Operation Results of a 23.5-T REBCO Magnet Prototype Towards a Benchtop LHe-Free 1-GHz Microcoil NMR

Dongkeun Park[1)], Wooseung Lee[1)], Juan Bascuñán[1)], Ho Min Kim[1), 2)], and Yukikazu Iwasa[1)]

[1)] *Francis Bitter Magnet Laboratory/Plasma Science and Fusion Center, Massachusetts Institute of Technology*
[2)] Visiting Scientist from Jeju National University, South Korea

Email: dk_park@mit.edu

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Outline

- Introduction to a *Benchtop 1-GHz Microcoil NMR Spectroscopy* (Micro1G)
- A Small-scale 23.5-T Prototype Magnet Validation
- Issue and Counterproposal – ***Extreme No-Insulation*** Winding
- Manufacture
- Operation Results up to ***25 T***
- Towards a 23.5-T/25-mm-RT-bore NMR Magnet for Micro1G

Introduction: Benchtop 1-GHz Microcoil NMR (Micro1G)

- Technical development goals in our proposed NMR magnet are:
  - Ultra high field: High NMR Sensitivity and Resolution $\propto B_0^3$
  - Liquid helium free: reliable and safe operation, and cost reduction
  - Compact design & small fringe field: placeable on a workbench or small laboratory space
  - Cost-efficient design: less cost than conventional φ54-mm bore NMR magnets

A Shielded Benchtop LHe-Free All-REBCO 1-GHz Microcoil NMR Magnet **(Micro1G)**

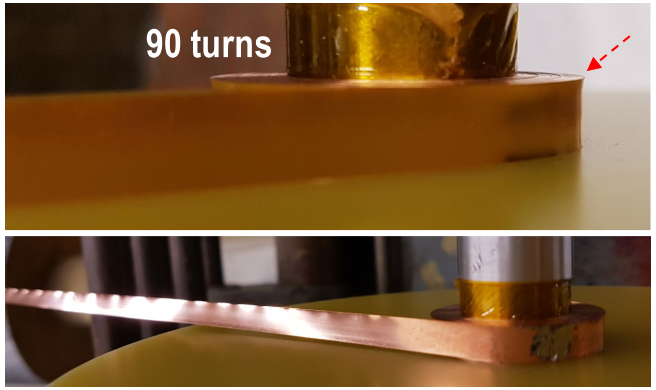
- 23.5-T NMR magnet with φ25-mm RT bore
- Merits: high performance, low-cost, and small installation siting

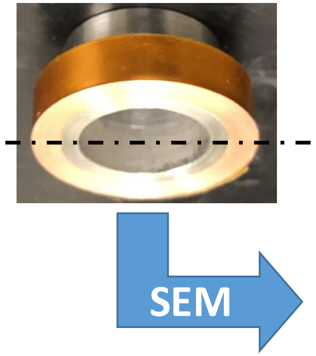
Region of Interest (ROI)	≤5 mm-DSV
Homogeneity in ROI	<0.1 ppm
5 Gauss Fringe Field	≤1.5 m

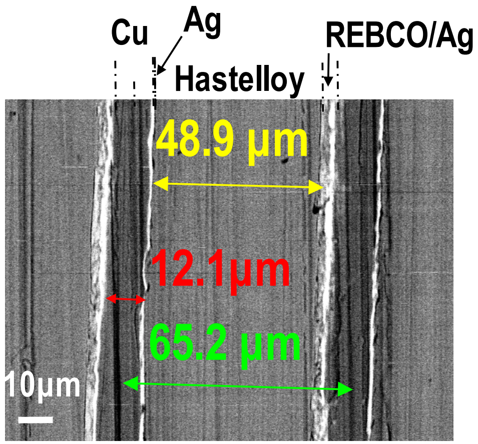
A Small-Scale 23.5-T Prototype Magnet Validation

- A small-scale ***<u>23.5-T / 12.5-mm</u>*** prototype magnet has been developed to validate:
  - ✓ Coil design parameters and conductor performance at ≥10 K operation
  - ✓ Screening-current effect and its reduction method
  - ✓ No-insulation characteristics: charging delay & quench behavior
  - ✓ Conduction-cooling characteristics
- Winding issue found with a *non-uniform* copper-plating thickness of the REBCO tape

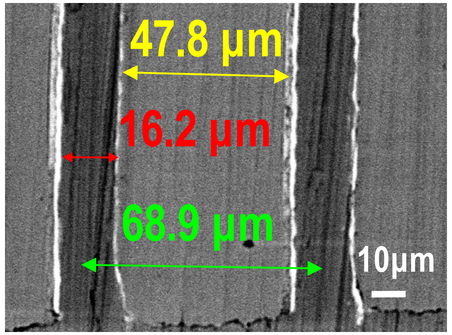
(Presented at ASC2020)







Middle



Edge

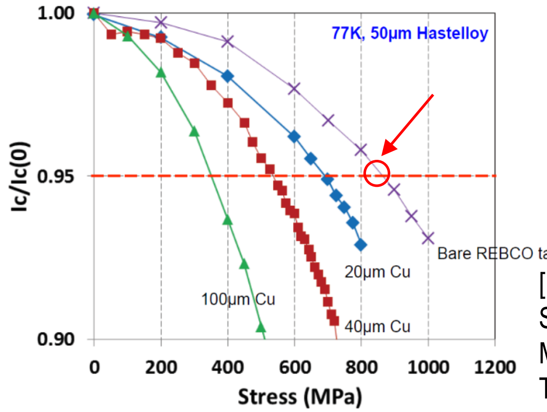
Extreme No-Insulation Winding

- Reduce copper thickness (≤2 μm) to minimize uncertain tolerance
- Add extra-shunting layers on top of winding surfaces of pancake coils

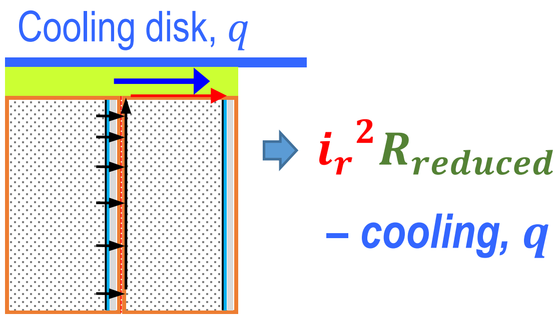
➡ ***A Novel Extremely-Thin Copper-Stabilized and Extra-Shunted No-Insulation Winding***

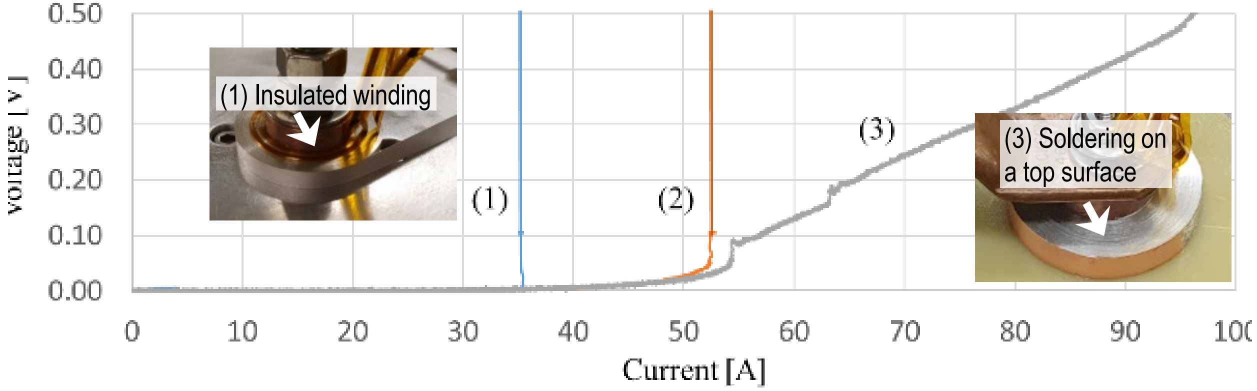
(Mechanical)	More strength (higher modulus) due to less copper (relatively soft)
(Electrical)	Higher current density ➔ compact, cost effective Lower (or adjust) turn-to-turn resistance ➔ self-protection
(Thermal)	Better contact with a conduction-cooling disk via soldered surface
(Process)	Less time and cost for copper electroplating ➔ low cost

$I_c/I_c(0)$ vs. stress, and $\sigma_{c,0.95}$ (critical stress)



[ref] Y. Zhang, SuperPower, MEM 2016, Tallahassee, FL





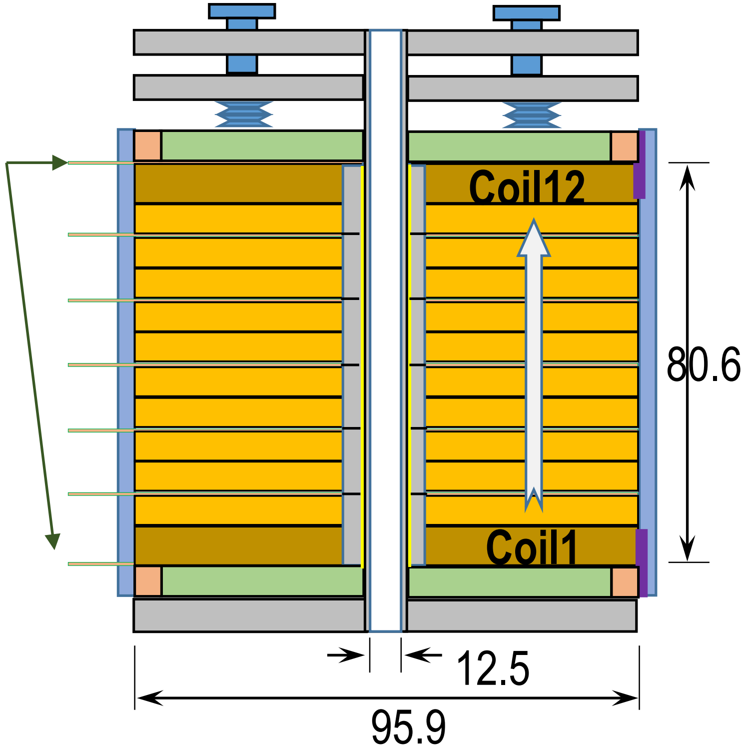
Manufacture and Test Setup

- Stack of single pancake coils with resistive joints (6 inner + 5 outer + 2 lead)
- Copper cooling disks between double pancake (DP) coils
- New charging operation concept: $T_{charging}$ control by disk heaters

➡ Reduce ***Screening Current***

Parameters	C2 – C11	C1 (B) & C12 (T)
Conductor-W [mm]	6 mm	8 mm
Conductor-T [mm]	0.053 – 0.056 mm	
ID ($2a_1$) [mm]	22.23	
OD ($2a_2$) [mm]	94.63 – 97.50 mm	
# of Pancakes	10	2 × 1
Turns per Pancake	650 – 688	
Length per Pancake [m]	120 – 127	
Total Length [km]	1.5	
Inductance	1.41 H	
I_{op} [A]	220	
Center Field @ I_{op}	23.5 (– SCF)	

Insulated Cu cooling disk & disk heaters



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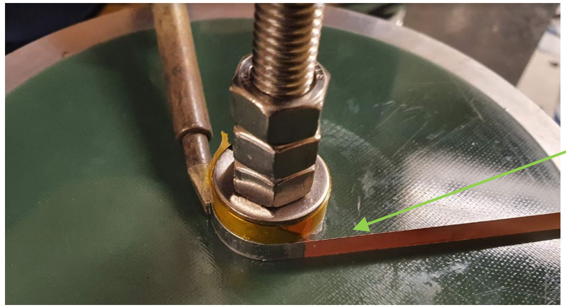
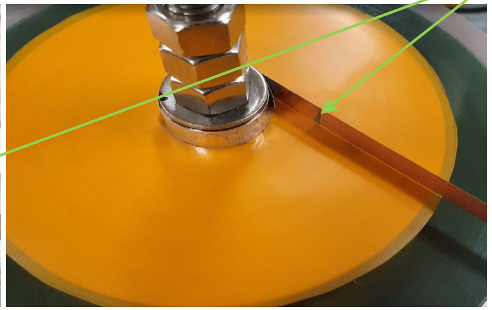
Manufacture – Extreme-NI DP winding

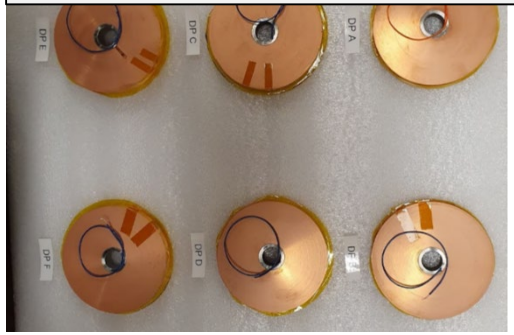
Inner Joint and DP winding

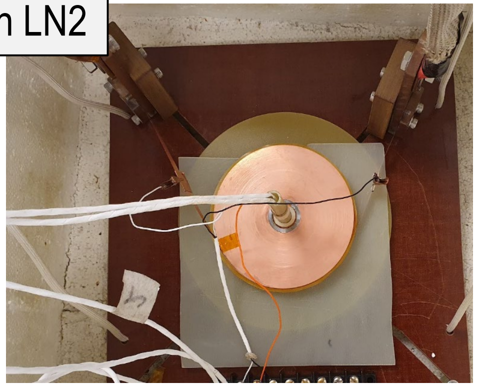


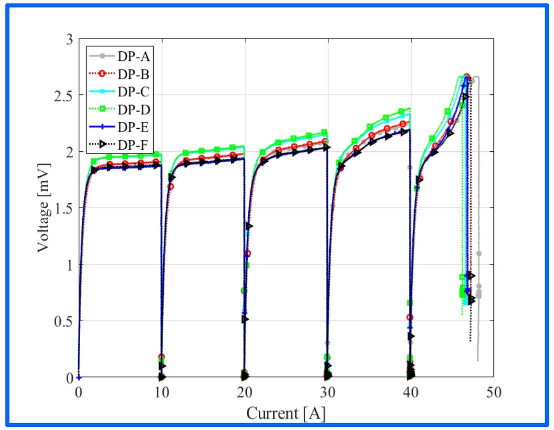


Thin copper sheets were attached to prevent from sharp pressing by boundary edges

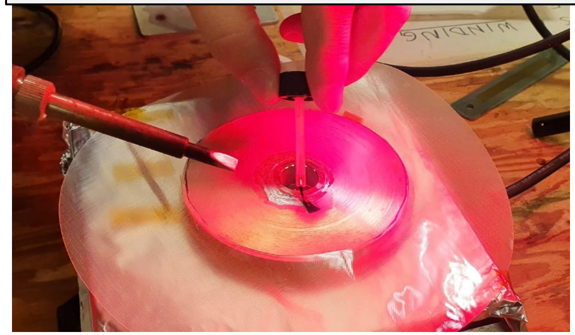
Individual DP coils were tested in LN2

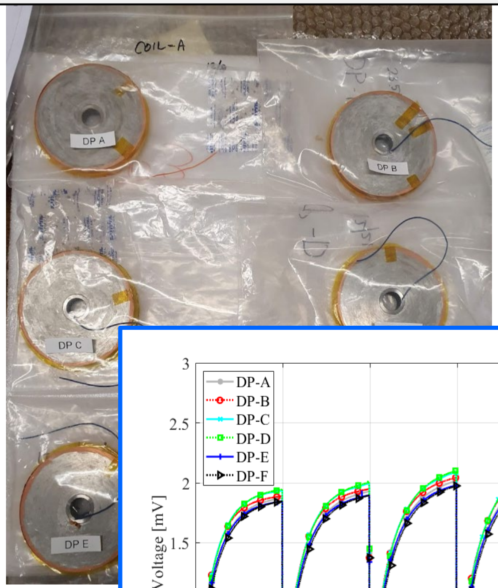


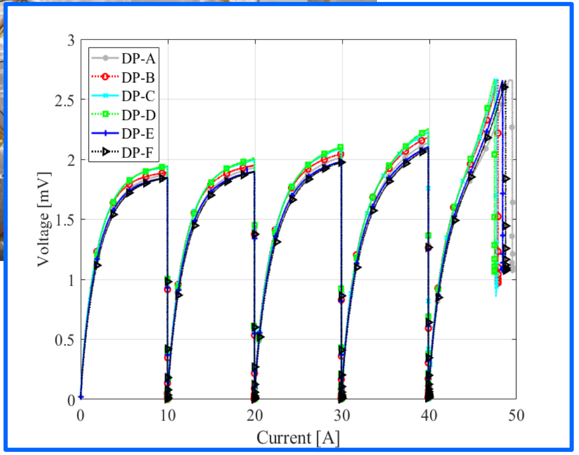




Extra shunting by soldering with 52In48Sn and completed DP coils

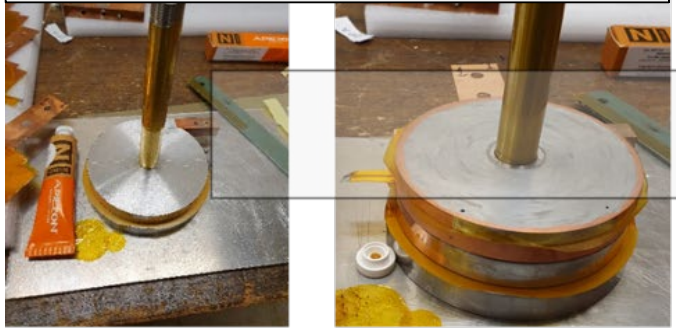




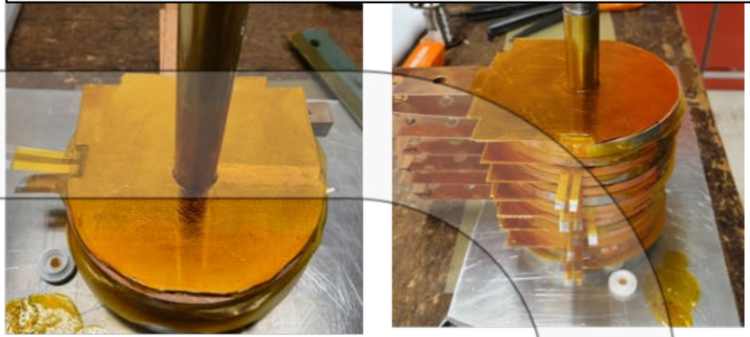


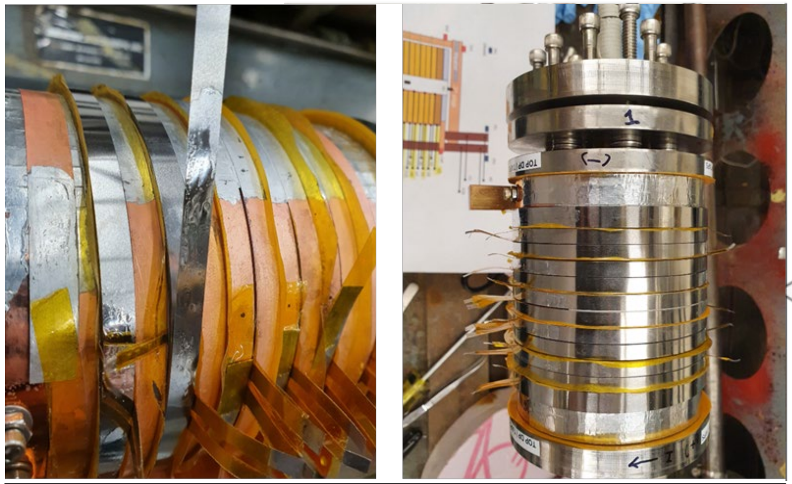
Manufacture – Magnet Assembly and Joint

Stacking with Apiezon N grease

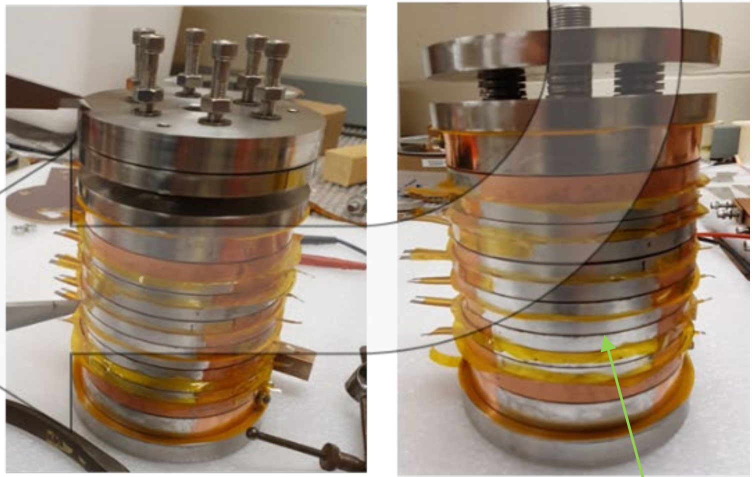


Copper and heater disks were stacked with insulation

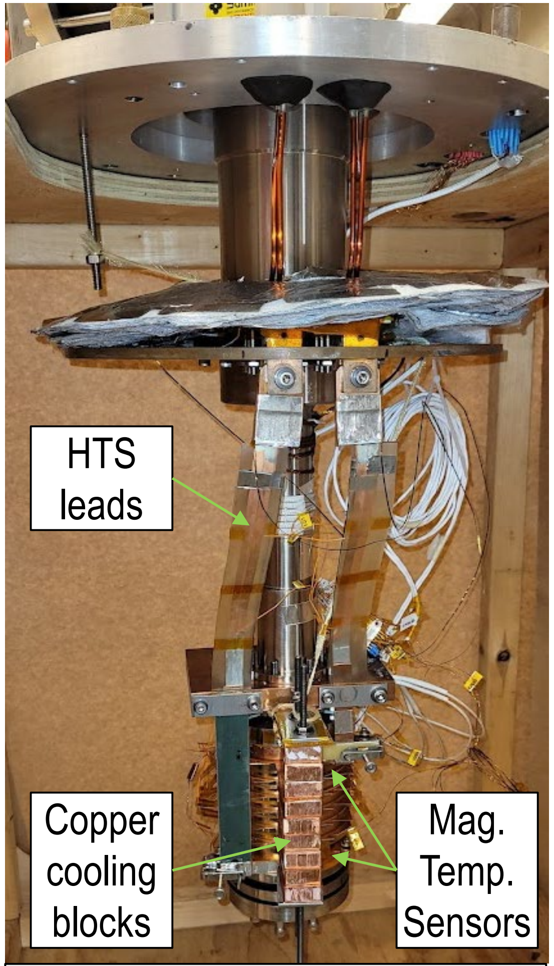




Over-banded with SS tapes



Pre-loading and outer joints by multiple 6-mm-wide tapes in parallel

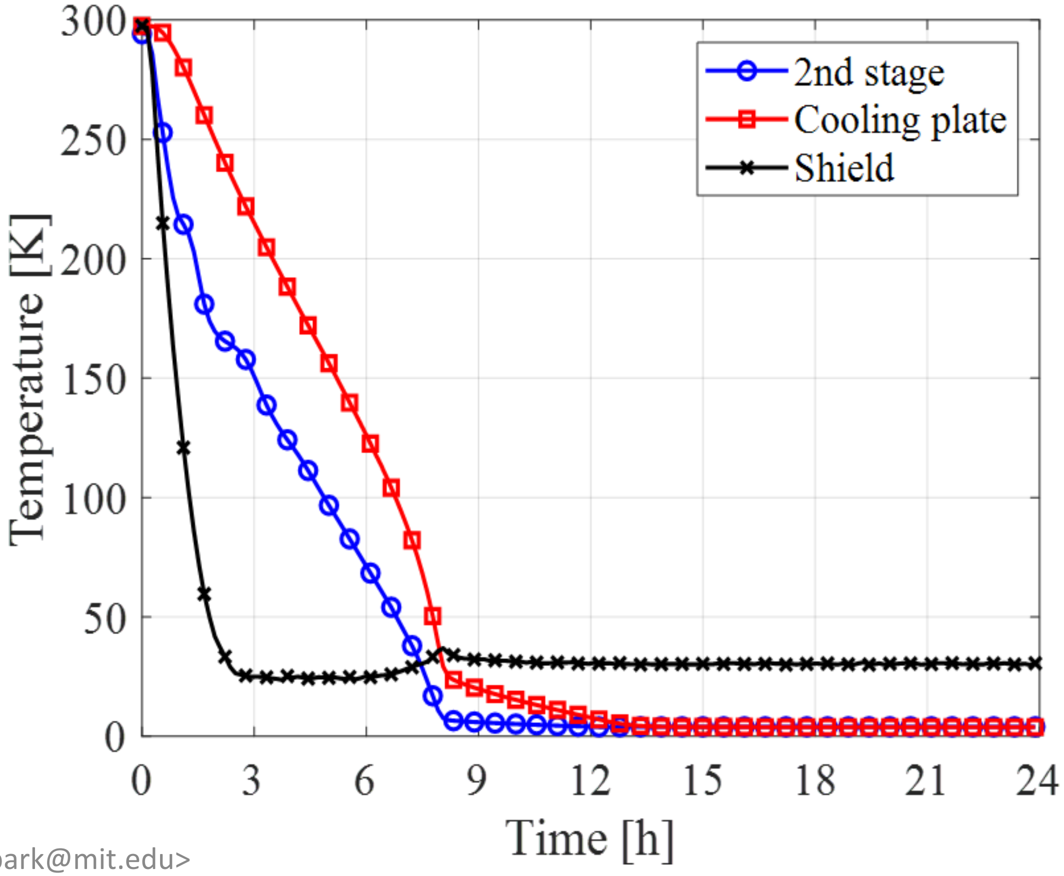


Mounted on a cryo-cooler system with a copper blocks and HTS current leads

Dongkeun PARK <dk_park@mit.edu>

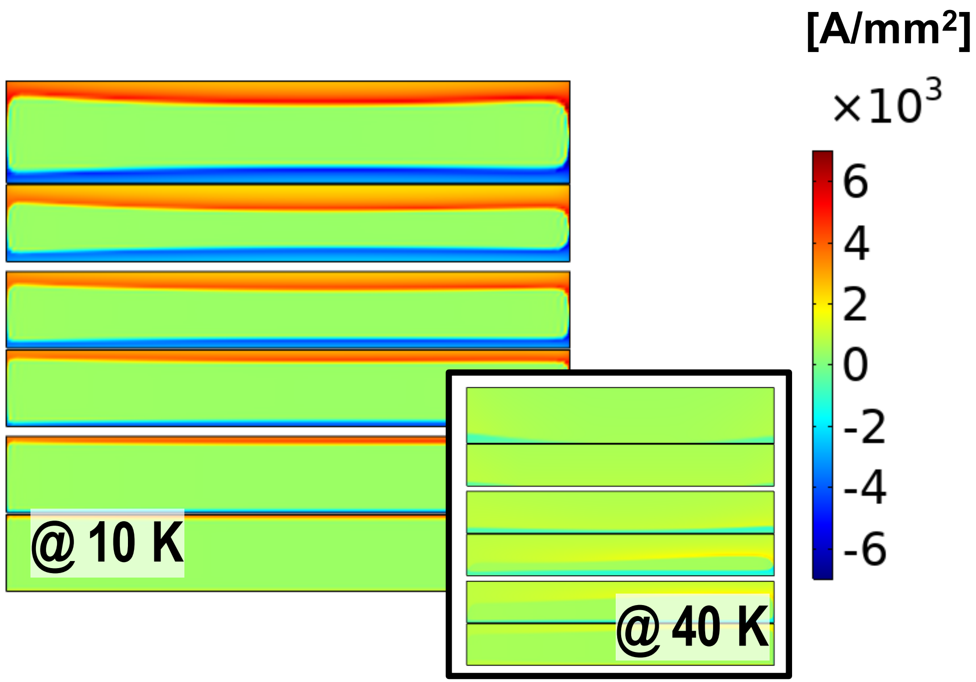
Operation – Cryo-Cooling

- Magnet temperature was successfully down to <4.2 K in 12 hours by a 1W@4.2K GM cryocooler.
- Heater was applied to adjust magnet operating temperature up to 50 K.

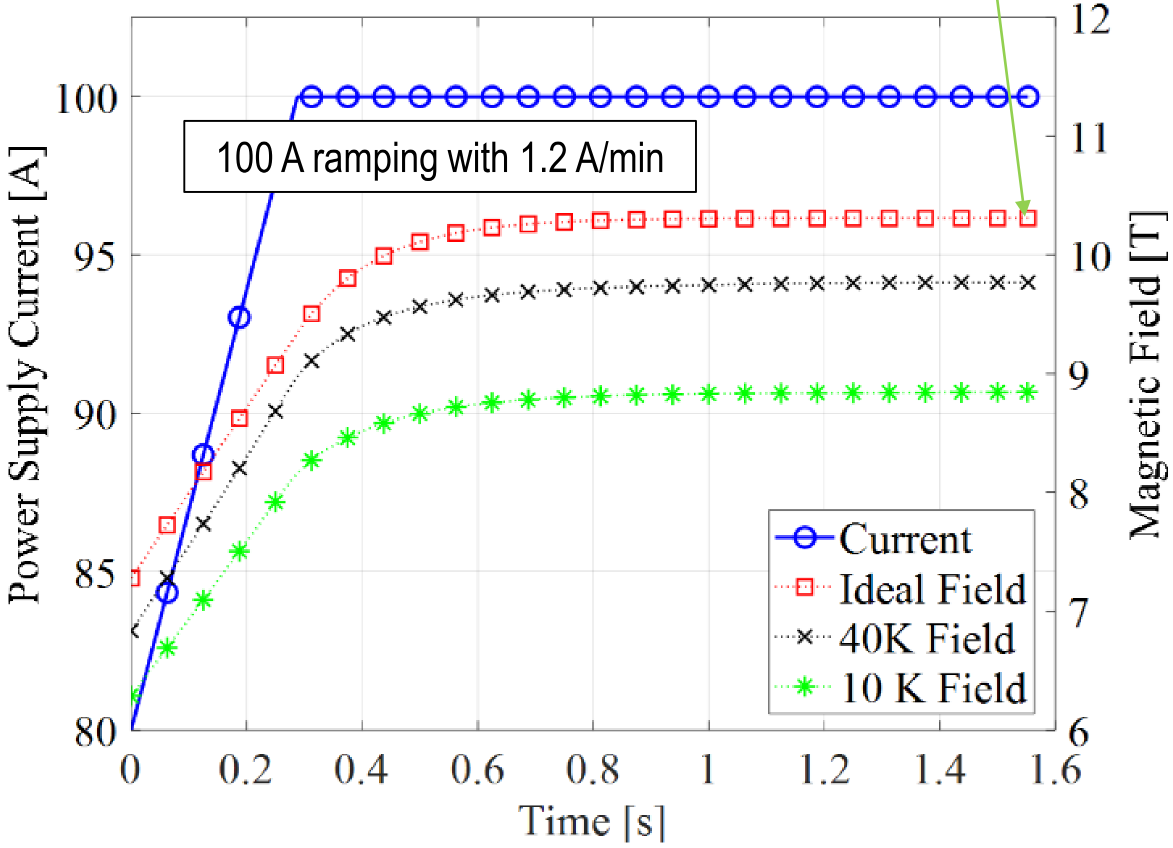


Operation – Screening Current Reduction

- Compare the center field in cases of ramping to 100 A at different temperature.
  - ✓ 8.85 T vs. **9.77 T** at 10K and 40K



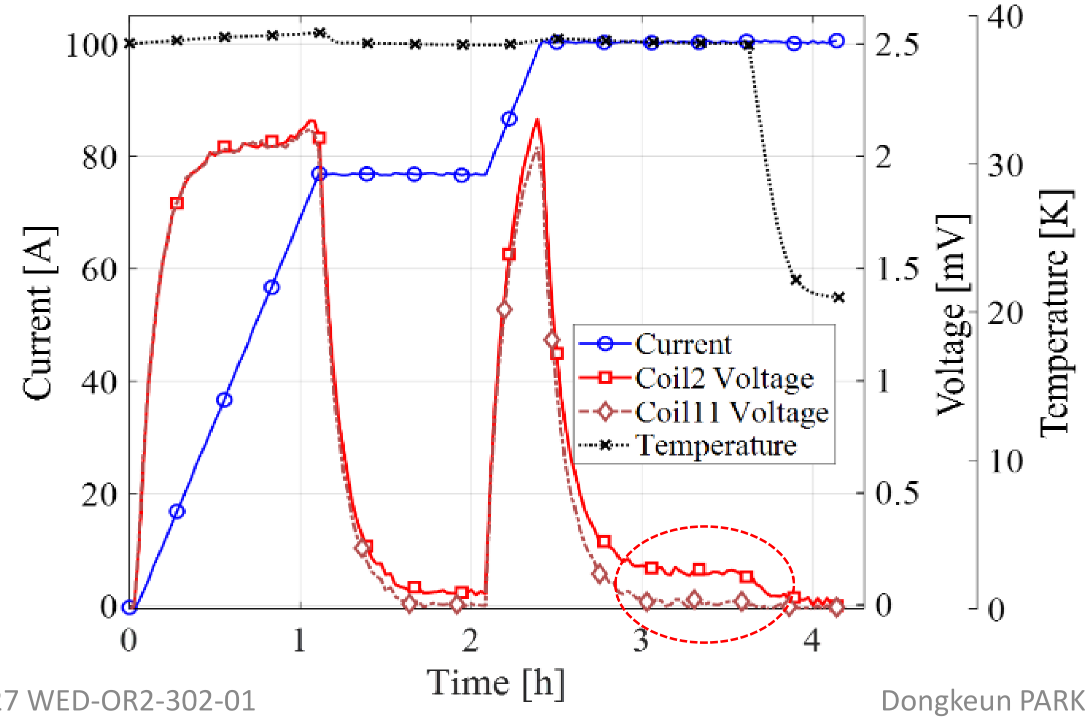
Cross-sectional view of the current density distribution while ramping to 230 A at 10 K and 40 K

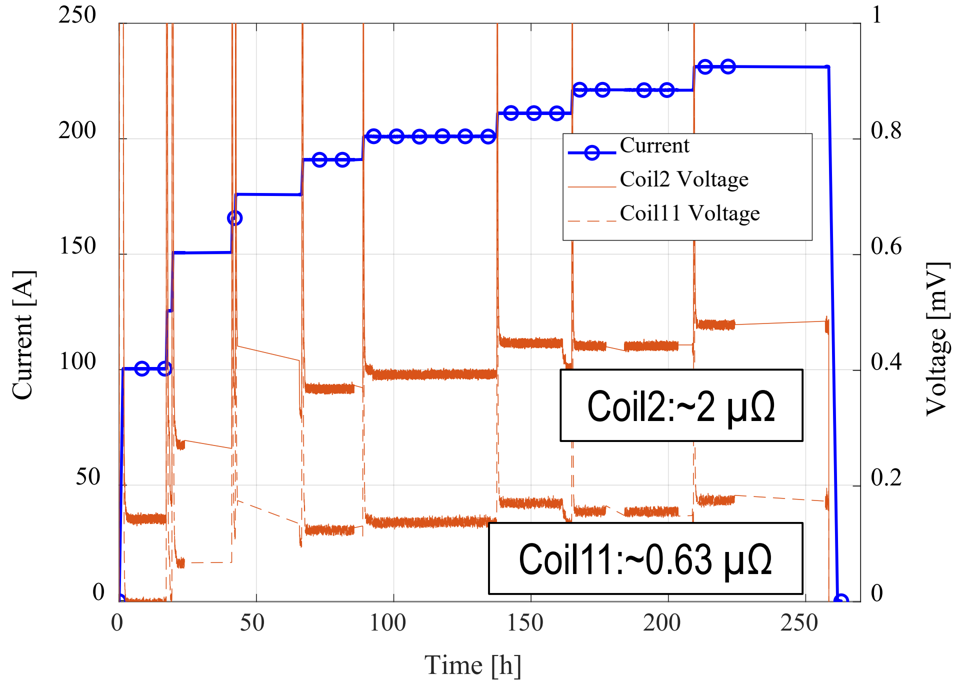


Operation – Stability against Local Resistive Hot Spots

- In Coil 2 and Coil 11, resistive voltages were observed.
- The resistive voltages may come from conductor defects during manufacturing.
- The resistances were ***not increased*** during ramping and operating up to 25 Tesla.

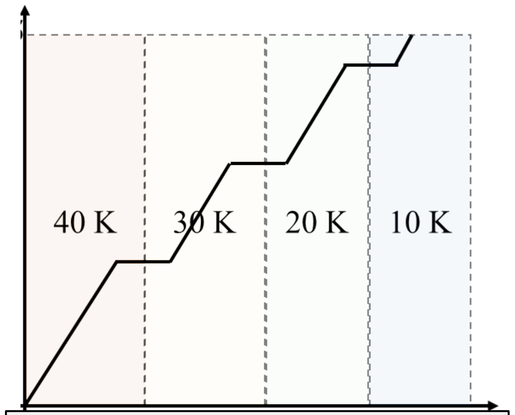
➡ **Excellent thermal stability** due to cooling disks (like cryo-stable)



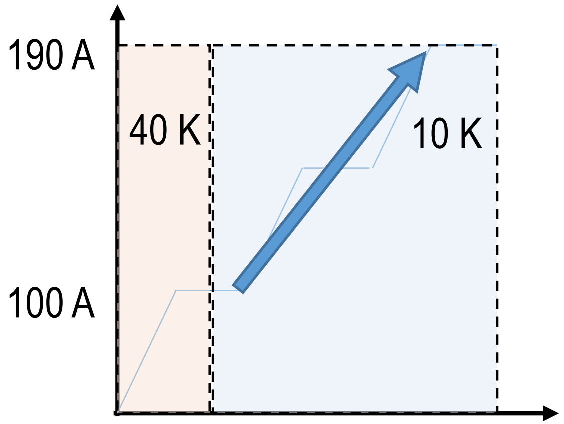


Operation – 1st Charging to 18.3 T

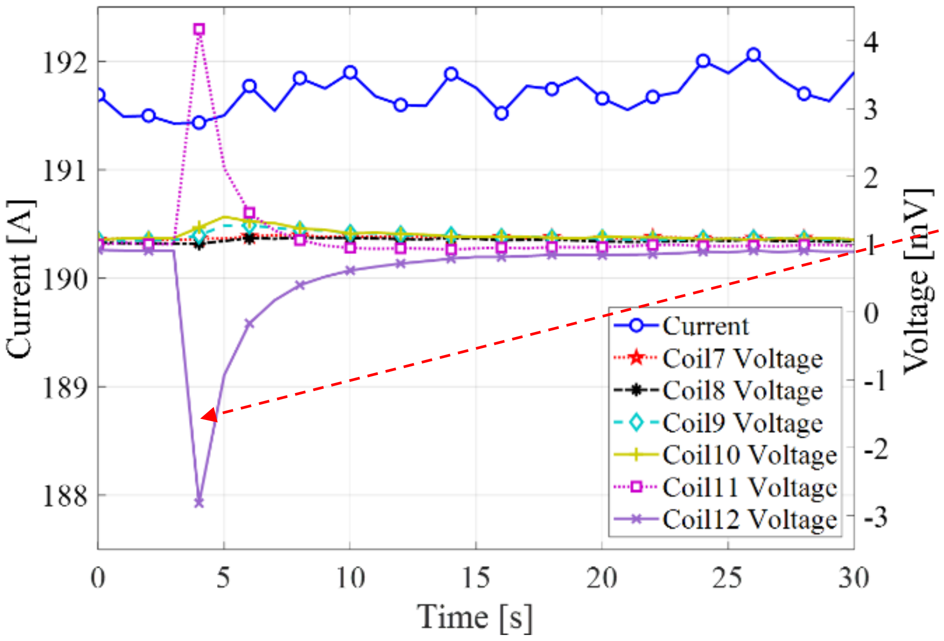
- Operation sequence to apply the screening-current reduction method
  - ✓ Start ramping at higher temperature in lower current region
  - ✓ Reduce the temperature as the current-and-field increase
  - ➔ To keep small I_c margin until reaching target field
  - ➔ To mitigate the screening-current induced stresses



Operation sequence example

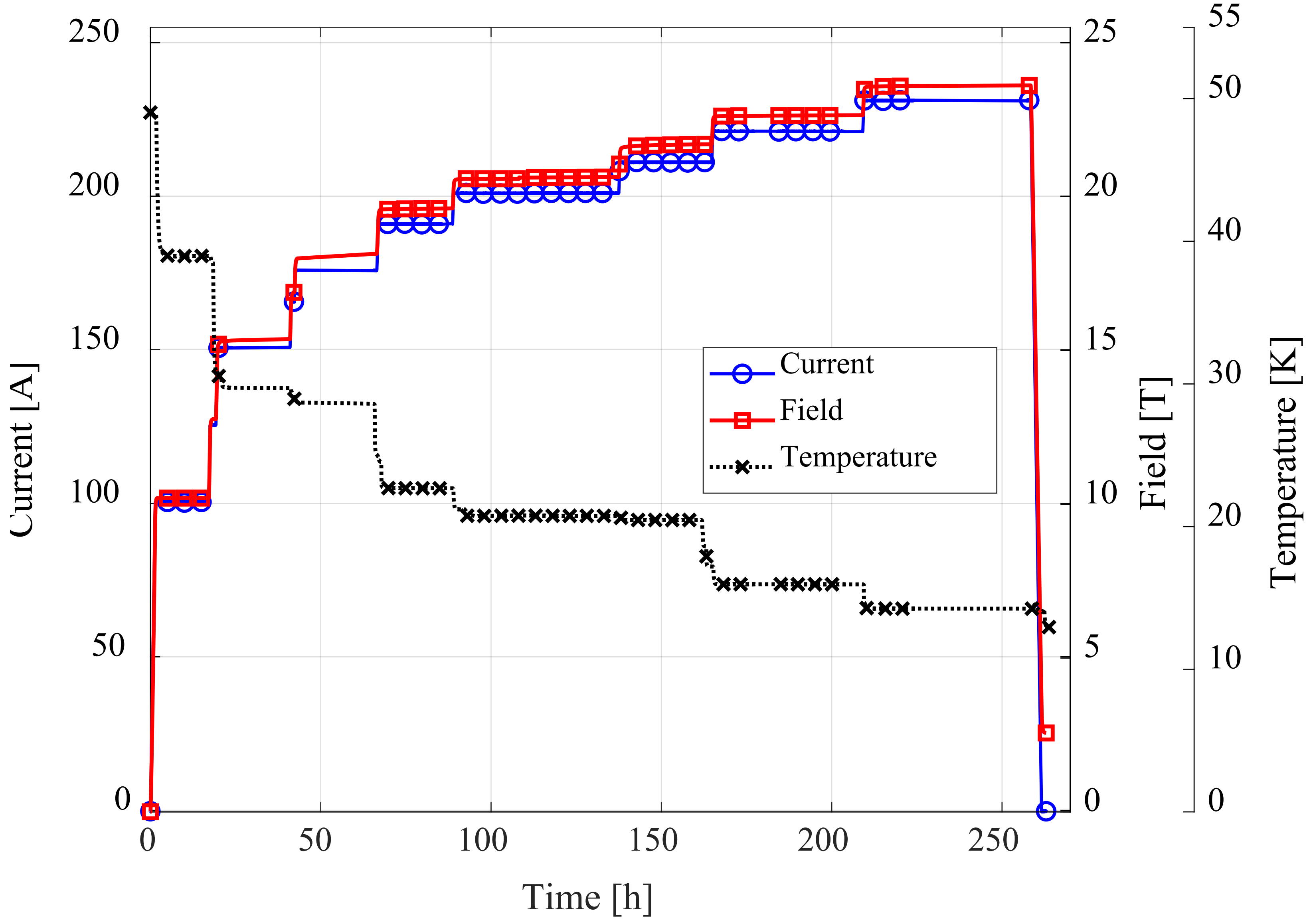


Inductive spike occurs at 190 A without fully applying SC-reduction operation sequence



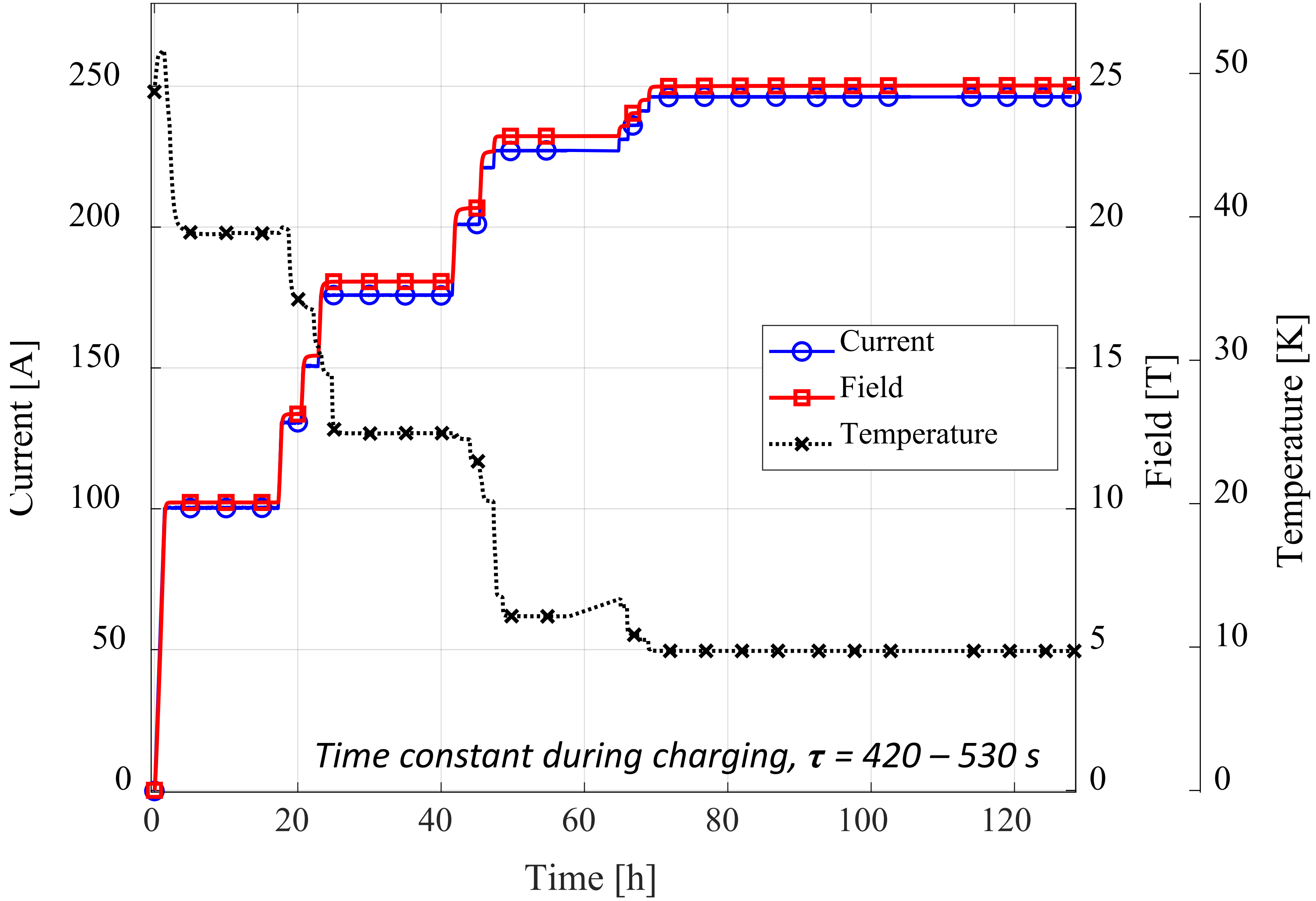
When microscopic resistive hot spot suddenly occurs in the NI winding, inductive voltage can be observed due to loss of complete turns.

Operation – 2nd Charging to 23.6 T @ 230 A, 14 K



- Successfully reached 23.6 T at 230 A and held for 50 hrs.
  (Note: with constant current density, 23.5 T @ 220 A)
- Operation sequence (temperature) was not optimized.
- Charging delay time constant: ~500 seconds

Operation – Final Charging to 25 T @ 245 A, 10 K



- Repeated ramping to 23.6 T at 230 A.
- Successfully reached ***25.0 T*** at 245 A and held for 60 hrs.

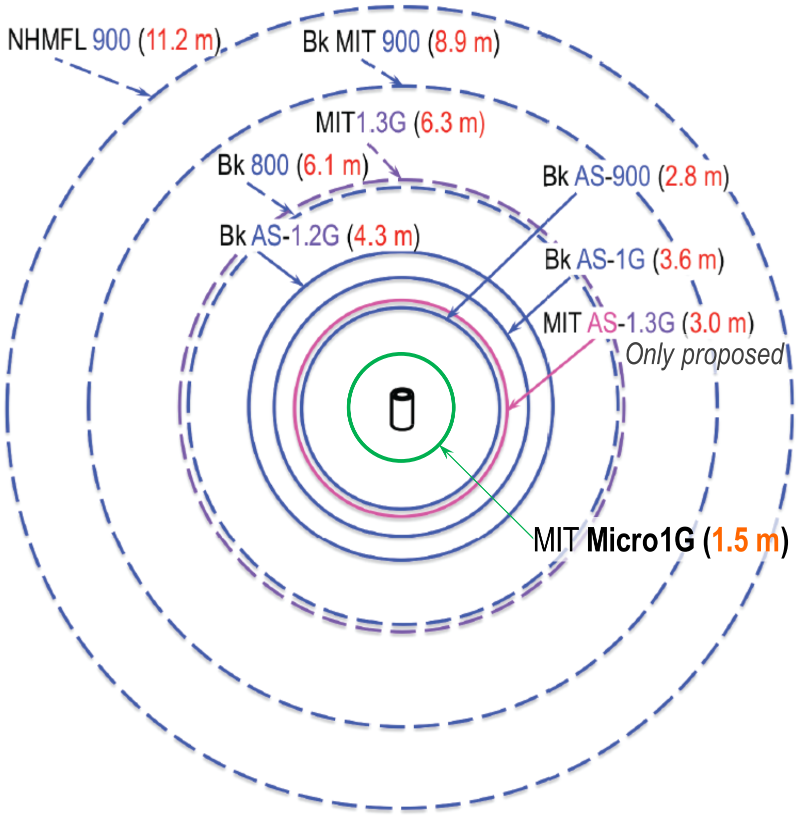
Over-heated power cables shut down the power supply suddenly.

Electrically shorted between pancake coils and copper disks. No physical damage observed.

Towards a Benchtop 1-GHz Microcoil NMR Spectroscopy

- Key design specifications: $B0$=23.5 T; φ25-mm RT bore; <0.1 ppm over 5-mm-DSV or φ5-mm 10-mm-long cylindrical volume; 5-gauss fringe field radius of ≤1.5 m; cryogen-free operation.
- Shielding method will be determined after further analysis during the next project period.

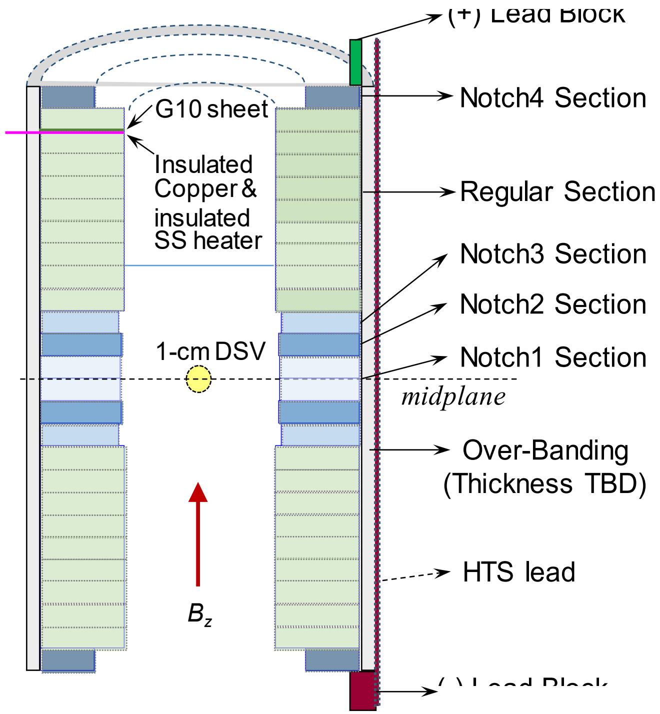
: Now considering using iron to reduce a 5-g radius ≤1.5 m, which is less than half of the Bruker's active-shielded 1-GHz magnet (3.6 m).



- Field homogeneity will be achieved by superconducting, ferromagnetic, and RT shims based on our magnet design with high homogeneity .

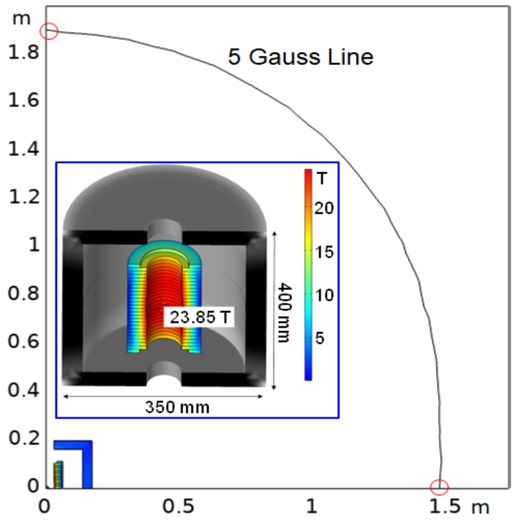
First-Cut Design for a benchtop 23.5-T NMR Magnet

- Multiple notched single-solenoid coil to achieve high homogeneity.
  ➔ Further optimization required considering shield design (and/or) SCF.
- Total <8 km (all 4-mm wide) REBCO tape is required.
- 140-kg iron for 5-g radius reduction and external interference screening.



Parameters		Notch1	Notch2	Notch3	Regular	Notch4
REBCO tape width / thickness	[mm]	4 / 0.065				
Spacer thickness (average)	[mm]	0.335				
Winding ID (2a1)	[mm]	63.25	62.47	64.55	60	83.79
Winding OD (2b2)	[mm]	126.3	126.3	126.3	126.3	126.3
Lower; upper Extent (b1; b2)	[mm]	-8.67; 8.67	-17.34; -8.67 / 8.67; 17.34	-26.01; -17.34 / 17.34; 26.01	-104.04; -26.01 / 26.01; 104.04	-112.71; 104.04 / 104.04; 112.71
Number of DPs		2	2	2	18	2
Turns per DP		970	982	950	1020	654
Conductor length per DP	[m]	289	291	285	299	216
Total conductor length	[m]	7,540				
Total inductance	[H]	16.8				
Operating current, Iop	[A]	179				
Center field* @ Iop	[T]	23.5				
Homogeneity* @ 1cm-DSV	[ppm]	0.010 (Vrms); 0.100 (Peak-to-Peak)				

* assuming constant current density in the winding. i.e. no screening current effects are taken into account.



Conclusion

- A compact cryogen-free 23.5-T all-REBCO magnet was successfully completed.
- Through this program we validated:
  1) Conductor Performance, Magnet Design, Operating Parameters
  2) Extreme-No-Insulation Winding Technique
  3) Conduction Cooling (T_{op}: 10 K – 50 K)
  4) Screening-Current Reduction
  5) Stability Enhancement: Local Hot Spot & Over Current.
- Towards a benchtop microcoil 1-GHz NMR magnet.