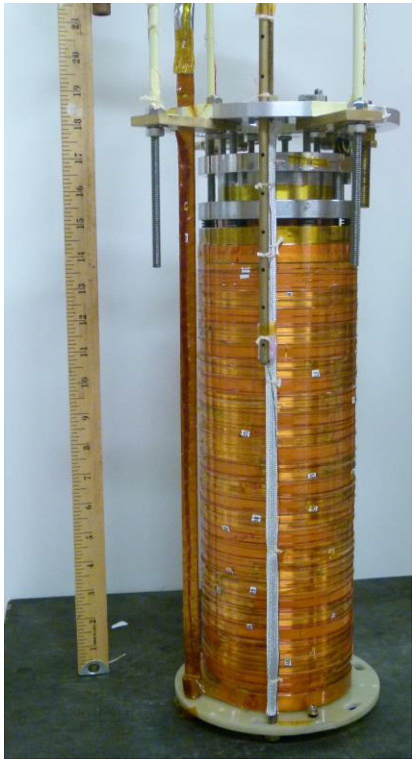
- Partial Element Equivalent Circuit (PEEC) Model for Transient Electromagnetic and Thermal Analysis of NI Coil (2014)



REF: T. Wang, S. Noguchi, X. Wang, I. Arakawa, K. Minami, K. Monma, A. Ishiyama, S. Hahn, and Y. Iwasa, " Analyses of Transient Behaviors of No-Insulation REBCO Pancake Coils During Sudden Discharge and Overcurrent," *IEEE Trans. Appl. Supercond.,* 25, June 2015 (4603409).

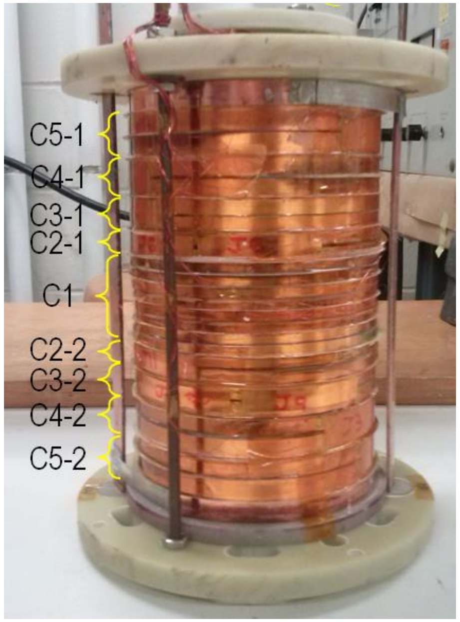
Progress in No-Insulation Magnets

8.7-T/91-mm REBCO (2014, MIT-FBML)



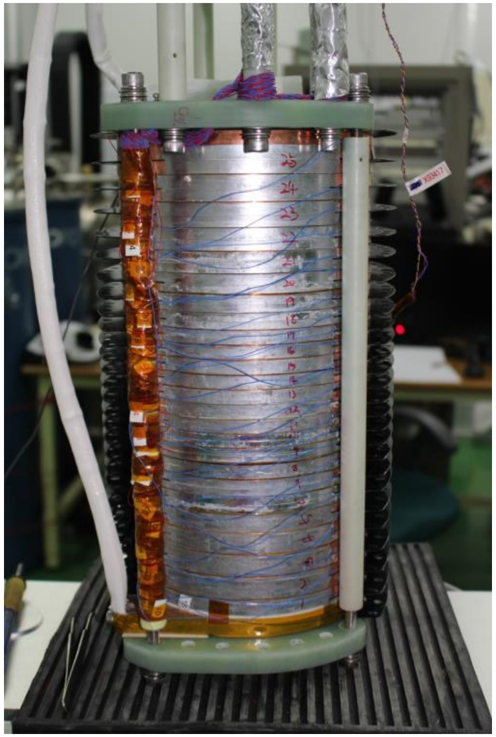
- Coil OD: 119 mm
- *Survived after quench* at J_e of 510 A/mm^2

9-T/78-mm MW REBCO (2014, MIT-FBML)



- Coil OD: 101 mm
- *Survived after quench* at J_e of 895 A/mm^2

26-T/35-mm MW REBCO (2015, SuNAM/MIT/FSU)



- Coil OD: 172 mm
- *Survived after quench* at J_e of 392 A/mm^2

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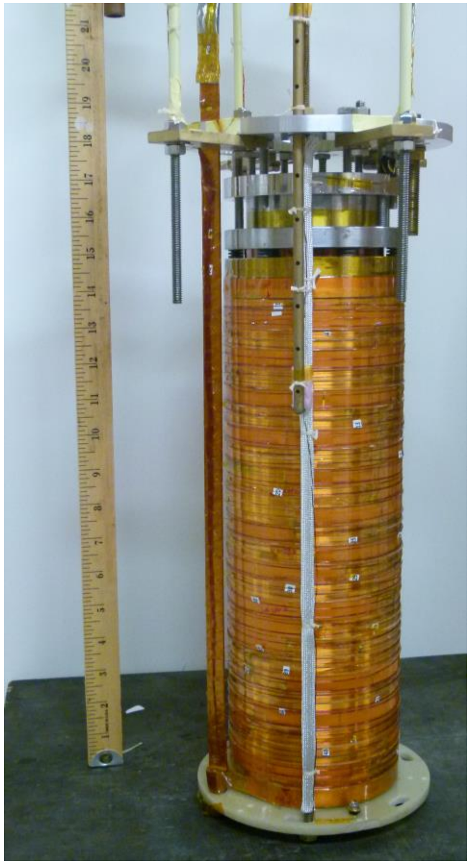
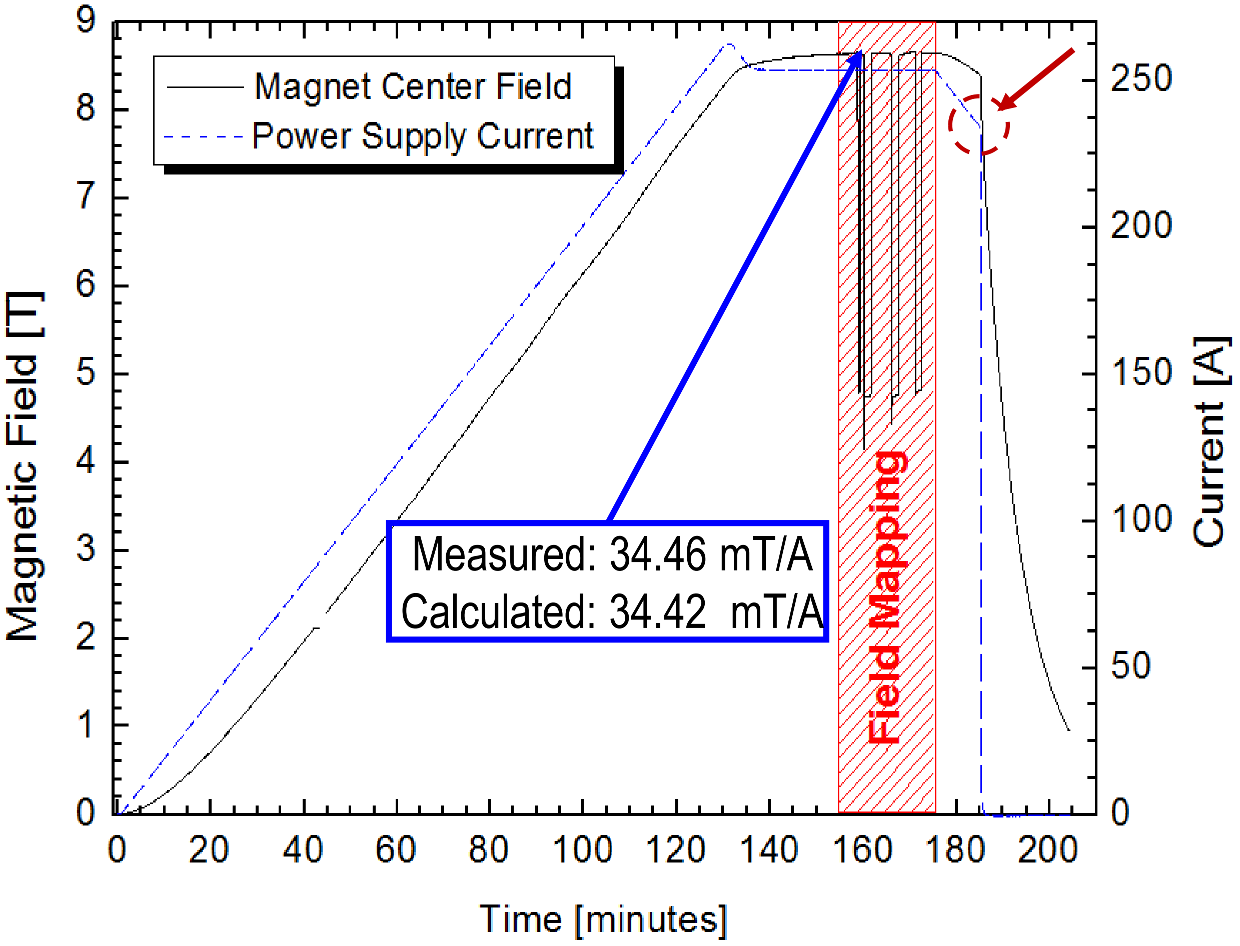
8.7-T/91-mm Insert1 Test Results at 4.2 K

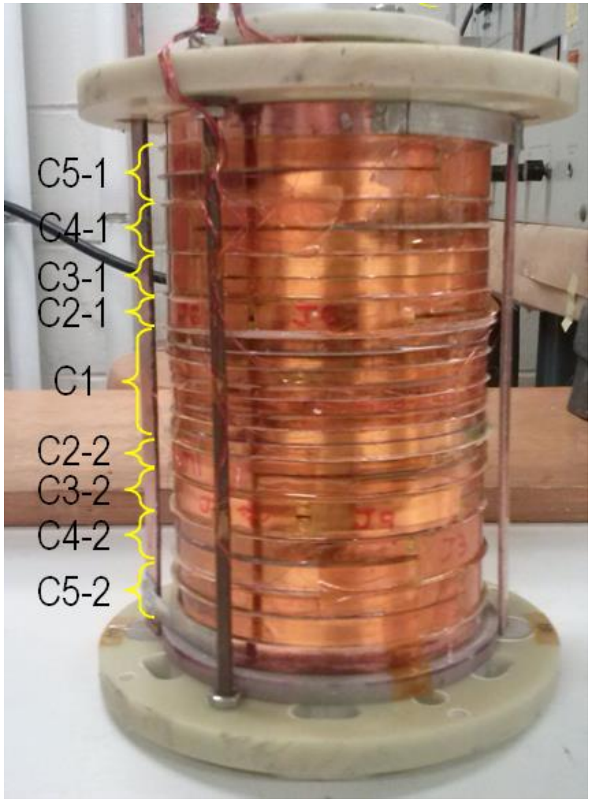
- Operation in Liquid Helium at 4.2 K (Charging Rate: 2.1 A/min)
  - ☐ Accidental power supply failure at 235 A (510 A/mm^2): tne magnet survived

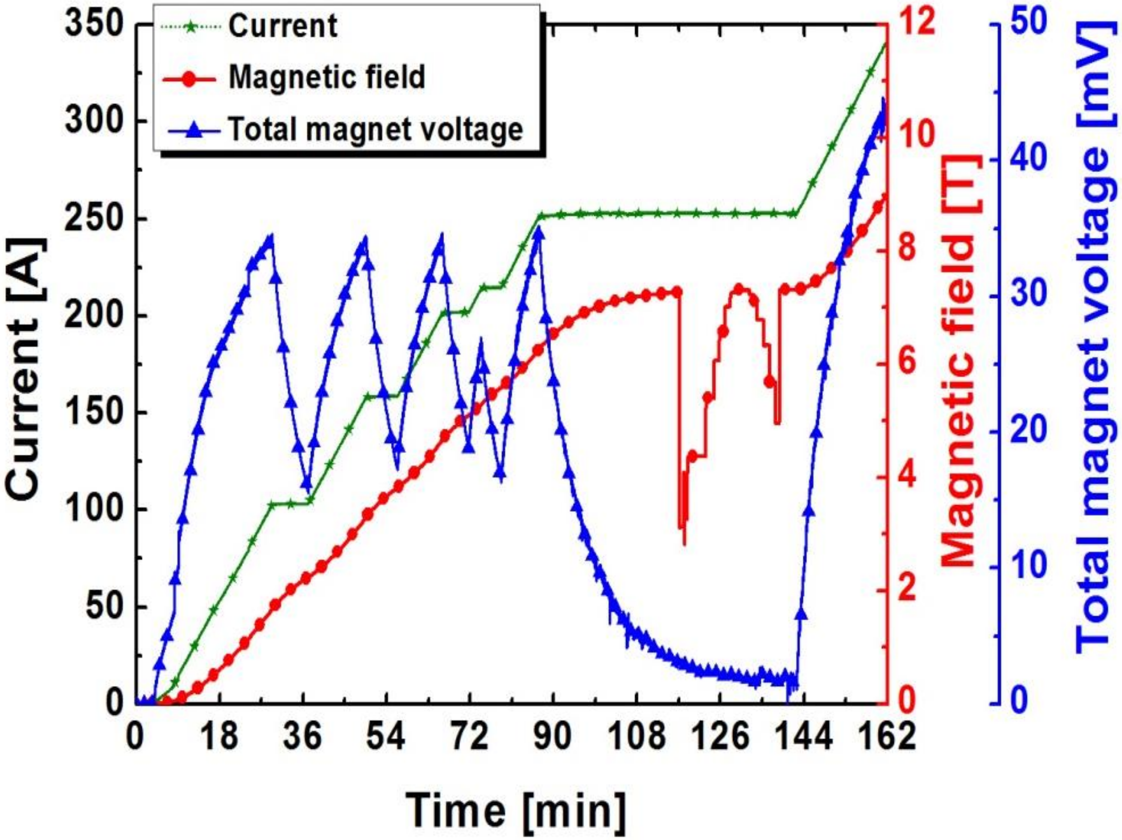




7-T/78-mm MW-NI Magnet Test Results at 4.2 K

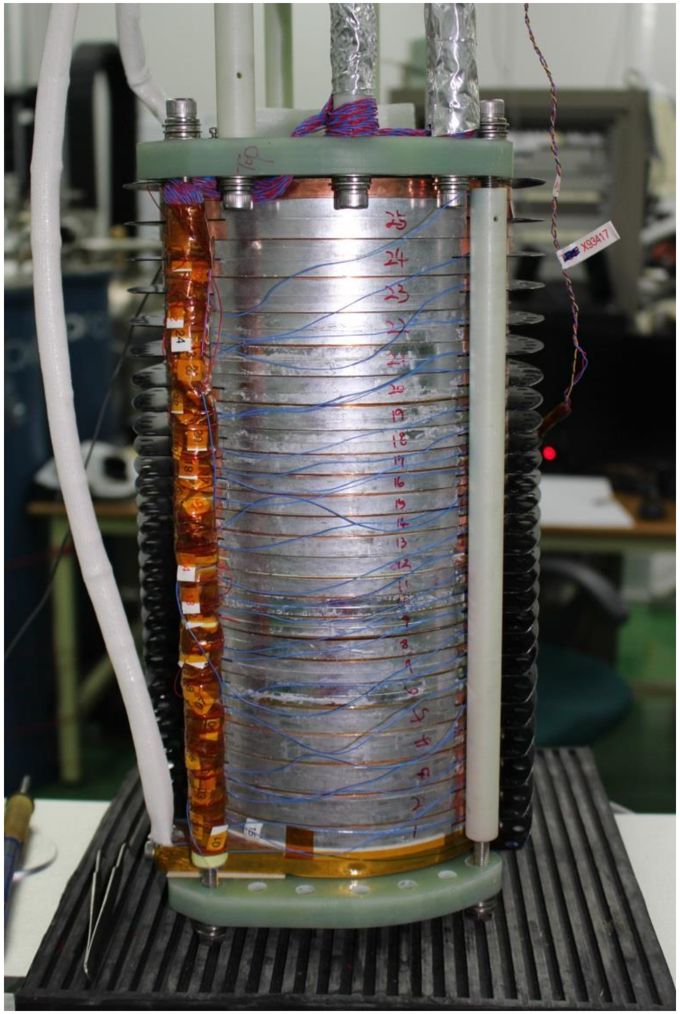
- Tests in Liquid Helium at 4.2 K
  - Surpassed the designed field strength of 7 T and reached 9 T
  - Magnet quench at 9 T (895 A/mm^2): the magnet survived





26-T/35-mm MW-NI Magnet Test Results at 4.2 K

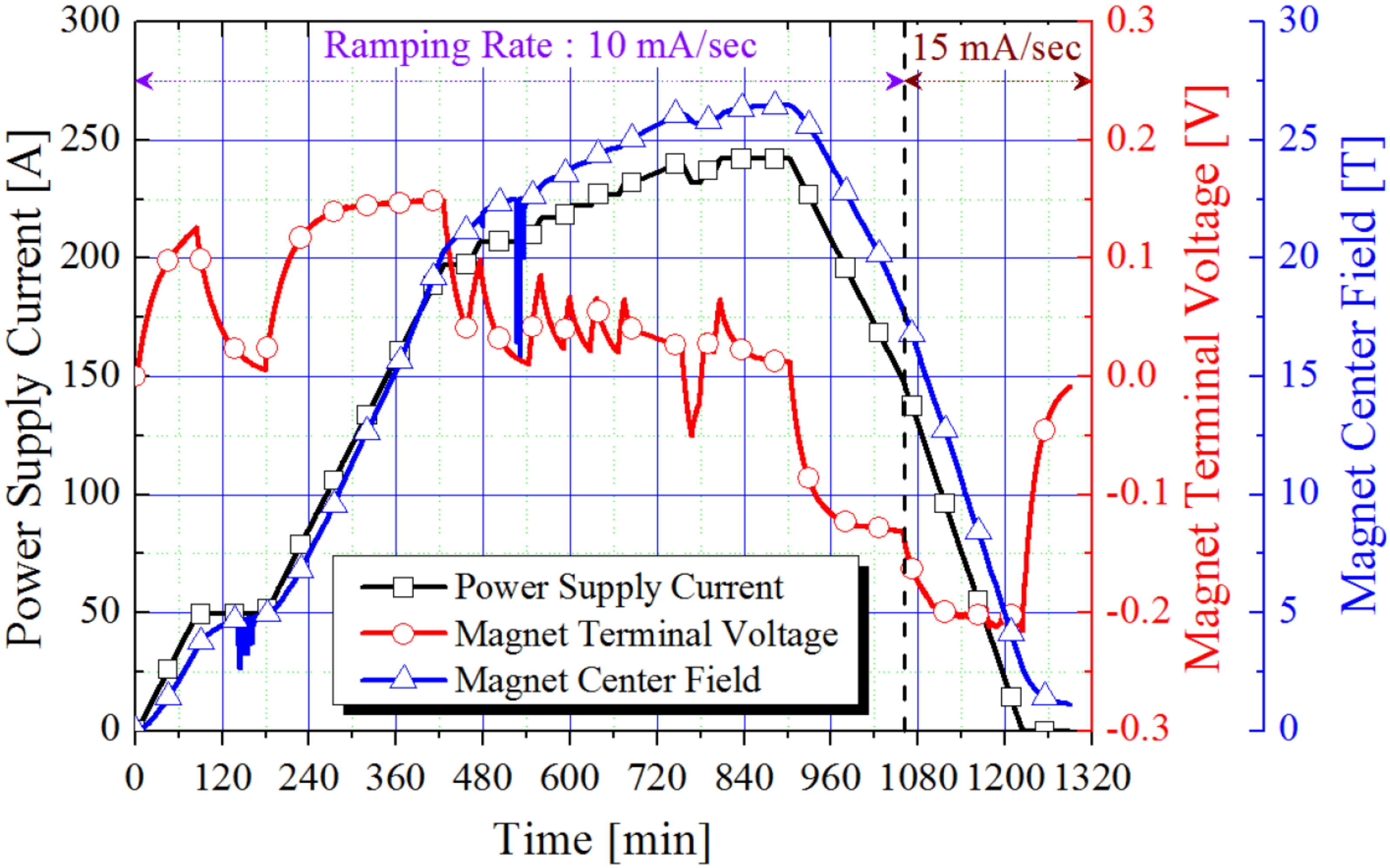
- 26-T/35-mm MW-NI All-REBCO Magnet
  - Designed by S. Hahn; constructed and firstly tested by SuNAM



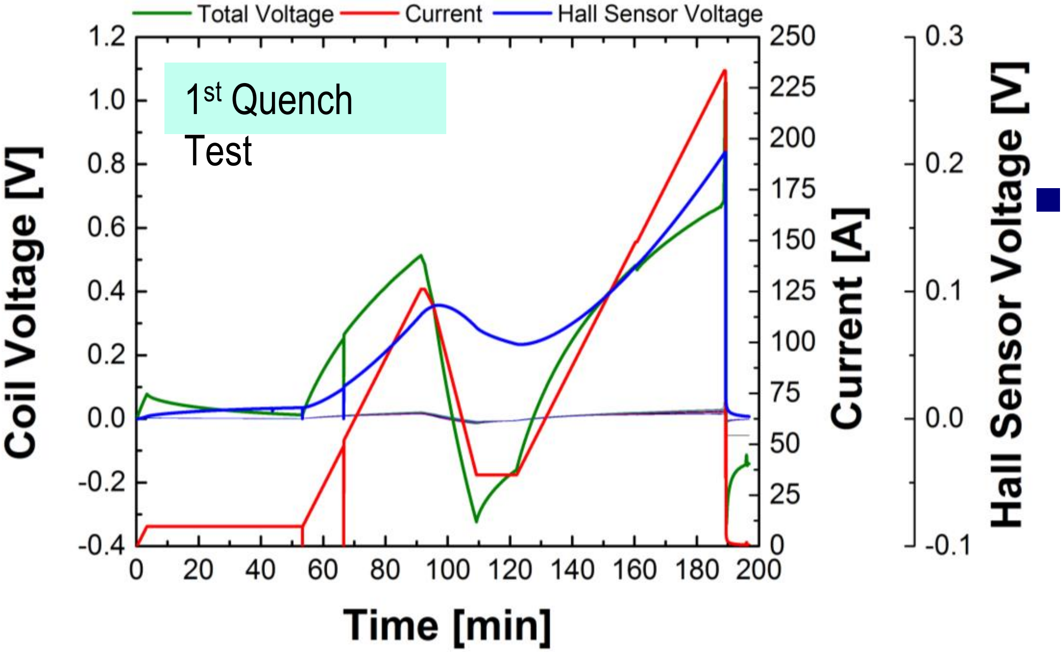
Parameter		M1	M2	M3	M4	M5
Magnet Configuration						
Average tape width	[mm]	4.1	5.1	6.1	7.1	8.1
Average tape thickness	[μm]	146	145	135	138	135
Pancake-pancake spacer	[mm]			0.2		
Coil i.d.; o.d.	[mm]			35.0; 171.9		
Overall height	[mm]			327		
Number of DP		10	4	4	4	4
Turn per DP		914	916	996	968	984
Conductor per DP	[m]	297	298	324	315	320
Total conductor	[km]	3.0	1.2	1.3	1.3	1.3
Operation and Performance						
Magnet constant	[mT/A]			109.2		
Operating temperature	[K]			4.2 (liquid helium)		
Current density at 26.4 T	[A/mm^2]	404	327	293	247	221
Inductance, L	[H]			12.79		
Peak $B_\perp$	[T]	1.54	1.59	1.82	2.08	3.68
Time constant (77 K), τ_c	[sec]			947 (12.79 H/13.5 mΩ)		
Peak hoop stress at 26.4 T	[MPa]			286		

26-T/35-mm MW-NI All-REBCO Magnet

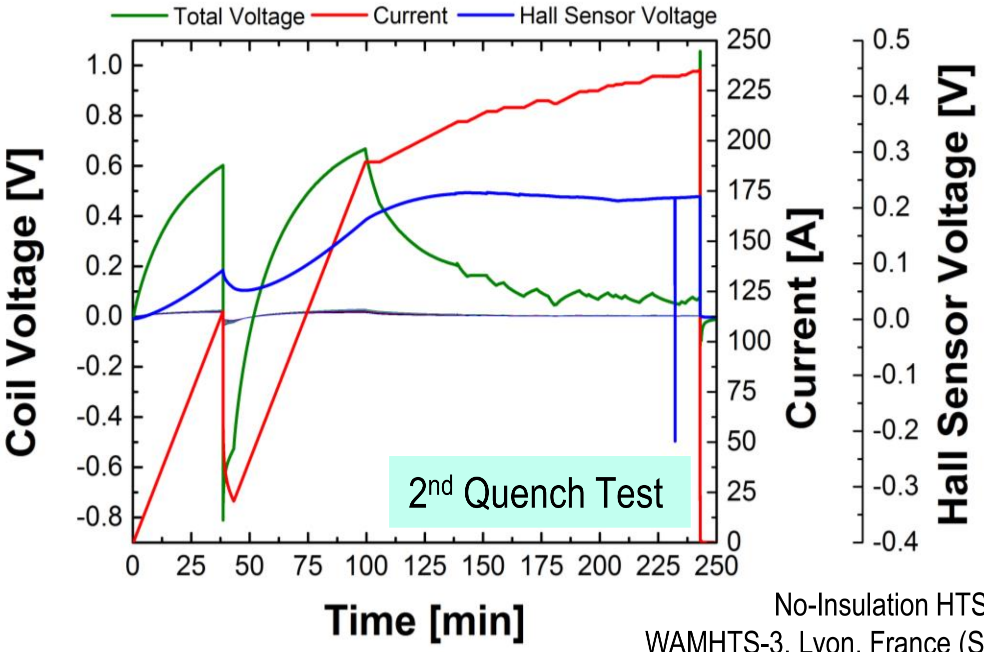
- First LHe (4.2-K) Test at SuNAM, Co., Ltd.
  - ☐ Current ramping rate: 0.01 A/s
  - ☐ 26.4-T (a record high in all-HTS magnet) at 242 A.



Two Consecutive Quench Tests of the 26T at the NHMFL



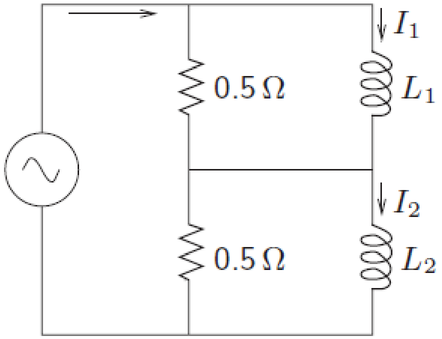
- First Quench Test
  - ☐ First quench at 230 A
  - ☐ Current ramping rate: 0.05 A/s



- Second Quench Test
  - ☐ Second quench at 235 A
  - ☐ Current ramping rate: 0.05 A/s for 0→200 A; 0.01 A/s for 200→235 A
  - ☐ The magnet survived after two consecutive quenches.

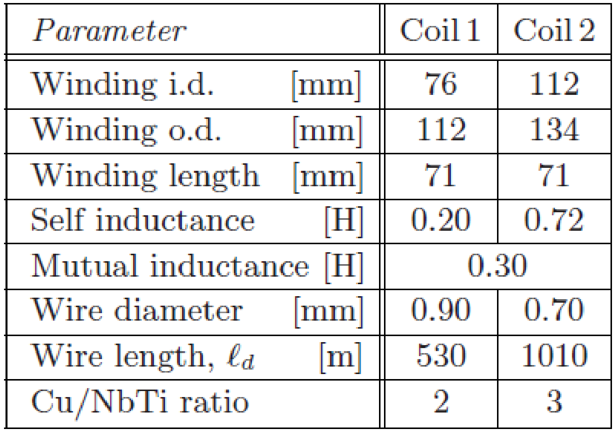
Passive Protection: Self-Protecting Magnet

- Test Example of an "isolated" and "nested" 2-coil magnet [Case Studies 2nd Edition]
  - ✓ (A): Initial quench in Coil 1 and initial increase of I_2 by the flux conservation
  - ✓ (B): Induced quench in Coil 2 and consequent increase of I_1
  - ✓ (C): V1+V2=10 V (power supply max voltage) and consequent decrease of I_1 and I_2

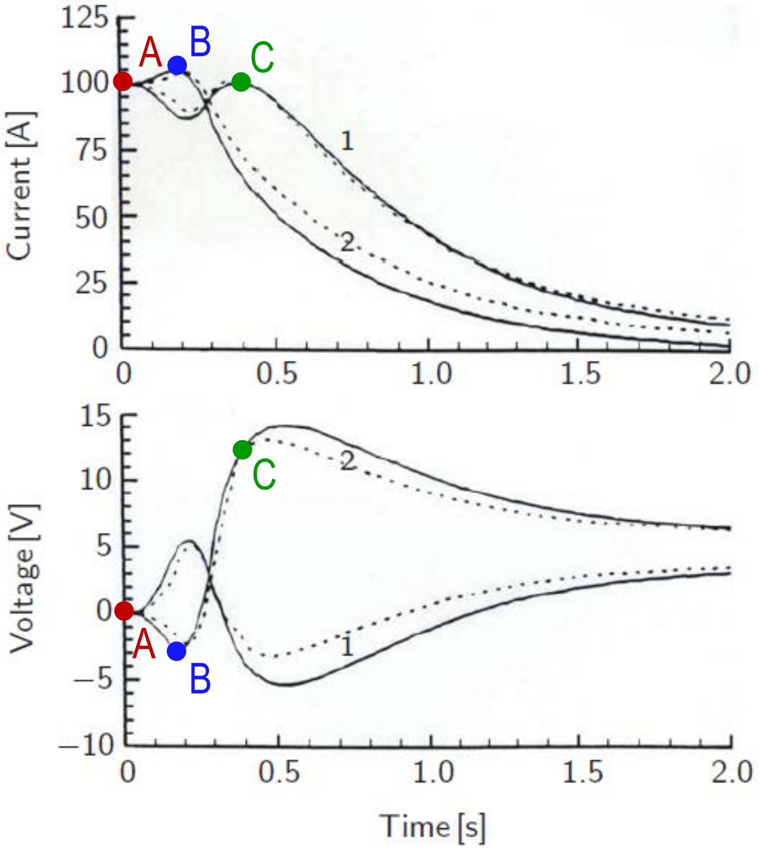


MAX. 10 V
with Constant
Current Mode

Table 8.6: Coil Parameters

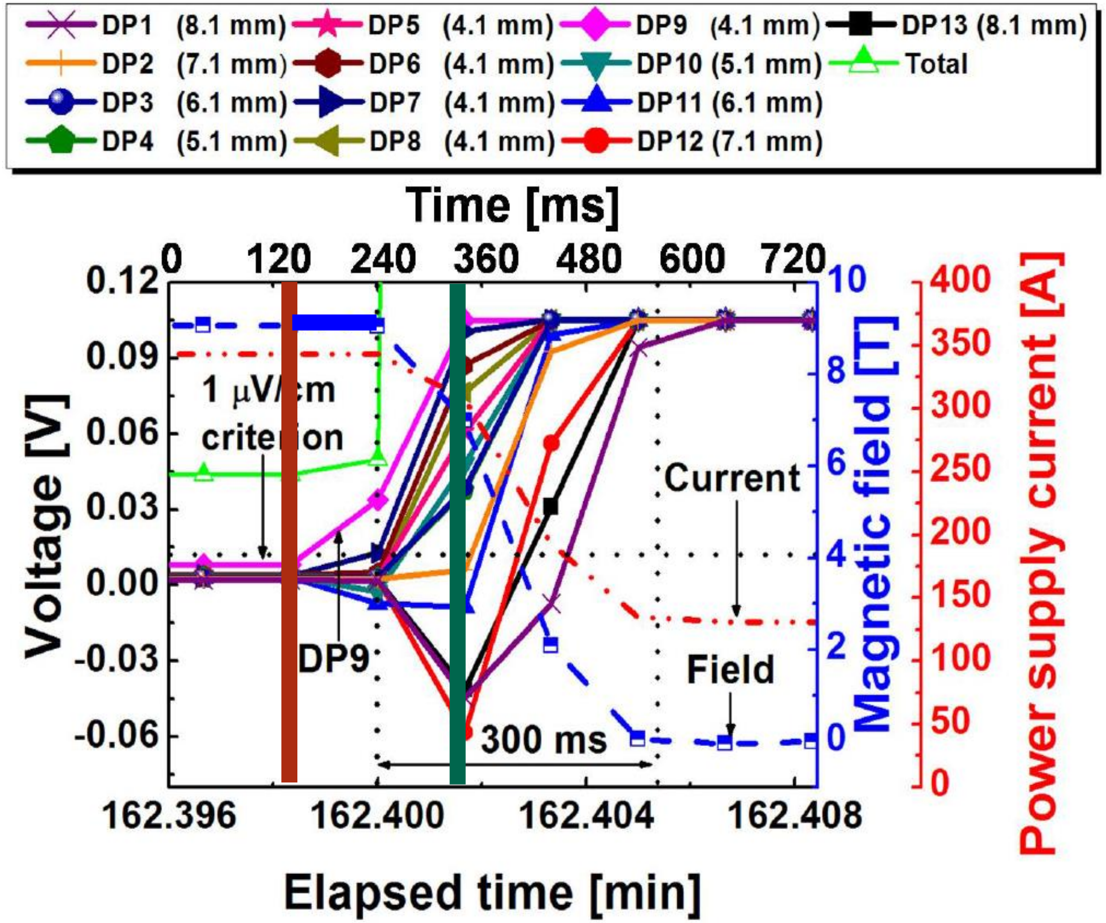


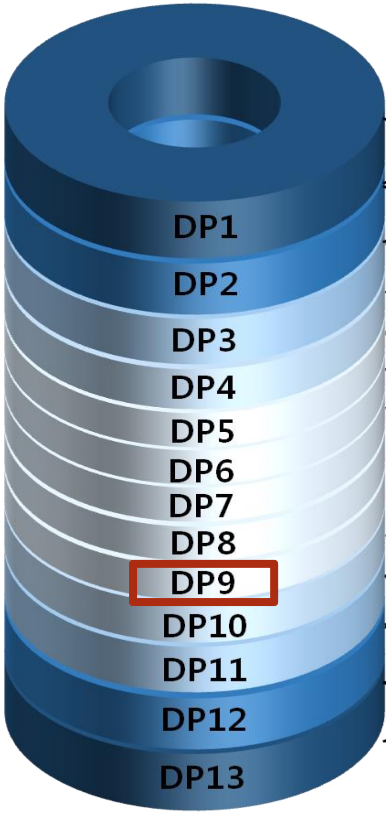
Parameter		Coil 1	Coil 2
Winding i.d.	[mm]	76	112
Winding o.d.	[mm]	112	134
Winding length	[mm]	71	71
Self inductance	[H]	0.20	0.72
Mutual inductance	[H]	0.30	
Wire diameter	[mm]	0.90	0.70
Wire length, ℓ_d	[m]	530	1010
Cu/NbTi ratio		2	3



7-T/78-mm MW-NI Magnet Test Results at 4.2 K

- "Self-Protecting" Behavior due to "Electromagnetic" Quench Propagation between Pancakes
  - Initial quench at DP9 → the DP9 voltage increase
  - Field maintained by the induced currents in "healthy" coils → healthy coil voltage decrease
  - Quench in the healthy coils → all coil voltage increase





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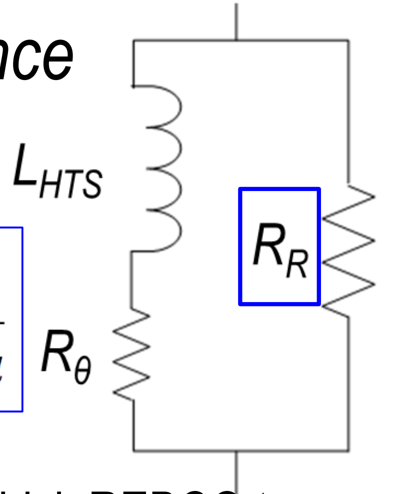
Summary: What Have Been Learned

1. Single Coil
   - *Key mechanism for electro-thermal self-protecting (no burn-out): "Quench current bypass" through turn-to-turn contacts*
   - *Experimental demonstration: >100 NI REBCO coils have been tested including one survived after a quench at 1580 A/mm^2 in liquid helium at 4.2 K.*
   - *Simulation: An equivalent circuit model has been successfully used for charging analyses; Comprehensive simulations have been proposed by multiple groups.*
2. Stack-of-Double-Pancake Magnet
   - *Key mechanism: Electromagnetic (thus fast) energy transfer between coils*
   - *Experimental demonstration: to date, 7 NI REBCO magnets have been built and tested; all of them survived after multiple over-current quench tests.*
     1) 8.7-T/91-mm REBCO Insert (MIT, 2014);
     2) 9-T/78-mm All-REBCO Magnet (MIT, 2014);
     3) 26-T/35-mm All-REBCO Magnet (SuNAM/MIT/FSU, 2015)
   - *Simulation: No magnet-level simulation has been reported so far.*

Backup Slides

Winding Tension and Characteristic Resistance

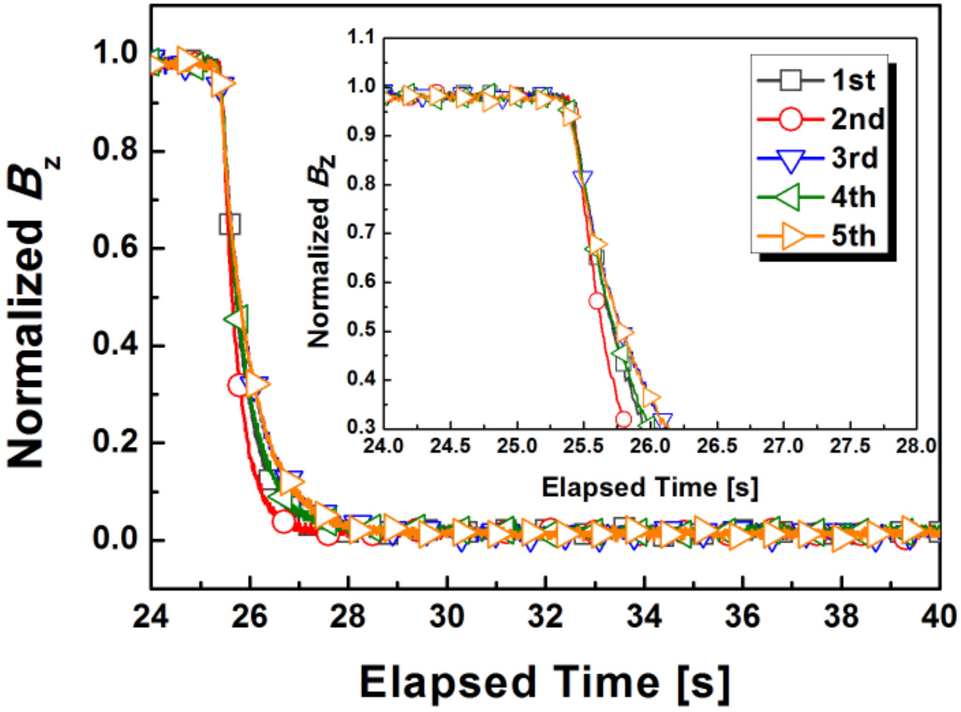


- Characteristic Resistance: R_R (sum of turn-to-turn contact resist.)
  - R_{ct} [$\Omega\cdot\text{cm}^2$]: average surface contact resistance (10 – 70 $\text{u}\Omega\cdot\text{cm}^2$)

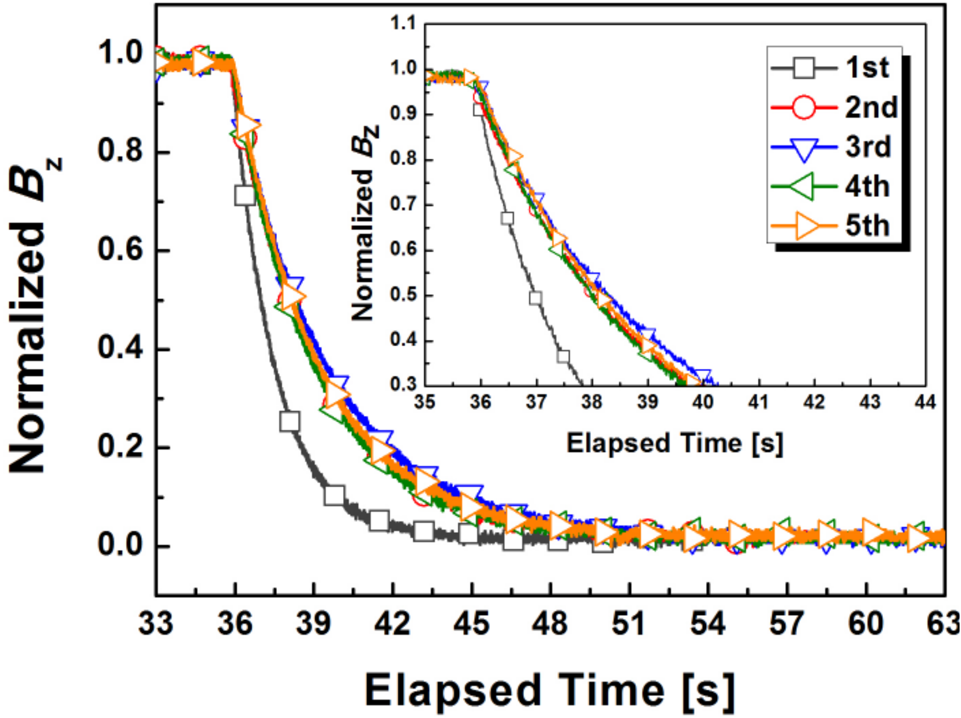
$$R_R = \sum_{i=1}^{N-1} R_i = \sum_{i=1}^{N-1} \frac{\boxed{R_{ct}}}{2\pi r_i w_d}$$

- Impact of Winding Tension on R_R
  - Sudden discharge tests of an NI coil wound with 4.1-mm wide, 0.1-mm thick REBCO tapes

"Low (12 N)" Winding Tension

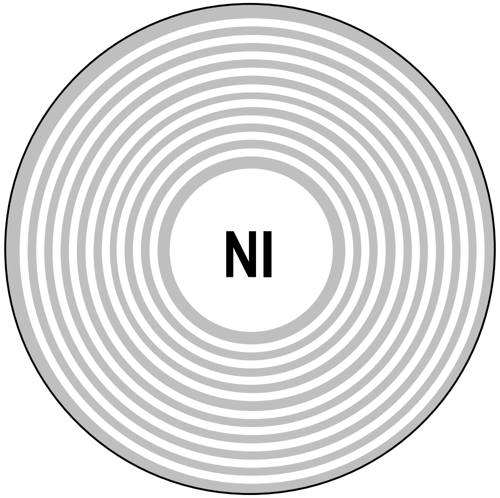


"High (20 N)" Winding Tension

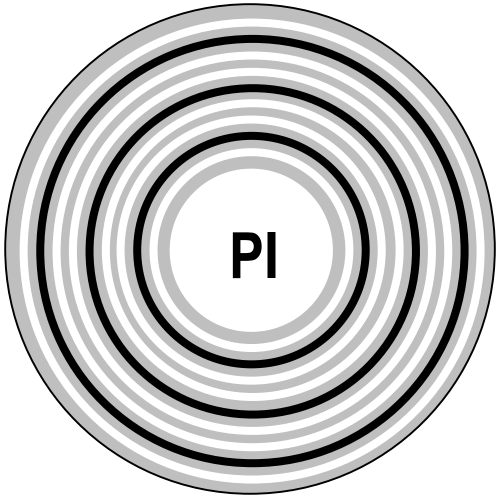


Major Drawback: “Slow” Charging

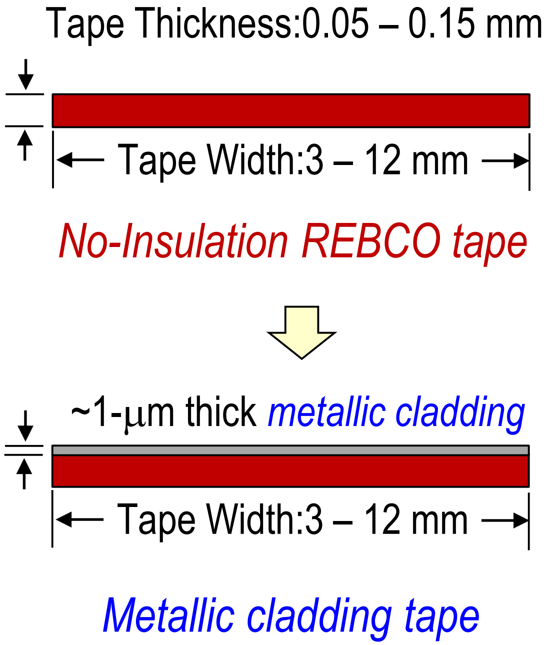
- No-Insulation



- Partial-Insulation[1]



- Metallic Cladding Insulation[2]



No-Insulation REBCO tape

Metallic cladding tape

- *Charging time constant*: 20 minutes for 26-T/35-mm; 15 hours for 60-T/40-mm
- ~5 times faster charging time constant of PI than that of NI, measured in LN2 at 77 K[1].
- ~12 times faster charging time constant of MCI than that of NI, measured in LN2 at 77 K[2].
- Self-protecting demonstrated in LN2 at 77 K but *not in LHe at 4.2 K*

REF 1: Y. H. Choi, S. Hahn, J.-B. Song, D. G. Yang, and H. Lee, “Partial insulation of GdBCO single pancake coils for protection-free HTS power applications,” *Supercond. Sci. Technol.*, 24, 2011 (125013).

REF 2: SuNAM, a report on test results of REBCO coils wound with stainless steel coating tapes, July 2015.