Test Results and Analysis of a Single Pancake Validation Coil for a Cryogen-Free 23.5 T/ϕ15 mm REBCO Magnet

**Original Title:*

Construction and Test Results of a Cryogen-Free 23.5-T REBCO Magnet Prototype towards a Tabletop 1-GHz Microcoil NMR Magnet

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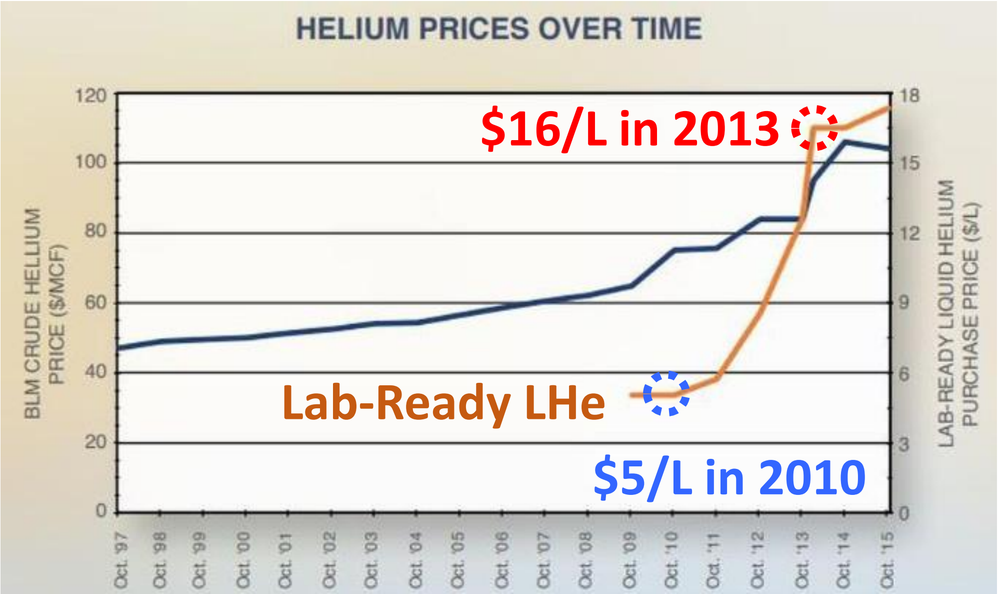
Introduction to a Tabletop LHe-Free 1-GHz microcoil NMR Spectroscopy

Primary technical development goal in NMR magnet

"The higher field, the better NMR signals"

➔ Increase NMR SENSITIVITY and RESOLUTION $\propto B_0^3$

➔ Liquid Helium Free: Reliability, Cost, Safety



AMERICAN PHYSICAL SOCIETY, MATERIALS RESEARCH SOCIETY, AMERICAN CHEMICAL SOCIETY

Microcoil NMR Spectroscopy

- In *Microcoil* NMR probes (e.g. < φ1 mm *rf* coil),

  Mass Sensitivity is 10–100X than in conventional one

Tabletop High-Field NMR Magnet

- **1-GHz** (23.5-T) NMR magnet with φ25-mm RT bore
- Merits: *Cost* and *Installation Siting*

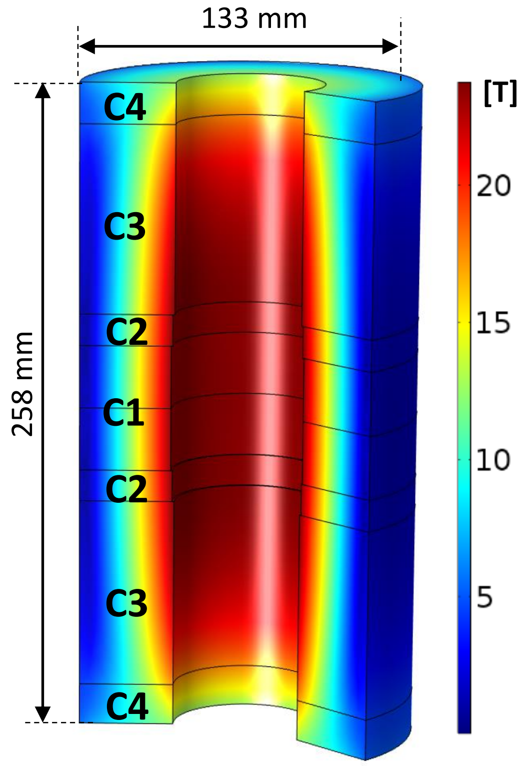
LHe-Free HTS Magnet

- All-REBCO composition
- Operation at **10 K**
- No-Insulation winding

→ Compact, Mechanically robust, Self-protecting

Design Required Specification of 1-GHz Microcoil-NMR (Micro-1G) Magnet

Parameters	Tabletop LHe-Free Micro-1G
Field Strength	23.5 T
RT Bore Diameter	25 mm
Region of Interest (ROI)	5 mm-DSV
Homogeneity in ROI	<0.1 ppm
Temporal Stability	<0.01 ppm/hr
Shimming Method	Active (HTS and RT) and Passive (RT)
Operating Temperature	>10 K
5 Gauss Fringe Field	<1 m
Shielding Method	Active Shielding
Cooling Method	Cryo-cooled (No Cryogen)
Vibration	Flexible Thermal Anchor, Anti-Vibration Pad



Harmonic error Terms @ 5-mm-DSV				
Z0	23.5	Tesla	1,000	MHz
Z2	-0.37	ppm	-5,926	Hz/cm^2
Z4	0.00	ppm	1,201	Hz/cm^4
Z6	0.00	ppm	-1,666	Hz/cm^6

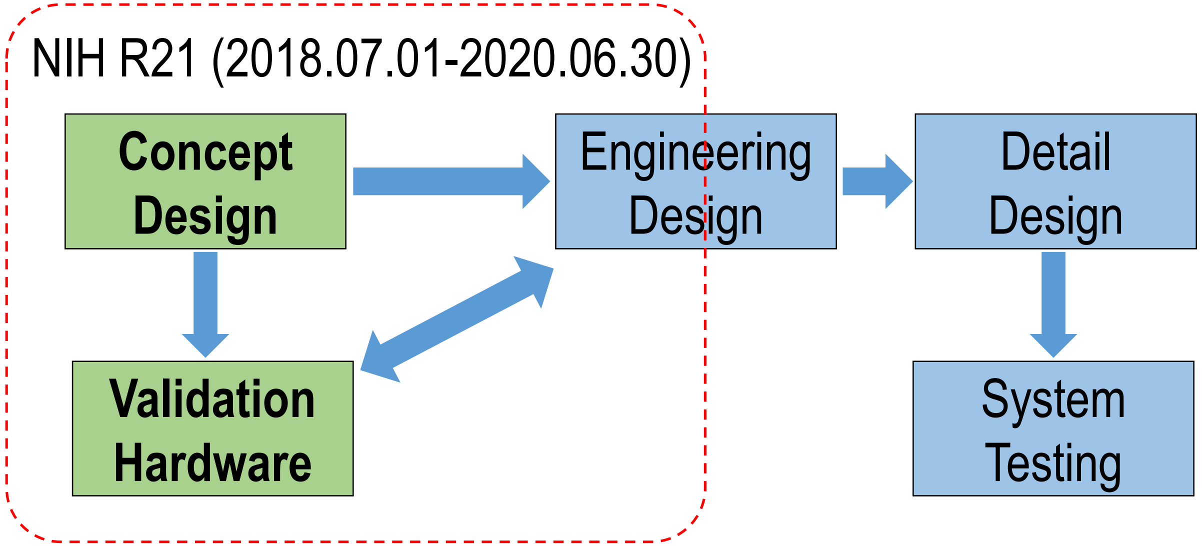
<1^{st}-cut unshielded Micro-1G magnet design presented in ASC2018>

Validation by a Prototype 23.5-T Magnet

What to *Expect*:

- ***Conductor***/*Coil* parameters (I_c, field, stress, charging delay)
- Thermal dynamics: *Charging*, *Quench*
- Preliminary studies on reduction of *SCF, Fringe field*

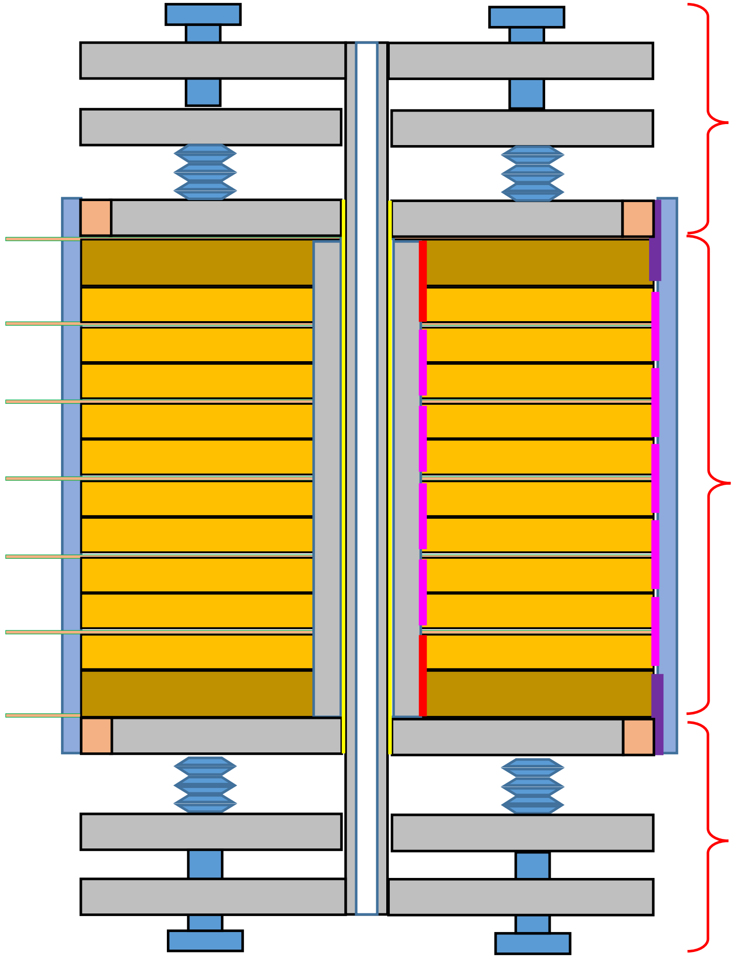
Towards a *Tabletop* 1-GHz Microcoil NMR Magnet



Parameters	C2 – C11	C1 & C12
Conductor-W [mm]	6 mm	8 mm
Conductor-T [mm]	0.067 mm	0.066 mm
Spacer (Cooling Channel)	G10-Cu*-G10	
ID ($2a_1$) [mm]	19.05	
OD ($2a_2$) [mm]	107.49	106.83
# of Pancakes	10	2× 1
Turns per Pancake	660	665
Length per Pancake [m]	131.2	131.5
Total Length [km]	1.6	
Inductance	1.41 H	
I_{op} [A]	236	
T_{op} [K]	>10	
Hoop Stress (with WT+CD+EM)	<150 MPa (@ 50N Winding Tension)	
Estimated Min. I_c @ 10 K	>380	>420
Center Field @ I_{op}	23.5 T – SCF (3 T @ 10 K)	

<Prototype 23.5-T magnet design presented in ASC2018>

Main Features of Magnet Structure – Stack of Single Pancake Coils (SPC)



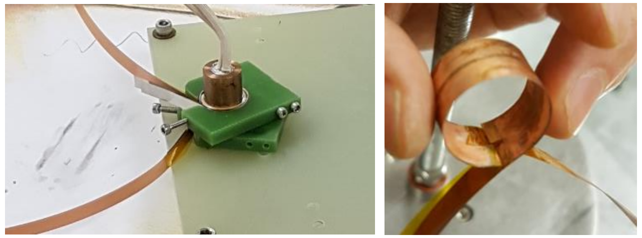
Preloading by Belleville washers.

- Stack of SPCs with resistive joints.
- Conduction cooling channels.
- Insulation and over-banding by carbon-fiber prepreg.

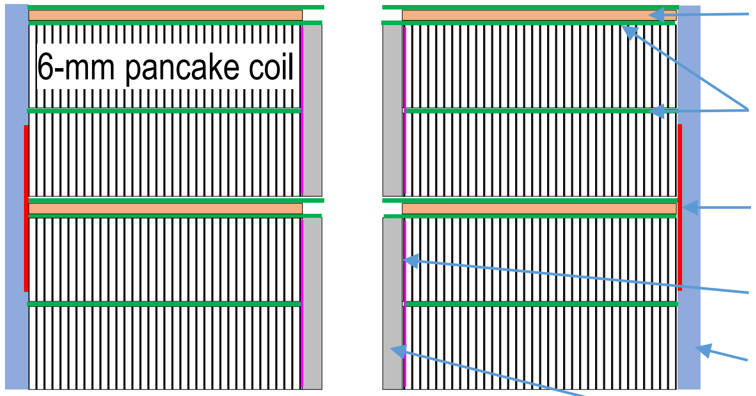
Preloading by Belleville washers.

<Concept drawings of a mechanical structure>

For a coil's elastic behavior during cooling and operation



Inside joint



Design Review taking into account the Screening Current Effect

- **Screening Current** affects: 1) **Field** (homogeneity, temporal stability) and 2) **Stress** (over-stress)
  - EM Design (Coil Optimization, Shimming)
  - Current Sweep Reversal
  - Prevent from Permanent Damage

- Modeling by using a ***T-A*** Method* (1-D current density, J_ϕ) to compute screening current.

$$\boldsymbol{J} = \nabla \times \boldsymbol{T} \Rightarrow J_\varphi = \frac{dT_r}{dz}$$

$$\nabla \times \boldsymbol{E}(\boldsymbol{J}) = -\frac{\partial \boldsymbol{B}}{\partial t} \Rightarrow \frac{dE_\varphi(J_\varphi)}{dz} = -\frac{dB_r}{dt}$$

$$\boldsymbol{E}(\boldsymbol{J}) = E_0 \left|\frac{J}{J_c}\right|^n \frac{\boldsymbol{J}}{|\boldsymbol{J}|} \qquad J_C(B_\parallel, B_\perp) = \frac{J_{C0}}{\left(1 + \frac{\sqrt{(kB_\parallel)^2 + B_\perp^2}}{B_C}\right)^b}$$

- **Simulate Screening Current:**

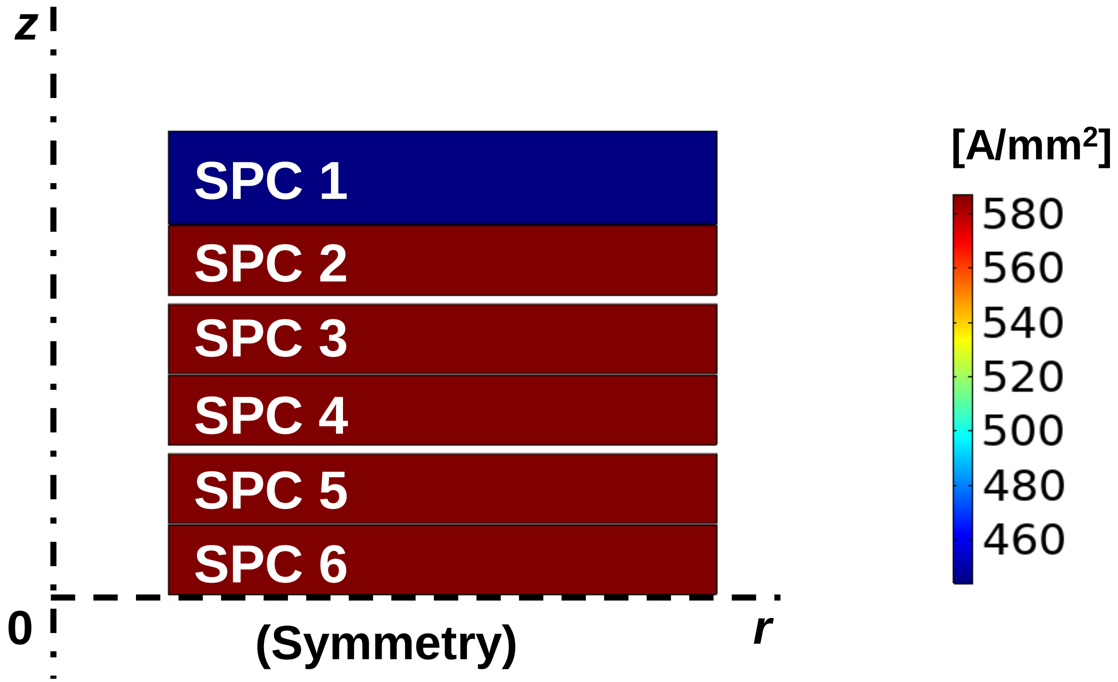
  I_{op} = 0 → 236 A @ 10 K (I_{c0} = ~3200 A),

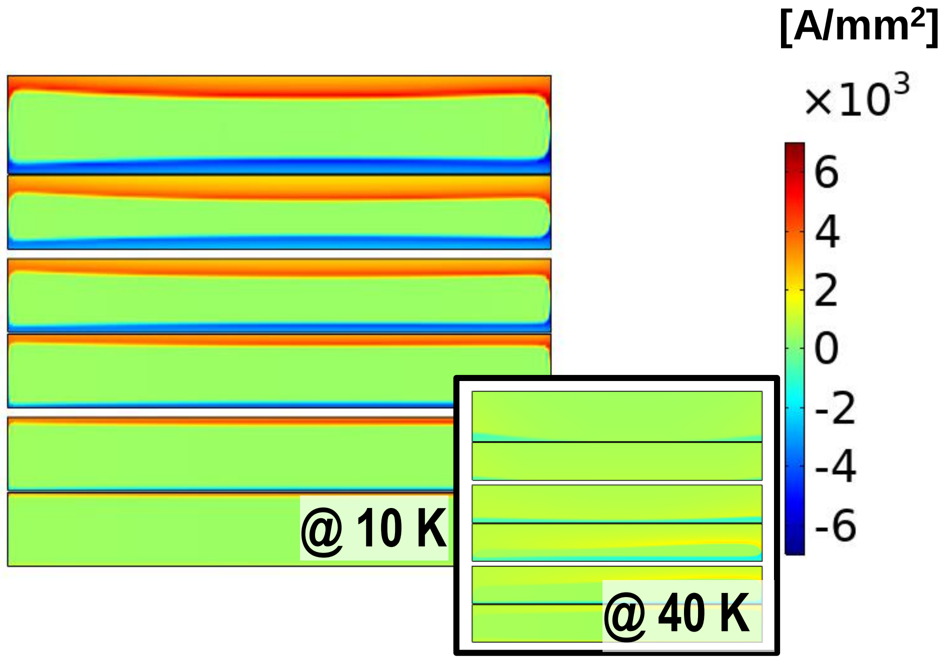
  @ 40 K (I_{c0} = ~1150 A).

*Yi Li, *et al*, "Magnetization and screening current in an 800 MHz (18.8 T) REBCO nuclear magnetic resonance insert magnet: experimental results and numerical analysis," Supercond. Sci. and Tech., vol. 32, no. 10, 105007, 2019.

Screening Current induced in a Prototype Magnet (Analysis)

- Distinguished screening currents in SPC 1 – 4.
- Screening currents suppressed with lower J_c (i.e. higher operating temperature)





<Current density of a 23.5-T prototype magnet: (left) constant Jc; (right) with screening current computation>

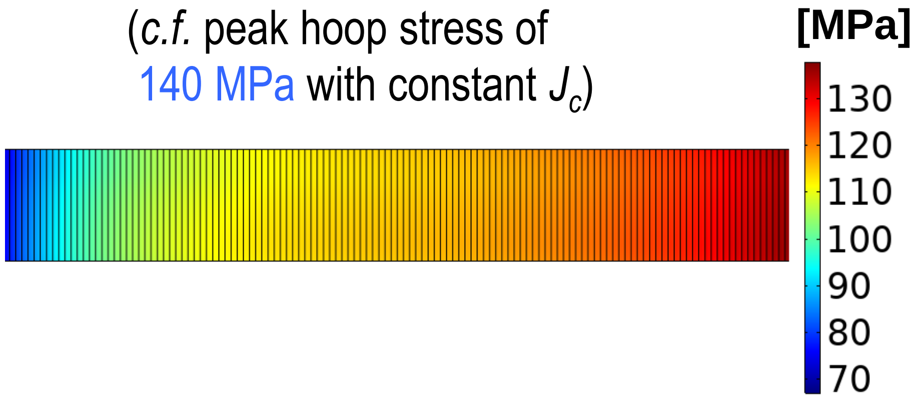
Screening Current inducing Stress (Analysis)

- Peak Hoop Stress **~910 MPa @ SPC 2**

(Modeling conditions) Winding Tension 50 N; Cool-down to 10 K; Screening current charging 236 A @ 10 K;

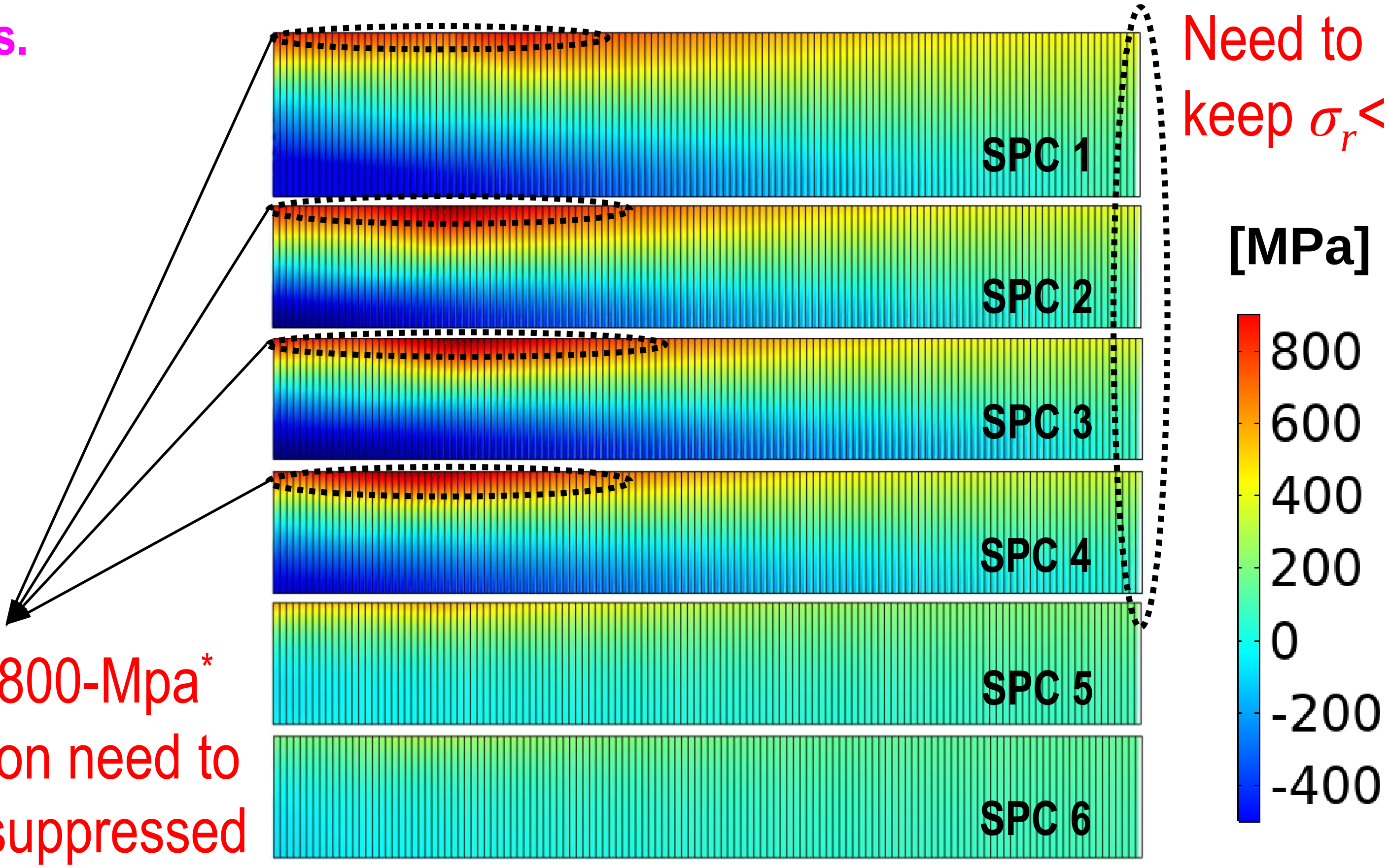
Friction-less contacts between turns and SPCs.

(*c.f.* peak hoop stress of 140 MPa with constant J_c)



<Hoop stress in SPC 2 without considering SC>

Need to keep σ_r<0

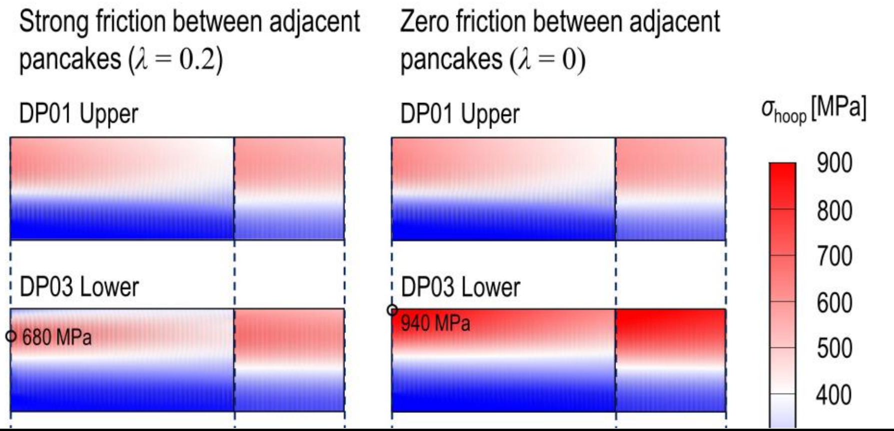
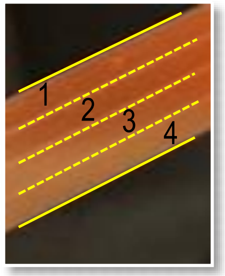
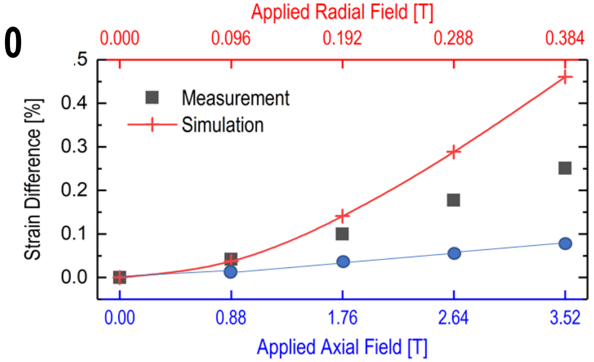


σ_ϕ>800-Mpa* region need to be suppressed

* $\varepsilon_{irr,0.99}$ (**≥0.5%**) × $E_{\phi,eff}$ (160 GPa)

<Hoop stress distribution with considering SC in the prototype magnet>

Screening Current Effect Mitigation Schemes

Increase **Friction**	**Carbon fiber prepreg** sheets hold the entire interfaces between SPCs strongly without Epoxy reach regions to reduce stresses induced by magnetic torques. Over-banding to keep σ_r<0 (comp)	ΔThermal Coefficient difference & Micro-Crack may be possible risk.	
Use **Slit** Conductor (multi-section)	**Smaller size REBCO** sections (8 mm vs. 4× 2 or 8× 1 mm) induce less screening current effects.	Coupling with copper will lead time delay to be temporally stabilized	**Mon-Af-Po1.11-10**  
Control **Temperature**	Temperature increase up to near T_{CS}, i.e. $I_{op} \approx I_c$, will reduce screening current. With no-insulation winding technique, this can be more reliable.	Different T_{CS} within entire coils. Difficult to control Temp. Gradient precisely.	Discuss in the **Next Slides**: SPC Validation Test and Analysis.

Single Pancake Coil (SPC) for Validation

- Check:

  1) Inner joint and winding process;

  2) Charging delay time constant;

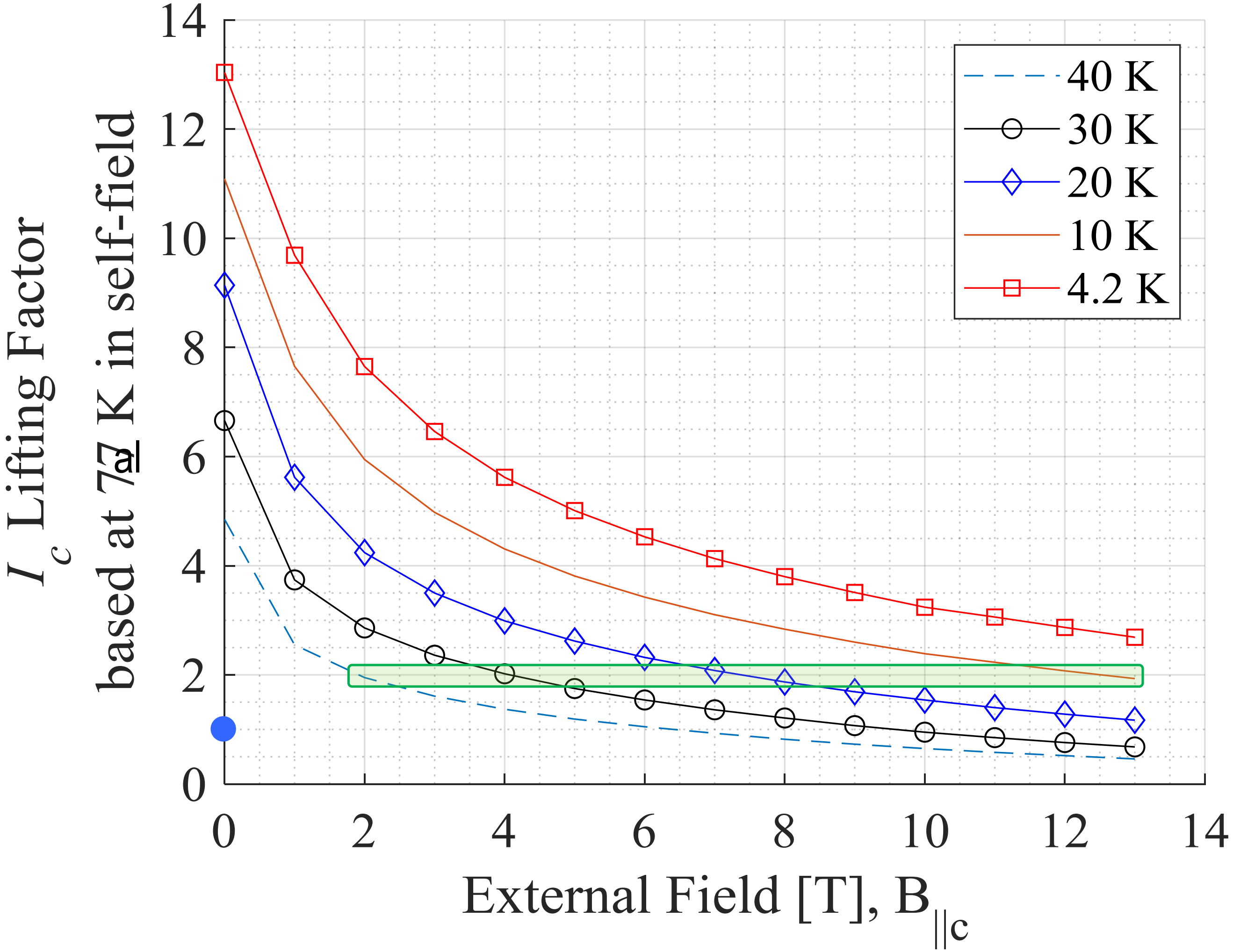
  3) Critical current

     I_c @ $B_{//c}$=13 T, 10 K (Proto 23.5-T)

     I_c @ $B_{//c}$=2 T, 40 K (SPC)

  4) Screening current effect vs. T_{op}

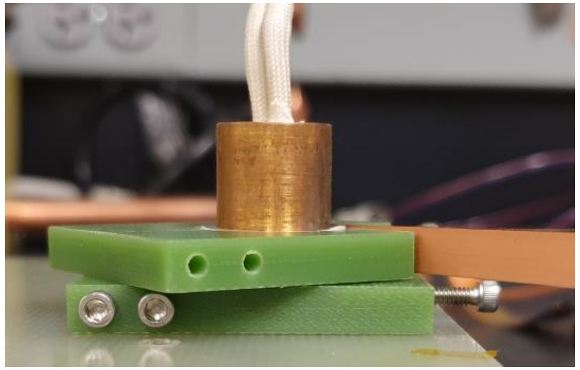
* 4.2, 20, 30 K data provided by manufacturer, Shanghai Superconductor Technology Co., Ltd. (10, 40 K data estimated)

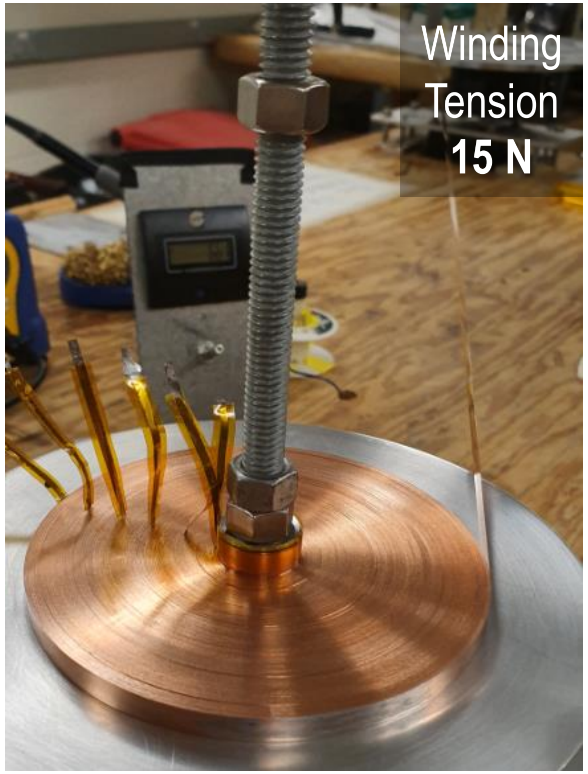


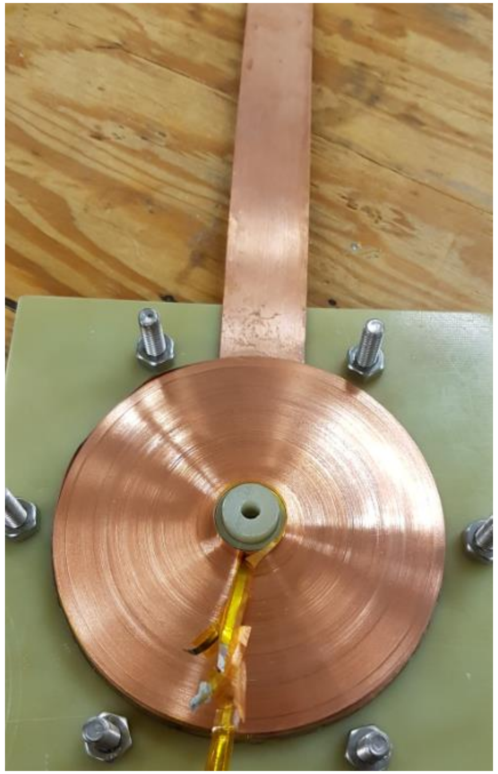
<Critical Current and Operating Temperature>

Winding (660-Turn SPC)

- Inside joint by using a 12-mm REBCO tape bridge between SPC and current lead (later between SPCs)
- Measured joint resistivity @ 77 K = 230 n$\Omega\cdot$cm^2
- SPC inductance 21.7 mH; Magnet constant: 16.2 mT/A ➔ **4.13 T @ 255 A**







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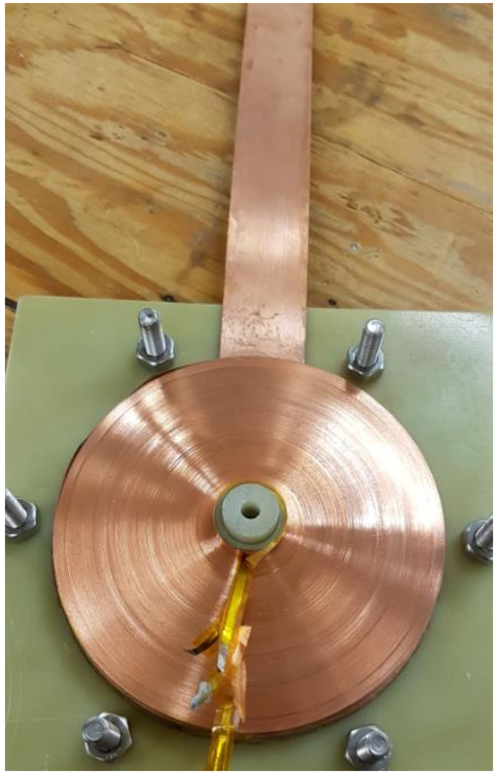
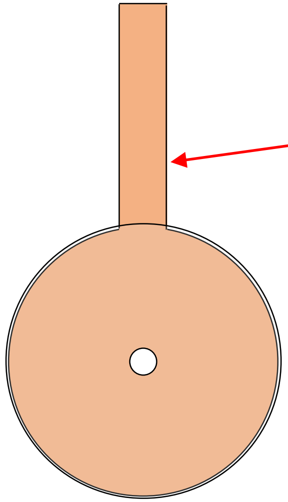
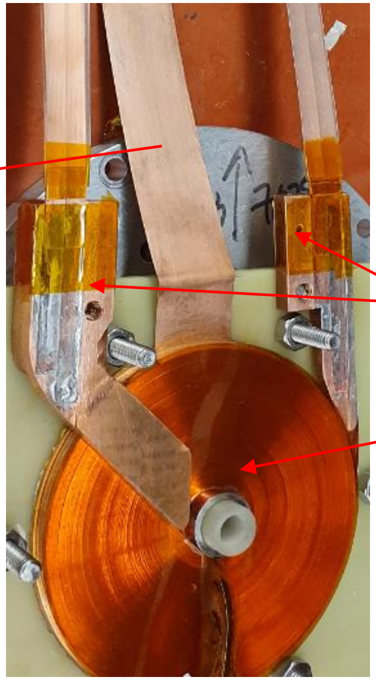
Conduction-Cooling Test Setup

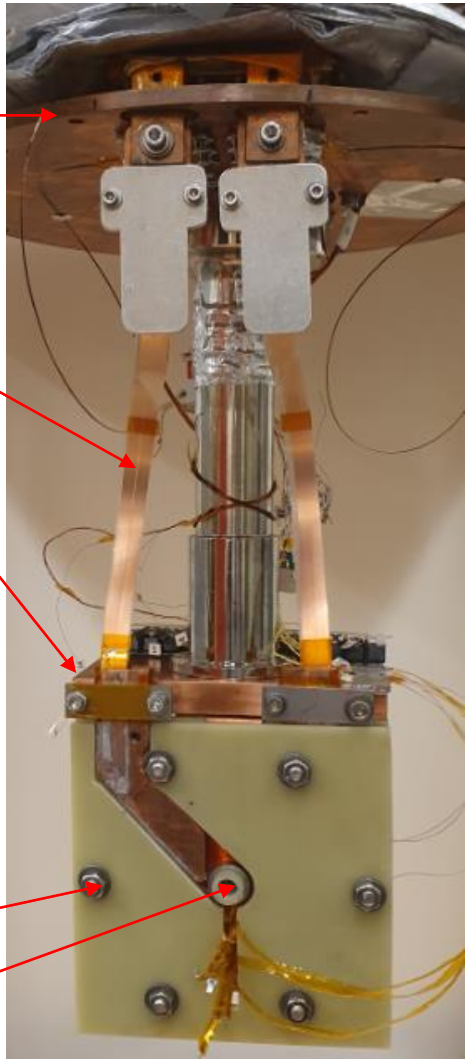
- Insulated Cooling Channel attached on Bottom Surface of SPC with Cryogenic Vacuum Grease (Apiezon N)
- Copper Junctions (Terminals) for Thermal & Electrical Stabilization





Both-side-Insulated copper cooling disk





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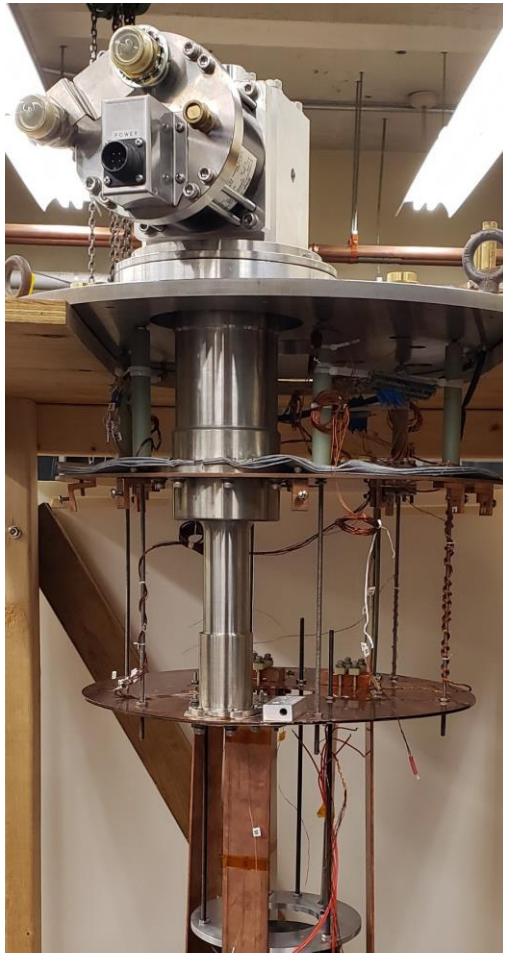
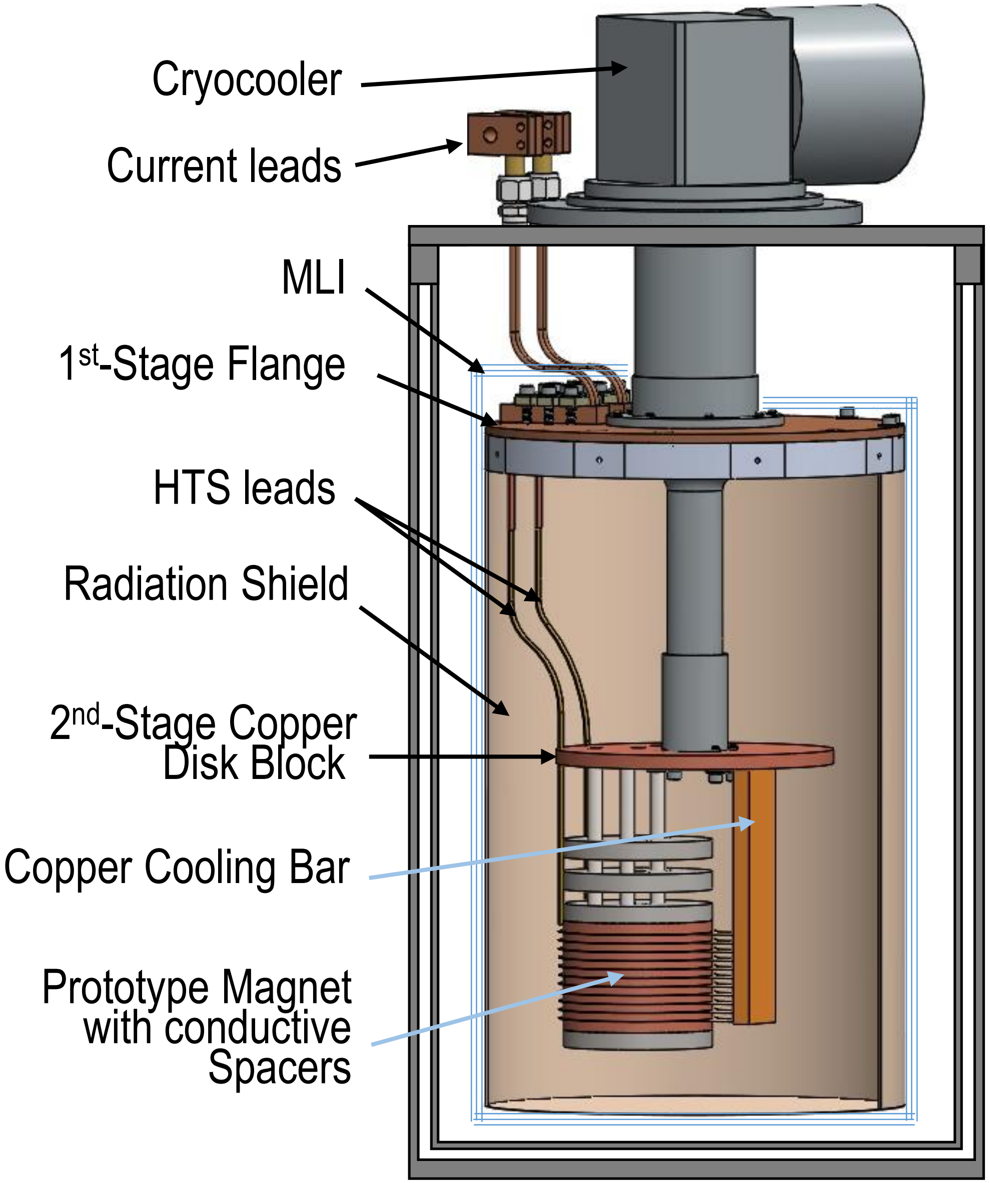
Cryostat System (will be also used for 23.5-T Prototype)

- Cooling Power: **8 W @ 10 K**





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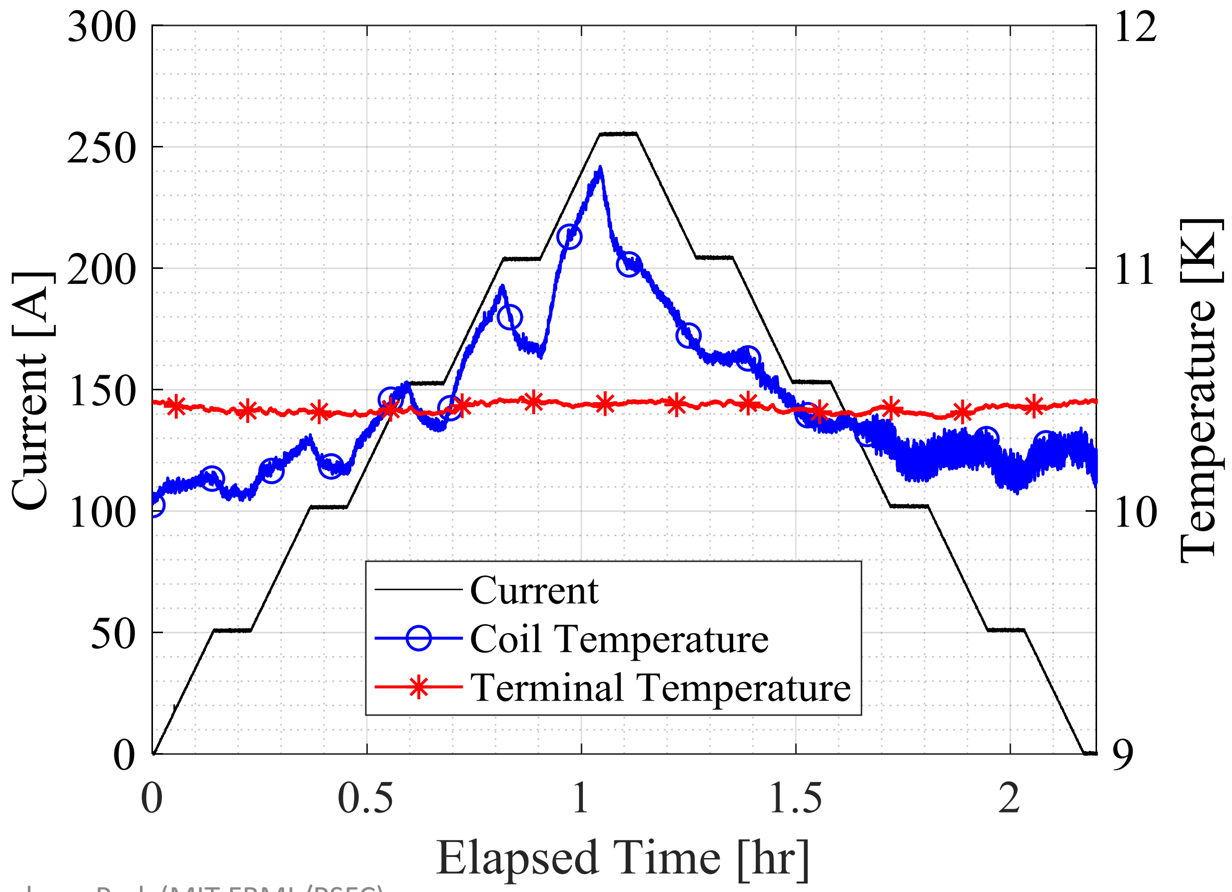
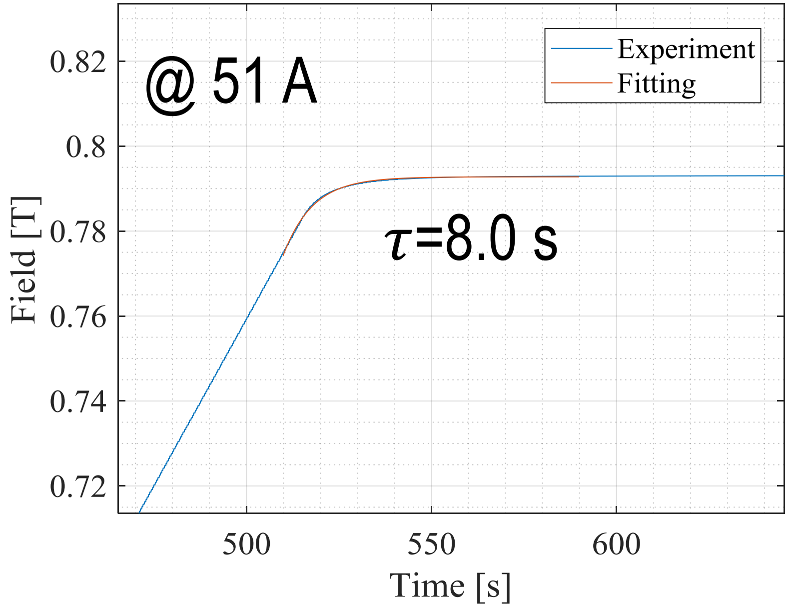
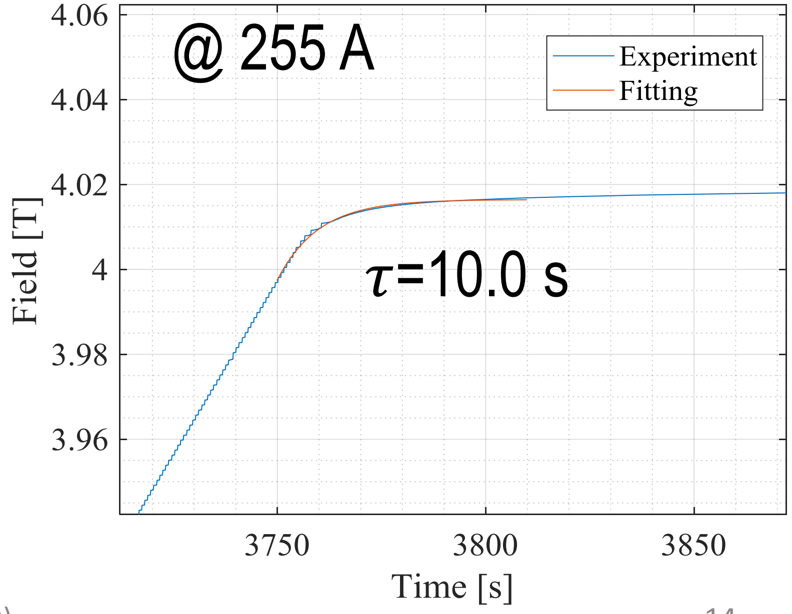
SPC Charging to 255 A @ 10 K

- Stable Coil & Terminal Temperature.
- Charging Delay Time Constant: 8 – 10 s
  R_C = 2.17 – 2.71 mΩ (ρ_C = 31 – 39 μΩ·cm²)

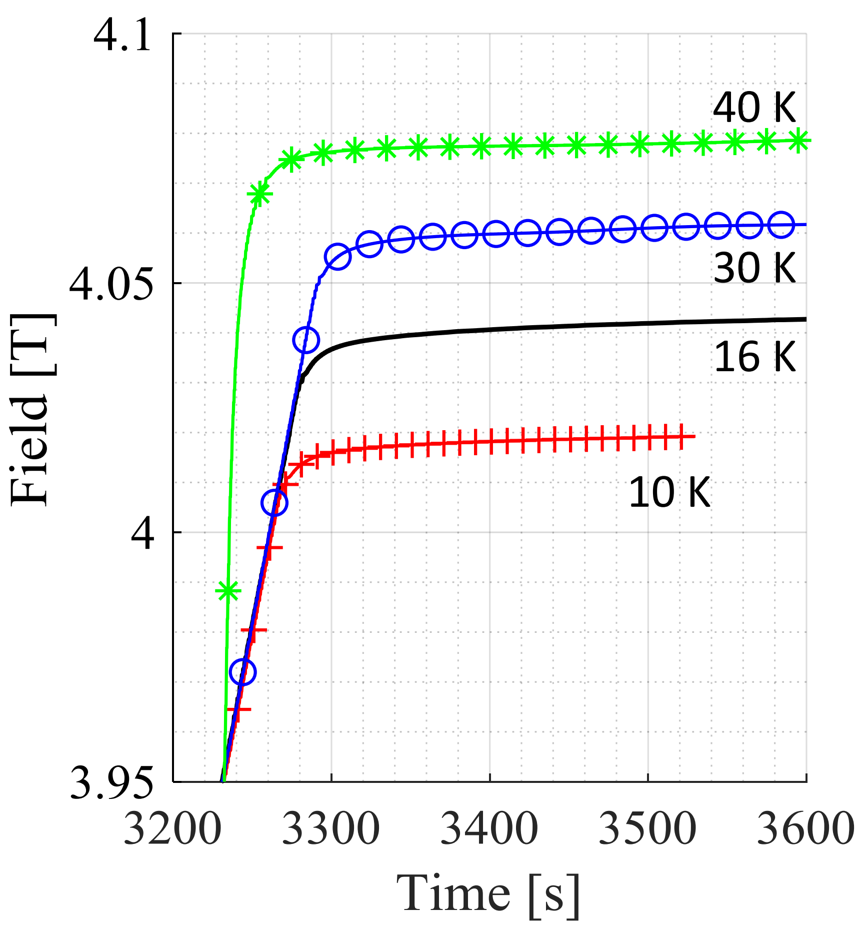


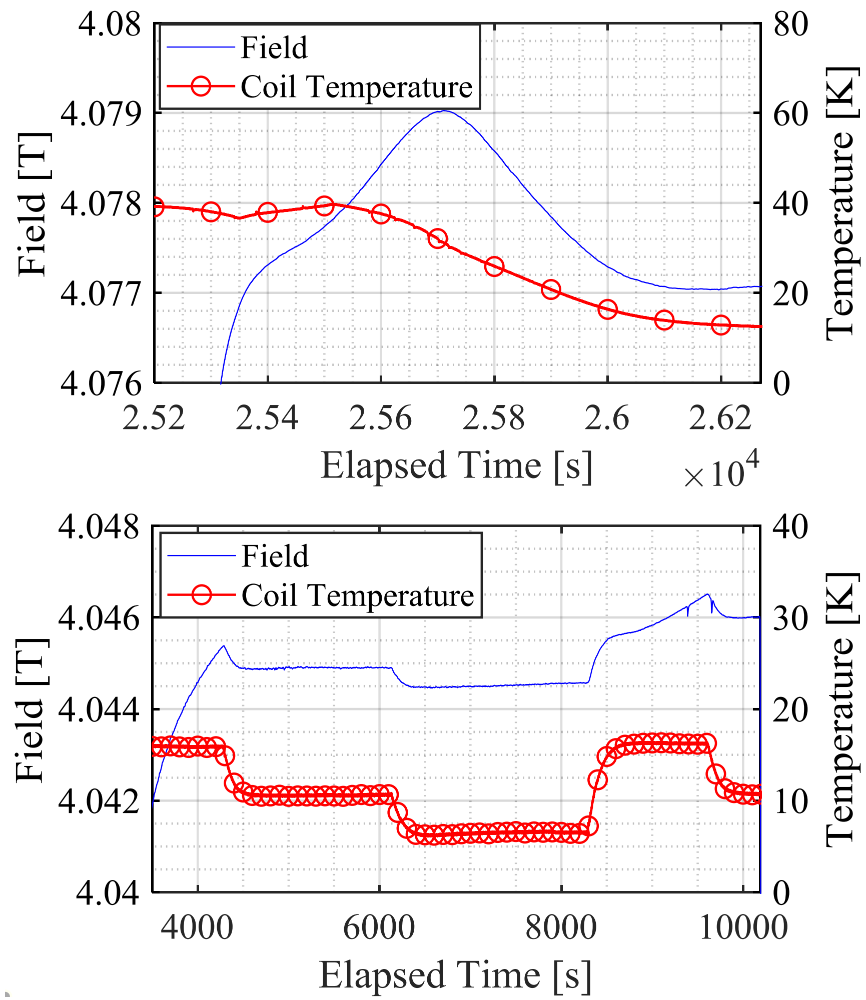


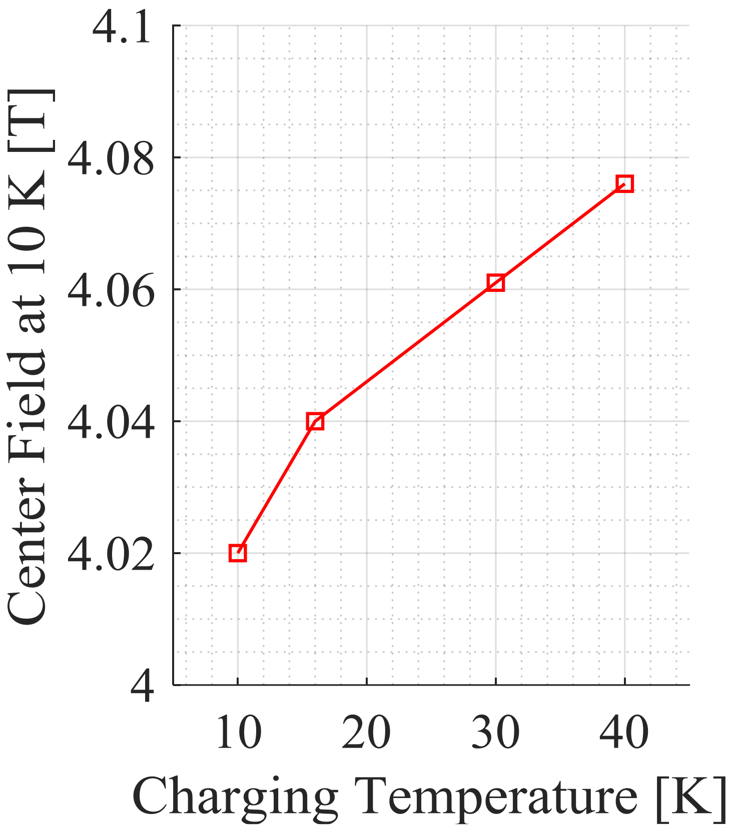


SPC Field Charged to 255 A in Different Temperature

- Test Sequence: Charging Up to 255 A @ **TEMPERATURE ➔ 10 K**.
- Measure **Center Field**.



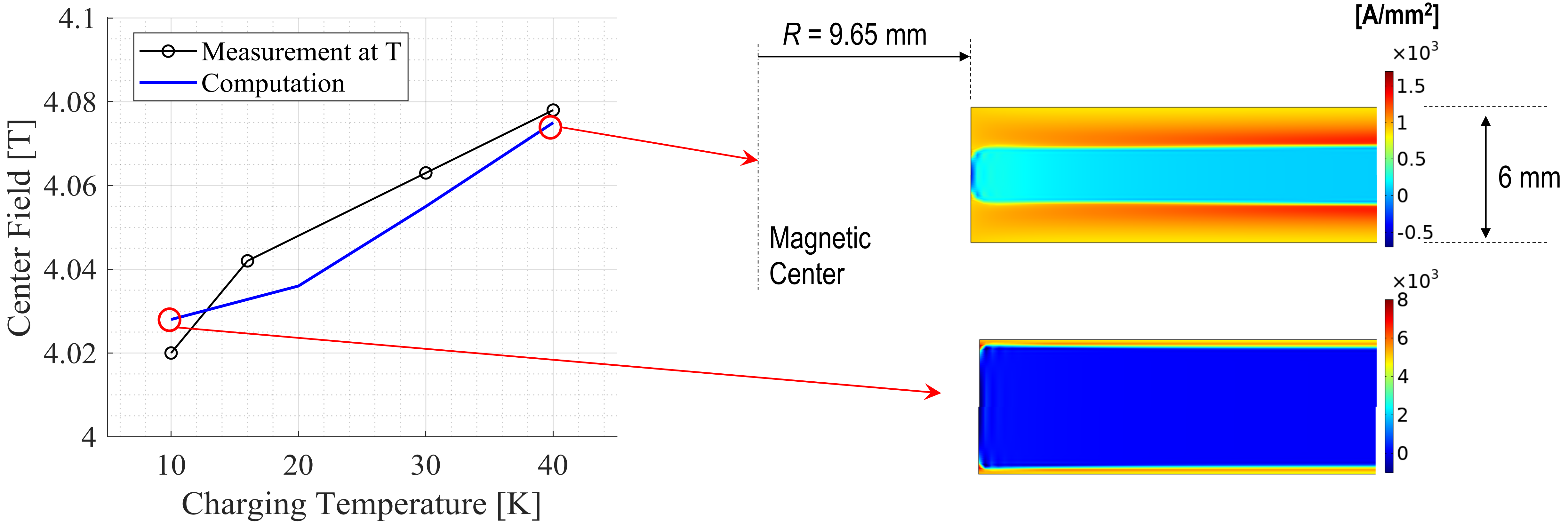




SPC Screening Current Analysis

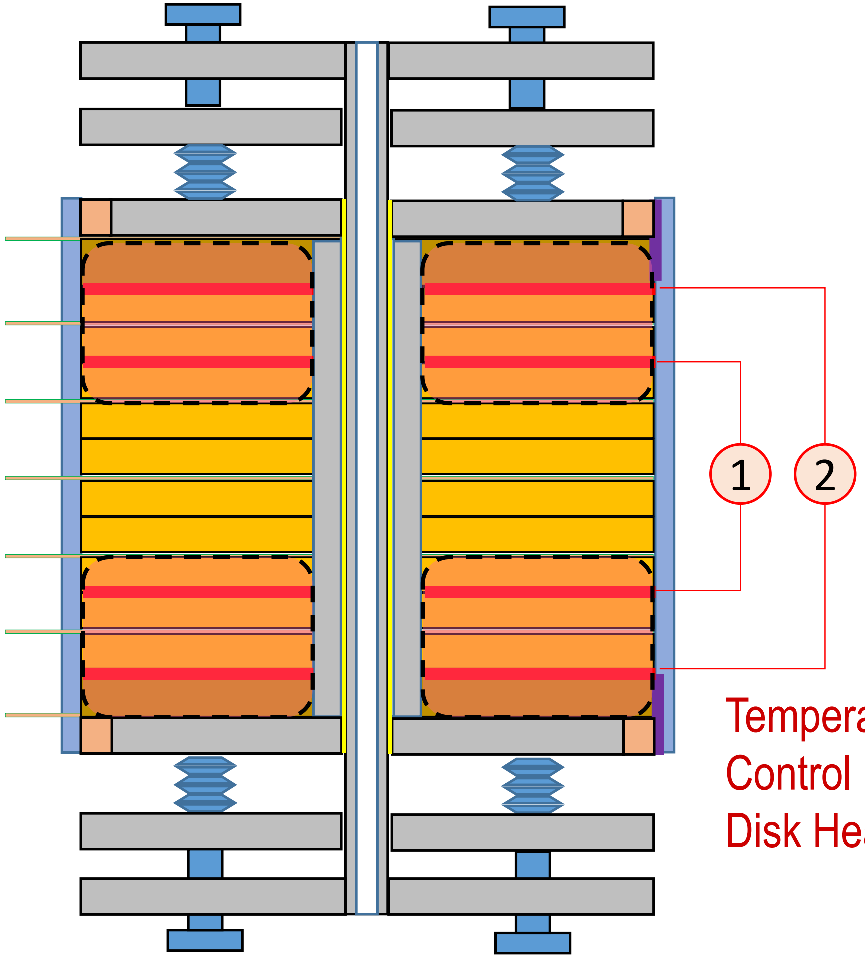
$$I_C(B_\parallel, B_\perp) = \frac{I_{C0}}{\left(1 + \frac{\sqrt{(kB_\parallel)^2 + B_\perp^2}}{B_C}\right)^b}$$

- Greatest screening current at lower temperature (higher J_c).
- Screening current strongly depending on ***$J_c(T, B, \theta)$***.



<(Left) center field vs. charging temperature; (Right) current density distribution>

Discussion on Charging and Operating Temperature



- Upper/Lower Coils may be heated up close to T_{cs} by specially designed heaters to **minimize** the screening current effects during **charging**:
  - ✓ Thin Disk Shaped, Meander or Bifilar;
  - ✓ Different Power Distribution(outer high, inner low)
- Heaters may be shut off after reaching stable operation.
- Expect to Mitigate the Screening Current inducing Over-Stress

Conclusion

- Single Pancake Validation Coil is successfully operated at 255 A in 10 – 40 K.

- Screening Current effects are Analyzed and Tested in Single Pancake Coil.
  - ✓ One Way to Suppress the Screening Current and thus possible Over-Stress is to charge REBCO Magnets (or only Outer Pancake coils) in Temperature T_{CS}, i.e. $I_{op} \approx I_c$.

- Cryogen-Free 23.5-T (1-GHz)/φ13-mm all-REBCO Magnet under Construction (2020).

- MIT FBML/PSFC will complete validation and electromagnetic design for a Tabletop LHe-Free 1-GHz Microcoil NMR Magnet in 2020.