Progress Toward the Critical Design of the Superconducting Rotor for NASA's 1.4 MW High Efficiency Electric Machine

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Outline

- Motivation & background
- Summary of the rotor & coil design
- Refined finite element analysis
  - Coil model
  - Combined thermal, centrifugal, & electromagnetic loading
- Risk reduction testing
  - Coil fabrication
  - Thermal cycling testing
- Conclusions & future work

Motivation

- **Reduced energy consumption, emissions, and noise of commercial transport aircraft [1]**
  - Electrified aircraft propulsion (EAP) enables system-level benefits to these metrics
- EAP concepts require advances to electric machines
- NASA's High-Efficiency Megawatt Motor (HEMM) sized as generator for NASA's STARC-ABL concept


STARC-ABL

Performance impact of HEMM

(relative to STARC-ABL rev A: 96% elec. machines with 13.2 kW/kg)

	With HEMM (>98% electric machines with 16 kW/kg)
Fuel burn, %	–1 to –2
Waste heat in generator	½ to ¼ (–30 to –44 kW)

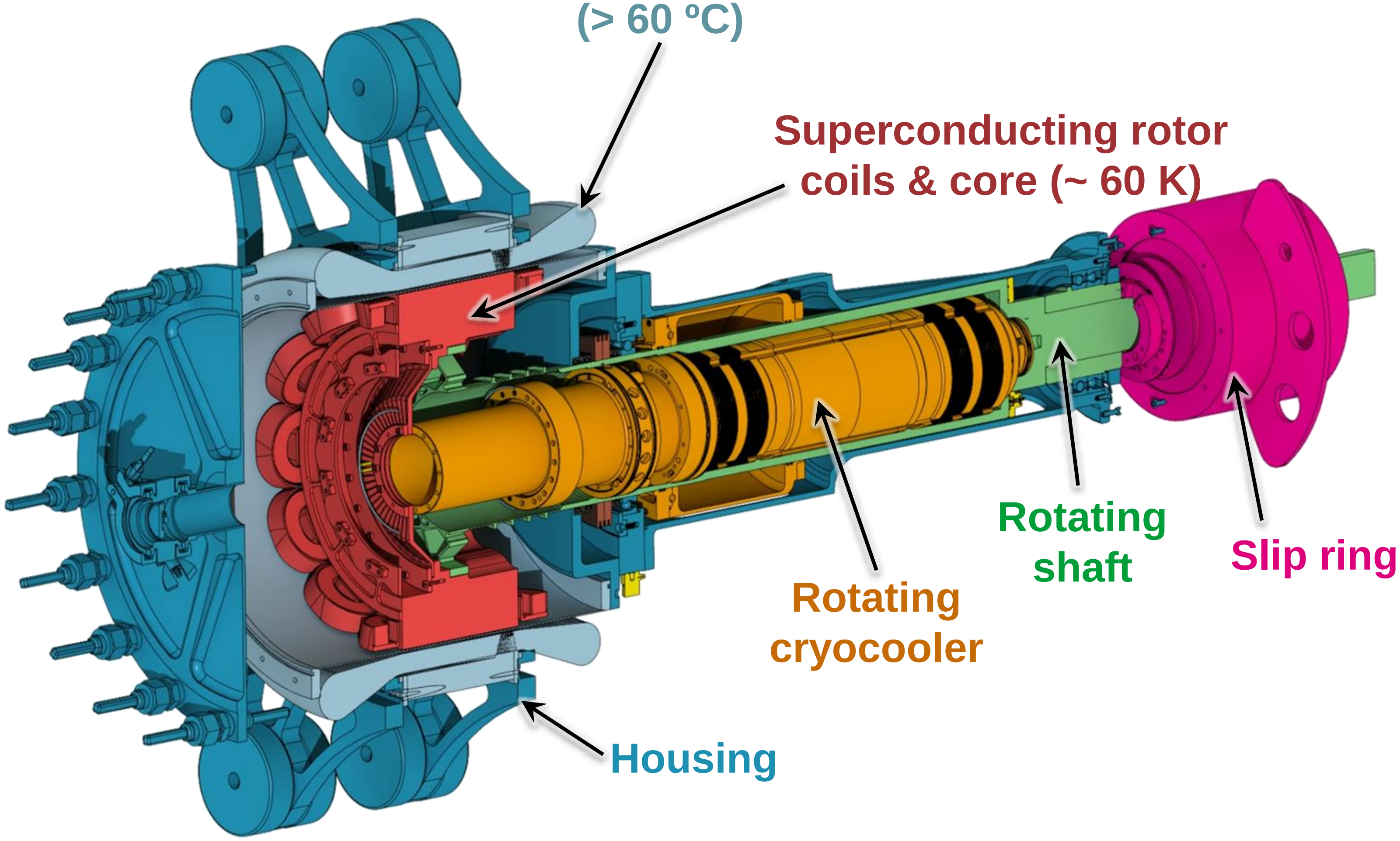
Refined analysis of baseline STARC-ABL (96% elec. machines with 13.2 kW/kg):

STARC-ABL uses 4% less fuel than future vehicle with assumed technology advancement

NASA's High-Efficiency Megawatt Motor (HEMM)

Parameter	Value
Rated continuous power	1.4 MW
Nominal speed	6,800 rpm
Tip speed	Mach 0.31
Rated torque	2 kNm
Specific power goal	16 kW/kg
Efficiency goal	> 98%

- Wound-field synchronous machine
  - Tolerant of stator fault
- Superconducting rotor
  - Negligible energy loss
  - Very strong magnetic excitation



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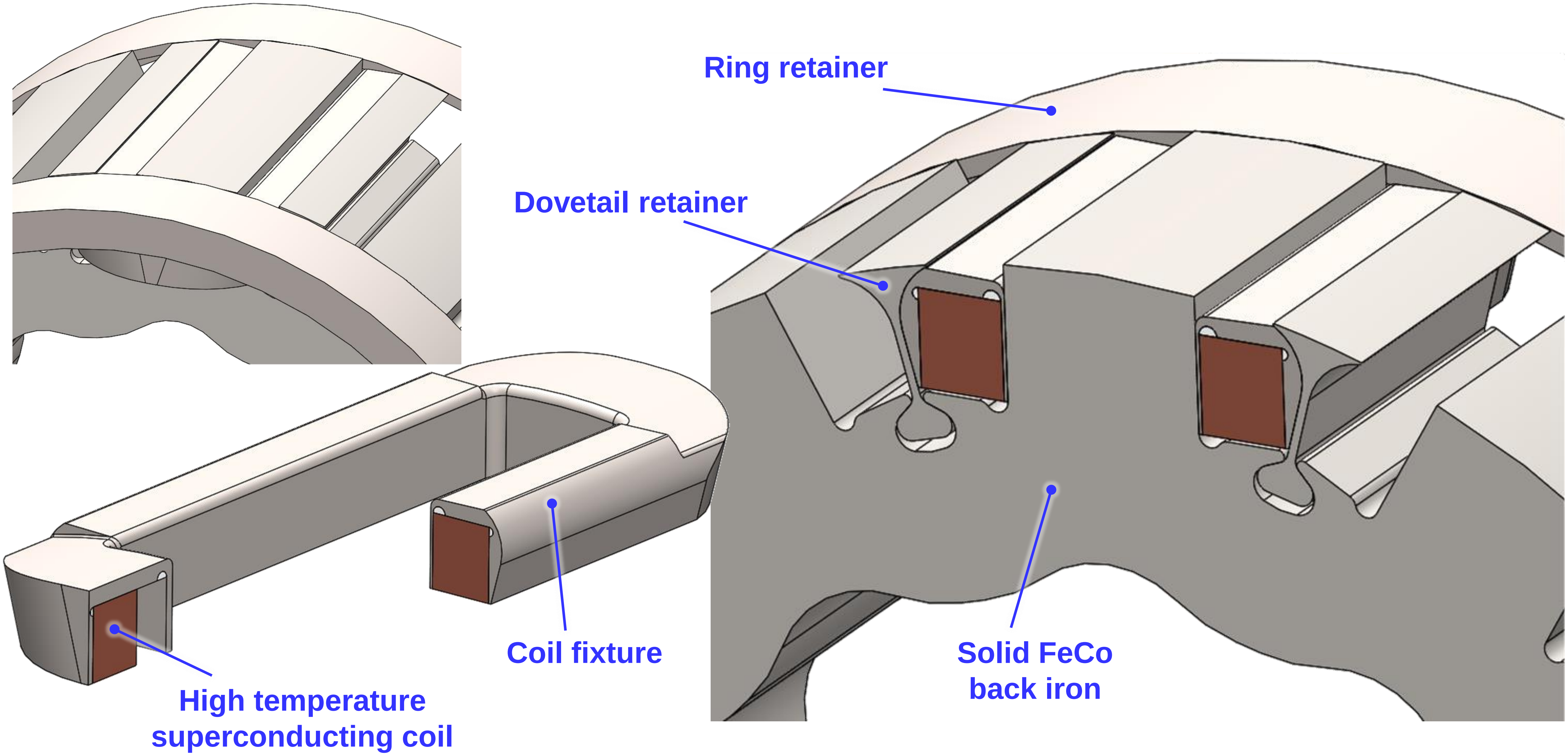
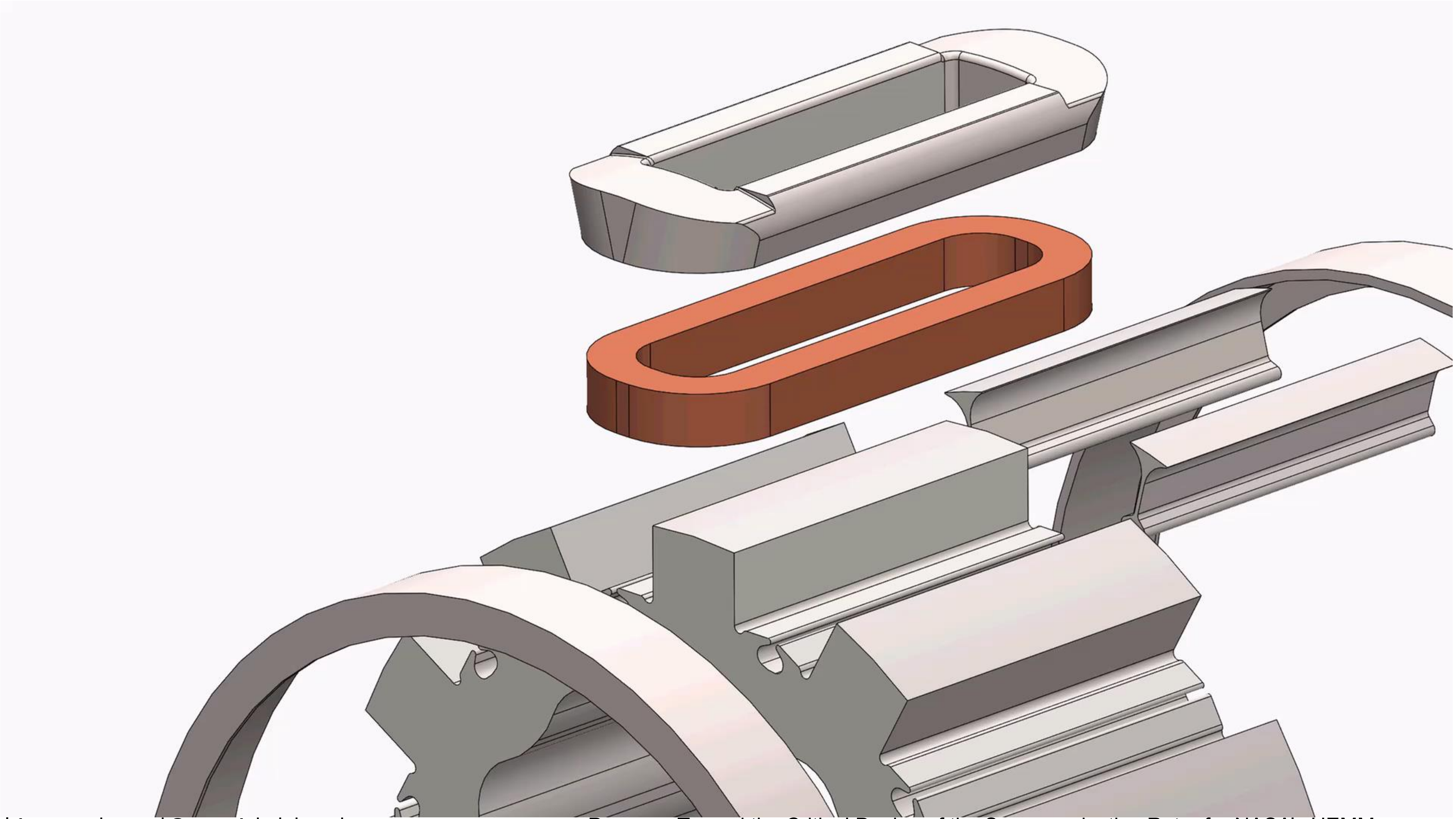
Rotor Design



Rotor Design



Coil Design

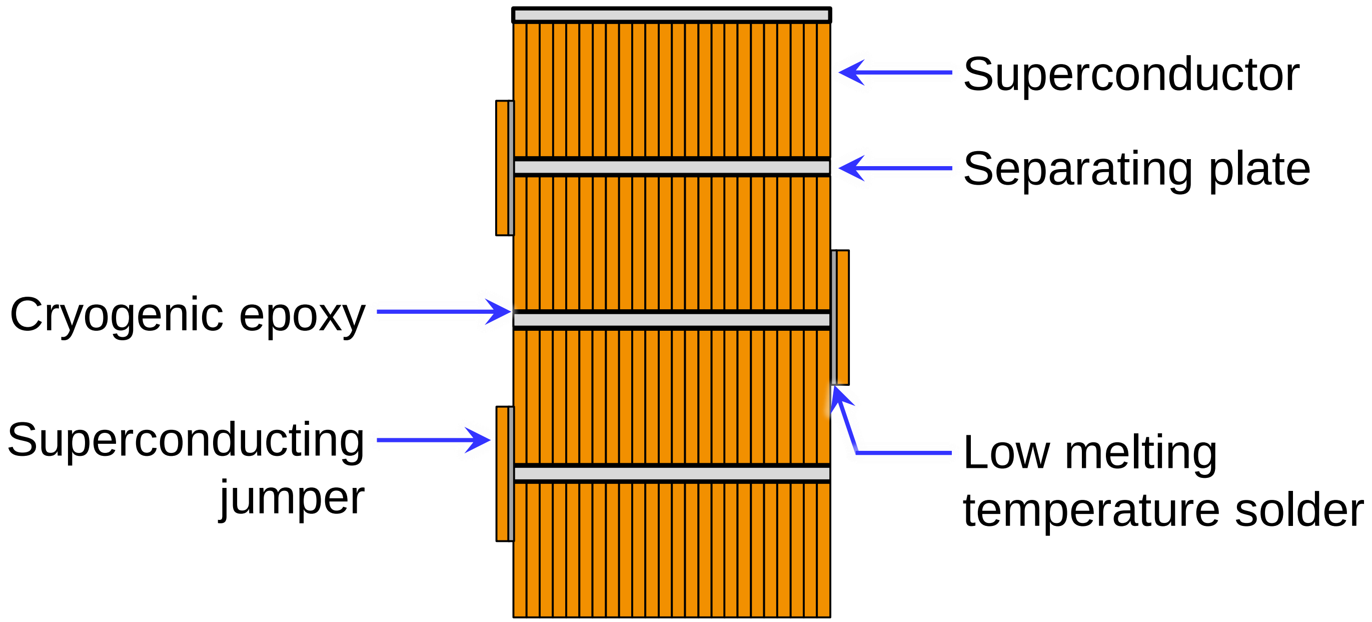
Coil characteristics

Parameter	Value
Operating temperature	< 62.8 K
Operating current (DC)	51.5 A
# of turns	~ 920

Superconductor characteristics

Parameter	Value
Material	REBCO
Width	4 mm
Thickness	65 micron
Min. bend radius	15 mm

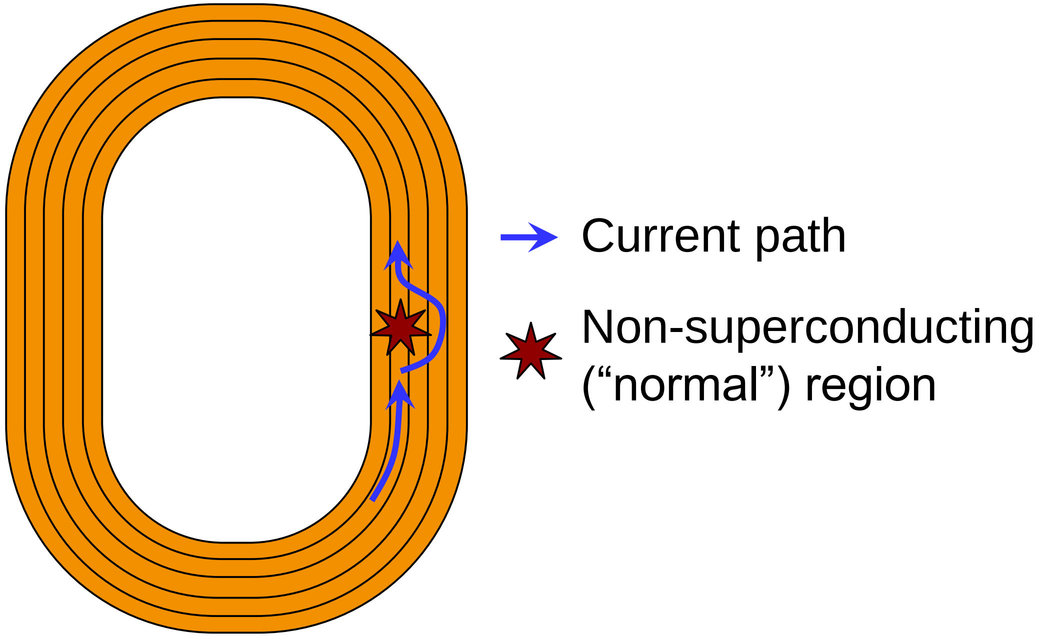
Coil's cross-section



Coil Design

- High temperature superconductor (**ribbon-shaped**)
- No electrical insulation between turns of conductor
  - Benefits**:**
    - **Fault tolerant** – Inherent protection from loss of superconductivity
    - **Can fit more turns into same cross section**
    - Higher mechanical strength
  - Requirement**:**
    - Sufficient contact between turns everywhere (for current transfer and heat transfer)

Self protection via no turn-to-turn insulation



No-insulation superconducting coils are very promising, but have not been studied for rotating systems

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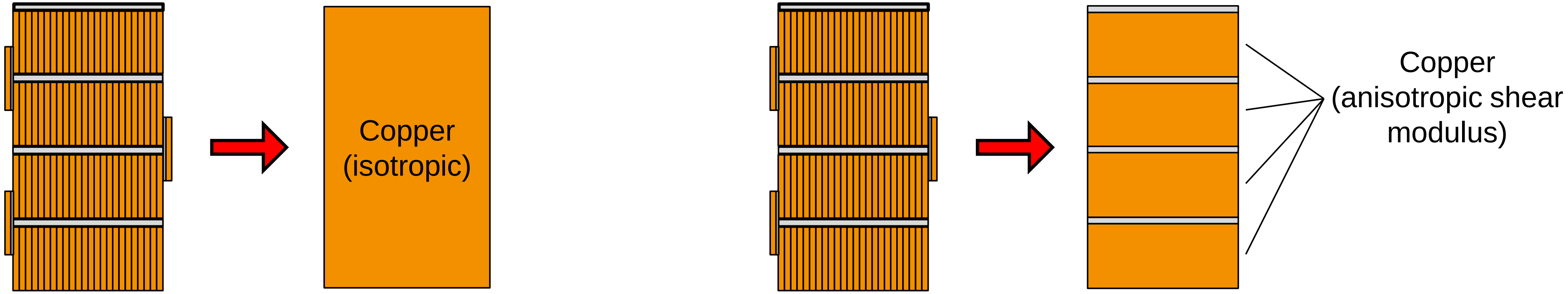
Refined coil model

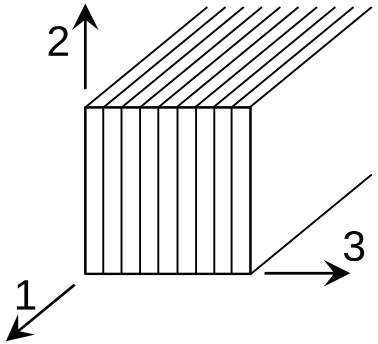
Coil's cross-section

Old model | Refined model



- **Ideal, but practically impossible:** explicitly model each turn with mechanical contact between adjacent turns
- Was unable to approximate mechanical contact between turns by including a Young's modulus in the turn-to-turn direction that depends on strain

E_1, E_2, GPa	150
E_3, GPa	150
ν_{12}	0.32
ν_{23}, ν_{13}	0.32
G_{12}, GPa	56.8 $(= 0.5E_1/(1+\nu_{12}))$
G_{23}, G_{13}, GPa	3.5



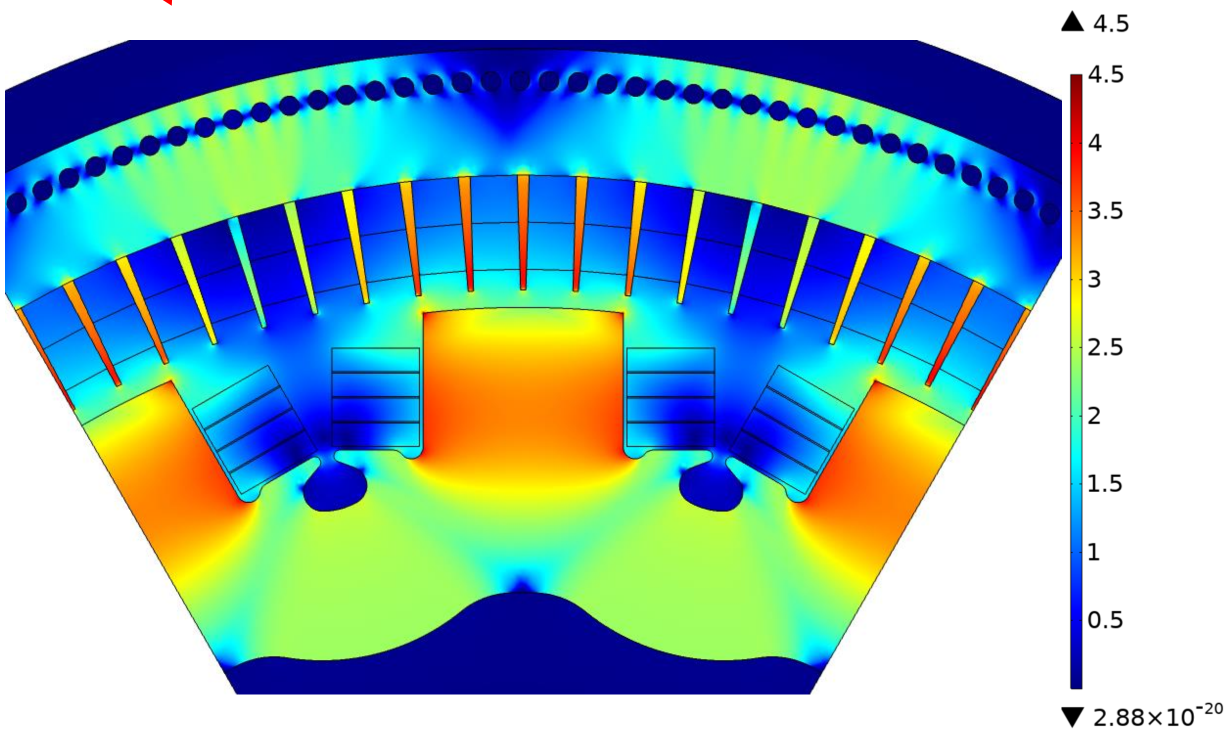
Combined Thermal, Centrifugal, and Electromagnetic Loading Model

- **Previous simulations neglected thermal response & electromagnetic forces**
- Refined model considers full combined loading & temperature-dependent material properties
    - Cool down from RT to 60 K (thermal forces),
    - Then rotation of cold rotor (centrifugal force),
    - Then rotor current (electromagnetic forces on coil)

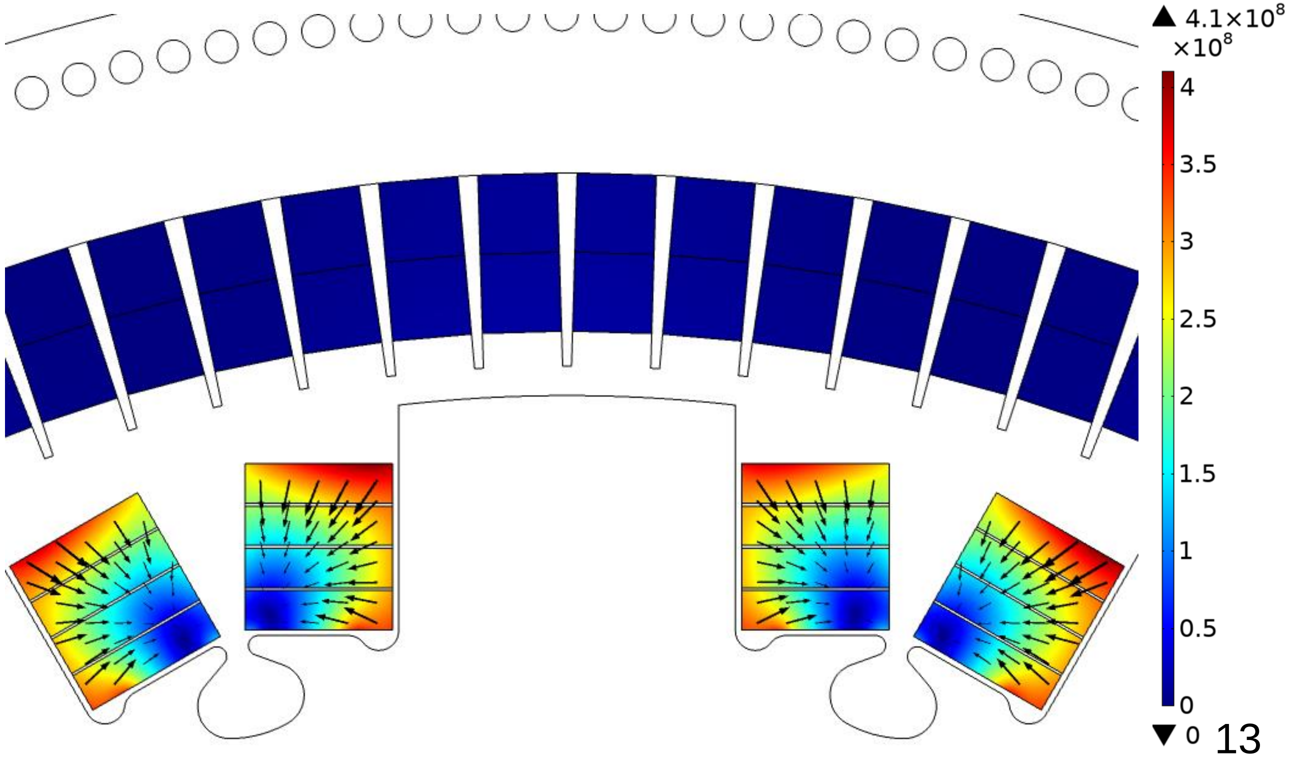
Combined Thermal, Centrifugal, and Electromagnetic Loading Model

- Interesting observations of this machine
  - Superconducting rotor coils are significantly stronger than copper stator coils
    - Thus, **stator current ripple has negligible effect on rotor's magnetic response**
  - When optimizing specific power or torque, pushing FeCo back iron far into saturation is favored
    - Thus, **Lorentz forces on rotor coils are considerable**

2D simulation of $|\boldsymbol{B}|$ (T)

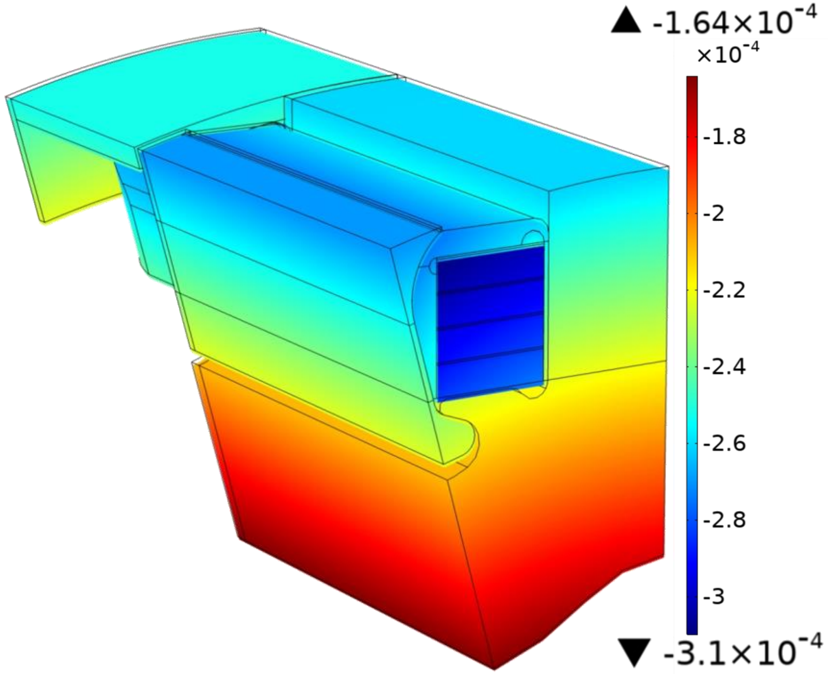
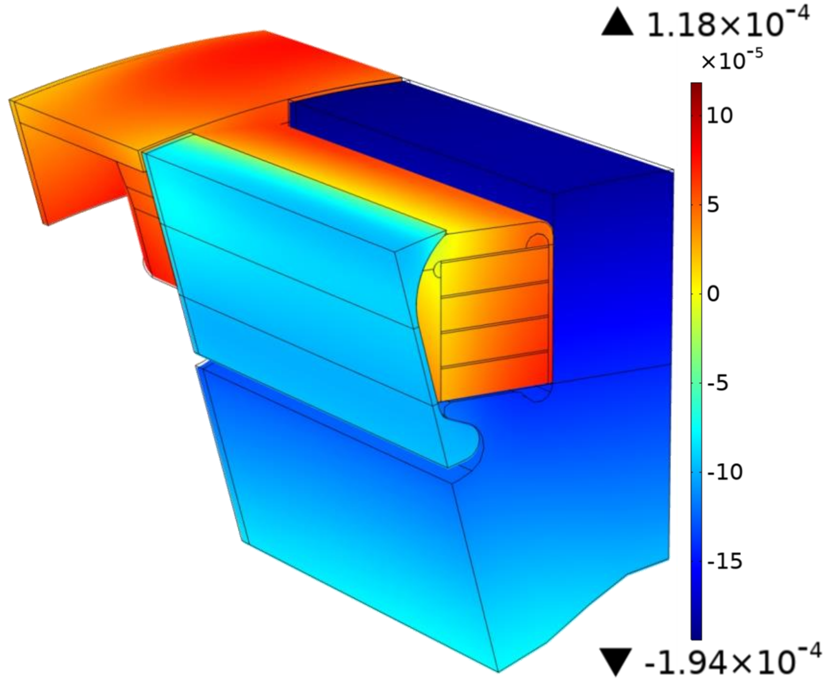
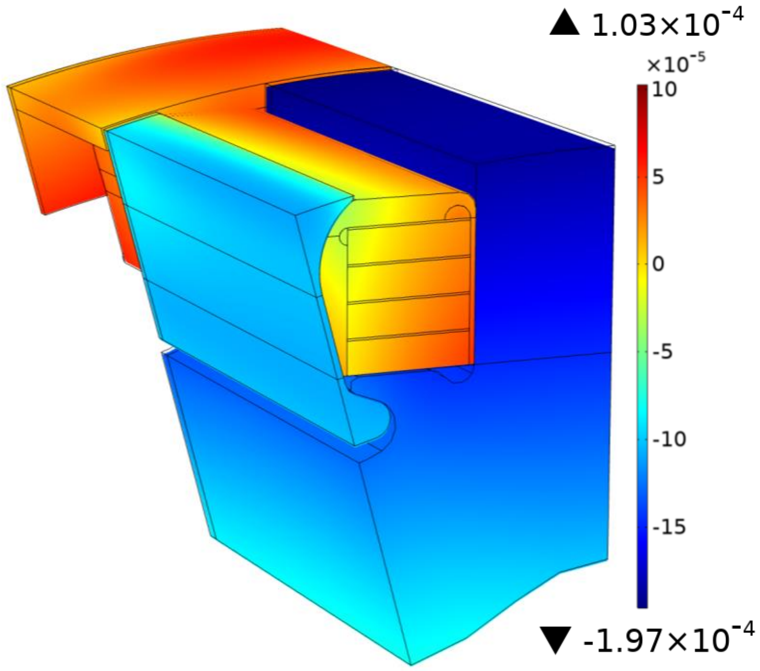


2D simulation of Lorentz force per volume (N/m^3)



Combined Thermal, Centrifugal, and Electromagnetic Loading Model

Radial deformation (m) results

End of cool down to 60 K	End of cold spin up to 6,800 rpm	At full power (60 K, 6,800 rpm, max current)
		

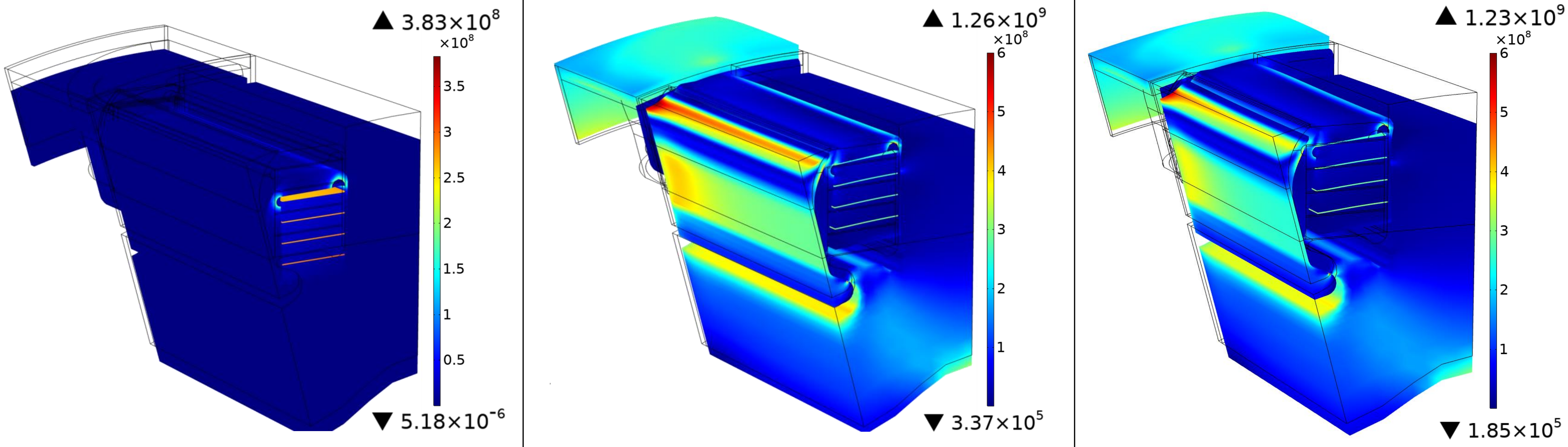
	End of cool down to 60 K	End of cold spin up to 6,800 rpm	At full power
Outermost point's radial deflection:	**-0.25 mm**	**+0.08 mm** (old model: +0.32 mm)	**+0.06 mm**
Physical radial gap:**	**1.25 mm**	**0.92 mm**	**0.94 mm**

** excludes assembly & geometry errors, deflection due to unbalance

Combined Thermal, Centrifugal, and Electromagnetic Loading Model

Von Mises stress (Pa) results

End of cool down to 60 K	End of cold spin up to 6,800 rpm	At full power (60 K, 6,800 rpm, max current)



Cannot rotate to full speed before cooling down

Combined Thermal, Centrifugal, and Electromagnetic Loading Model

Old model vs. refined model
Comparison of maximum von Mises stress (MPa) in each component

Component	Old FEA model (Rotation-only)	New FEA model (Cool down + rotation)	% change	'Failure' strength, MPa
Coil	124	127	+ 2.4	See next slide
Back iron	436	433	– 0.7	694**
Coil fixture	519	507	– 2.3	1100
Dovetail	1260	1260	0	1100
Ring	349	368	+ 5.4	1100

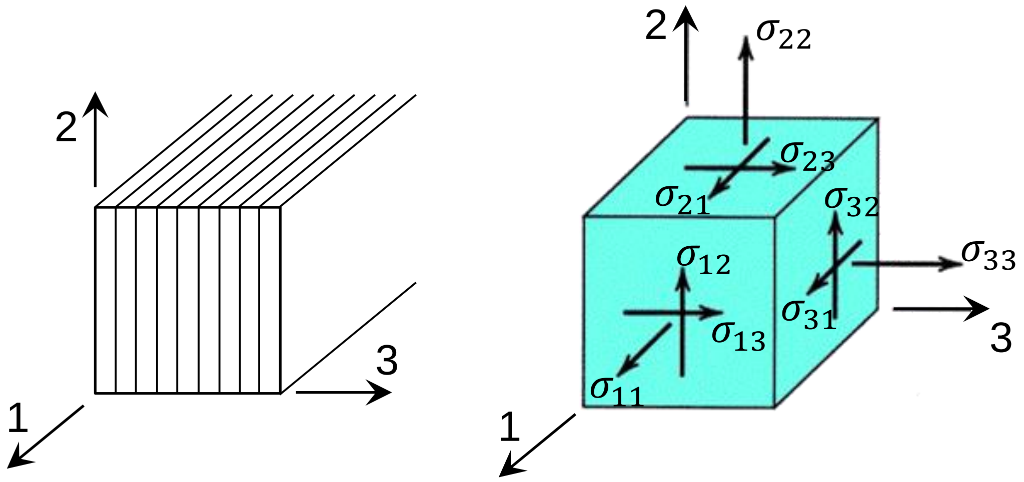
- Here, minimal differences in peak von Mises stress between old & refined models, but…
  - Peak stress & stress distribution in end turn of coil now captured
  - Radial deformation greatly over predicted before

Combined Thermal, Centrifugal, and Electromagnetic Loading Model

Range of each stress component (MPa) in the superconductor

Stress component		'Failure' strength	End of cool down to 60 K	End of cold spin up to 6,800 rpm	At full power (60 K, 6,800 rpm, max current)
Normal stress	σ_{11}	**> 550**	-86.1 to 63.5	-145 to 80.3	-137 to 90.2
	σ_{22}	**Low (?) in tension**	-18.8 to 27.8	-181 to 24.8	-162 to 24.1
	σ_{33}	**Very low in tension**	-37.1 to 9.8	-91.1 to 16.2	-89.8 to 15.2
Shear stress	σ_{12}, σ_{21}	**Low (?)**	-10.1 to 6.5	-19.8 to 40.6	-19.4 to 37.5
	σ_{23}, σ_{32}	**Very low**	-5.8 to 6.8	-6.0 to 12.0	-5.8 to 11.5
	σ_{13}, σ_{31}	**Very low**	-0.4 to 1.4	-2.1 to 2.8	-2.1 to 3.1

Stress components in relation to conductor orientation



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Risk reduction testing

Questions to answer

- Can we maintain superconductivity in the operating environment?
- Are we confident enough to spend $$$ on superconductor?

Key risks of the rotor

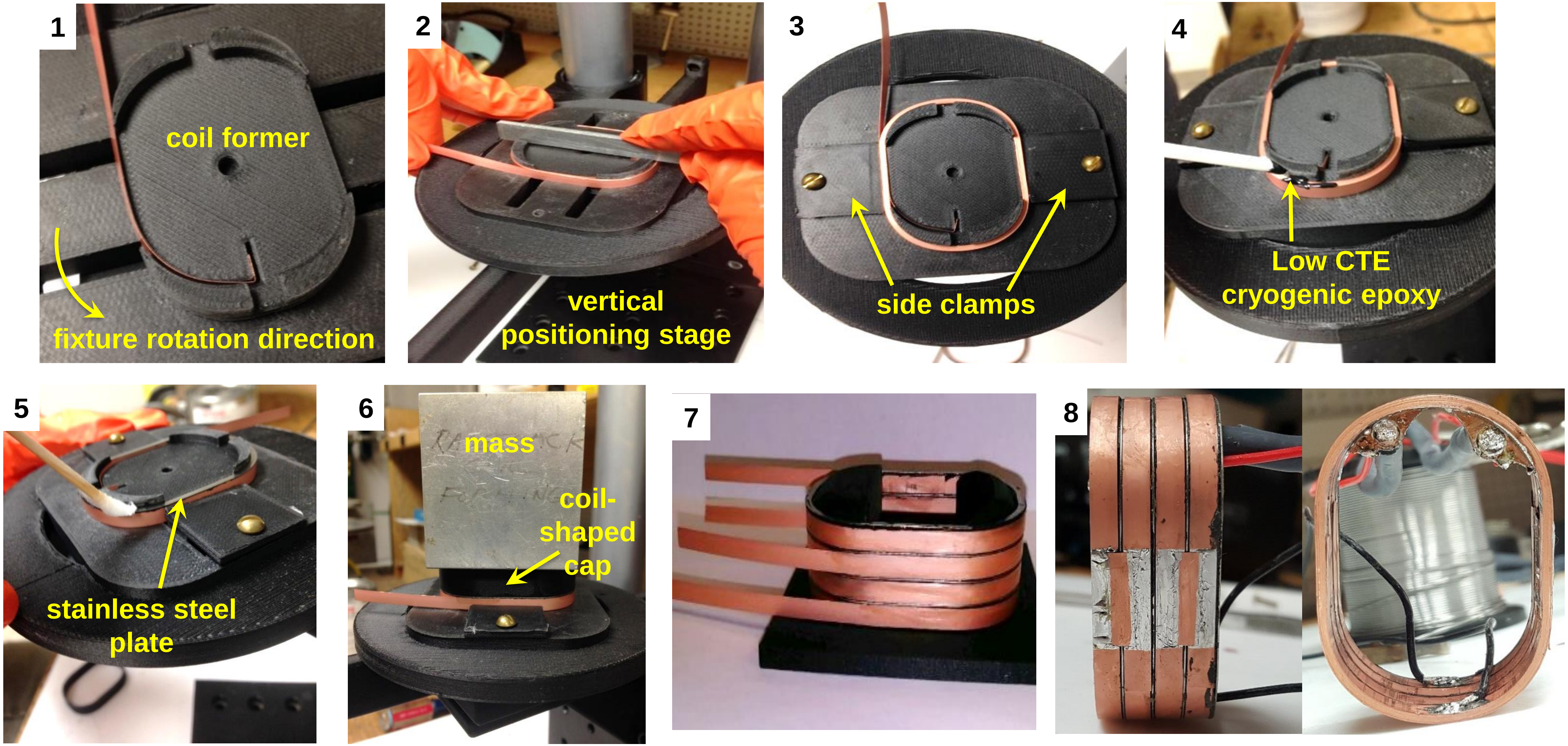
1. Rotor heat load will be higher than expected
2. Superconducting coils will not be able to handle the centrifugal loads
3. Superconducting coils will be difficult to manufacture
4. Superconducting coils will not survive the thermal cycling

Addressing these risks in this talk

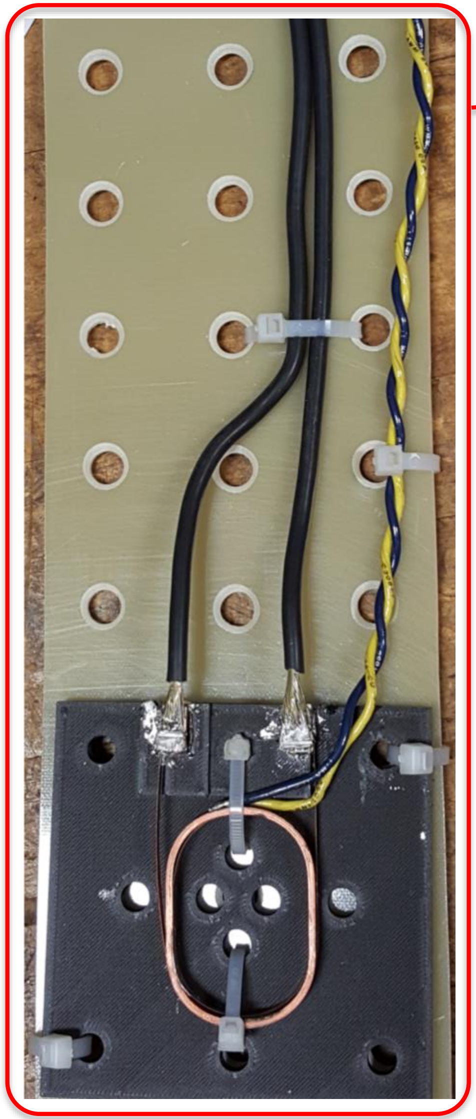
Why thermal cycling?

- **The problem:** superconductor has anisotropic thermal contraction → tensile stress
- Limited success in literature & only demonstrated for 1 to 7 thermal cycles

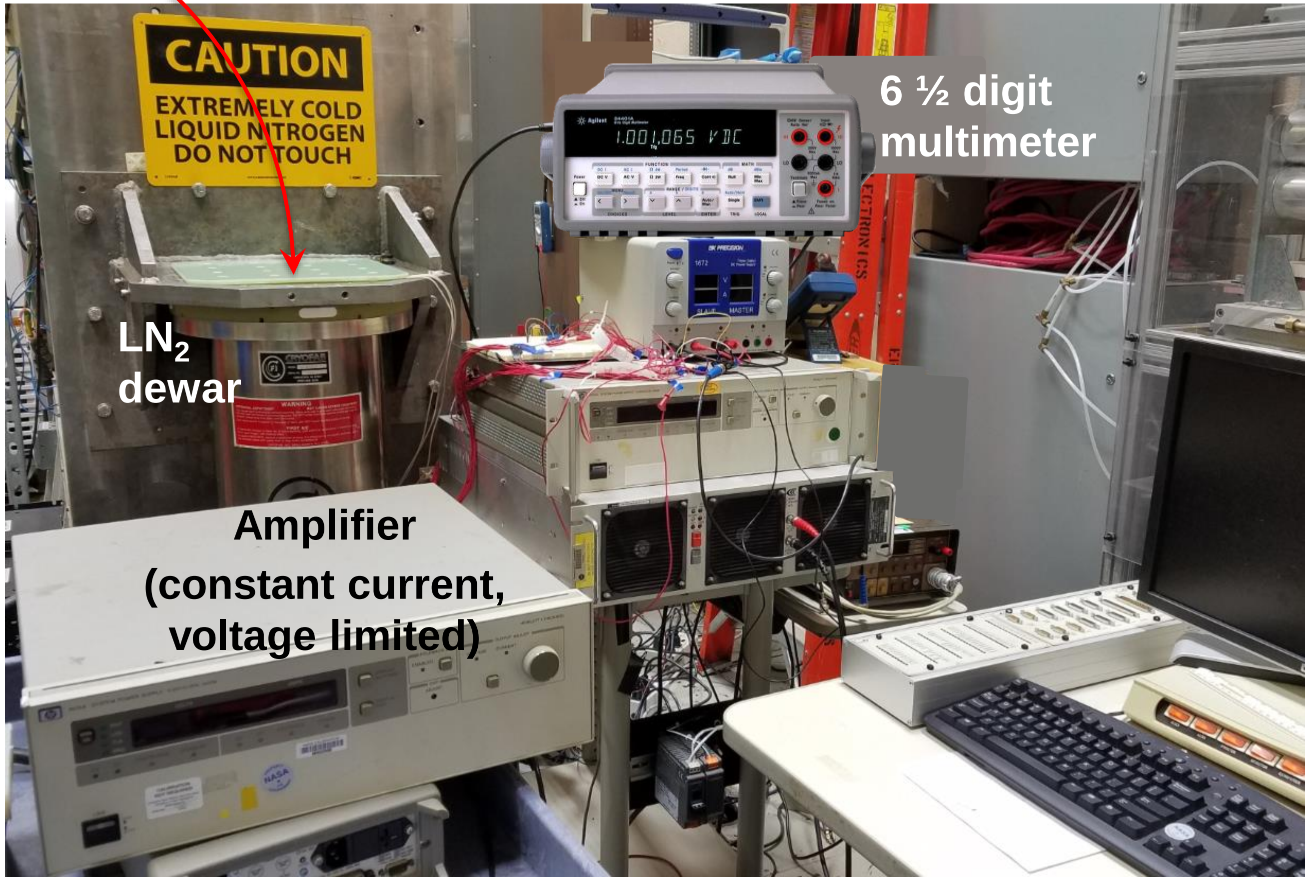
Coil fabrication process



Experimental Setup



- Coil mounted to G10 plate & suspended in liquid nitrogen
- **Measurements:** DC voltage & DC current

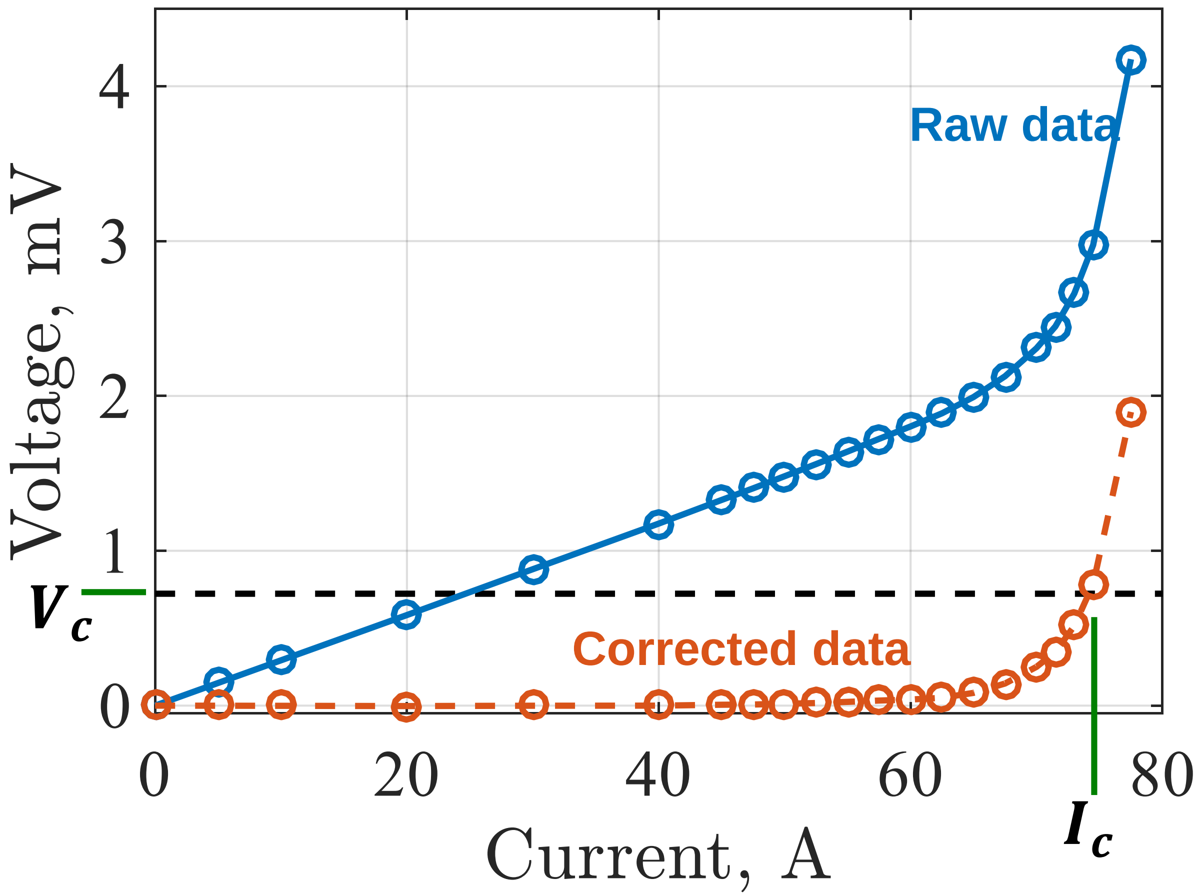


Thermal Cycling Procedure (summarized)

1. Very slowly lower the coil into LN2
    1. Wait ~5 minutes to reach steady state
2. Measure voltage vs. current response
    1. Change DC current at a rate of < 0.05 A/s
3. Thermally cycle
    1. Remove coil from LN2 and air quench for > 5 minutes
    2. Use fan for 3 minutes to finish warming up coil to room temperature
    3. Very slowly lower coil into LN2, wait ~5 minutes
4. Repeat steps 2 & 3

1 thermal cycle = room temperature to 77 K to room temperature

Superconductor performance metrics



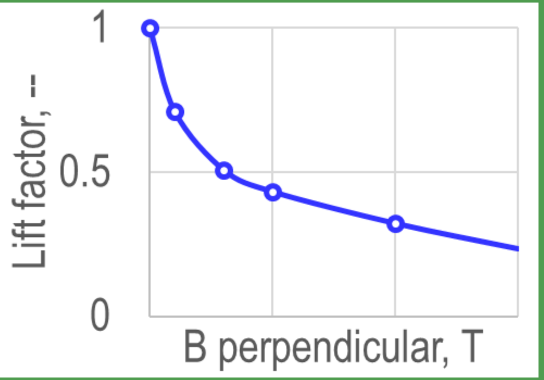
Superconductor's voltage versus current response commonly described by:

$$V = V_{\text{critical}} \left(\frac{I}{I_{\text{critical}}} \right)^{n}$$

- "n-value" indicates combined quality of superconductor & measurement
- Using 1 µV/cm criterion for V_c

Prediction of Experimental Critical Current

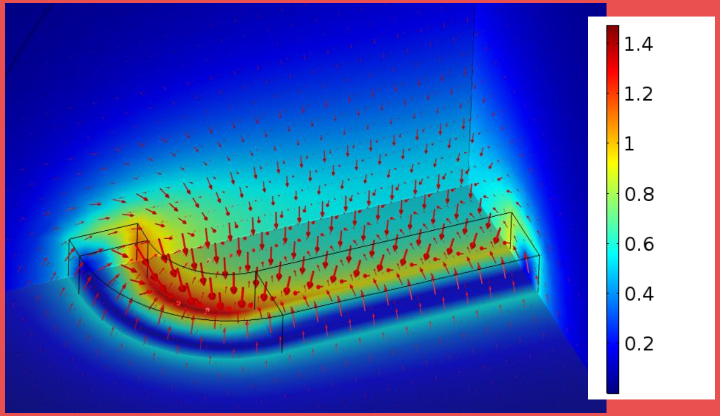
Manufacturer's data



+ coil's I_c

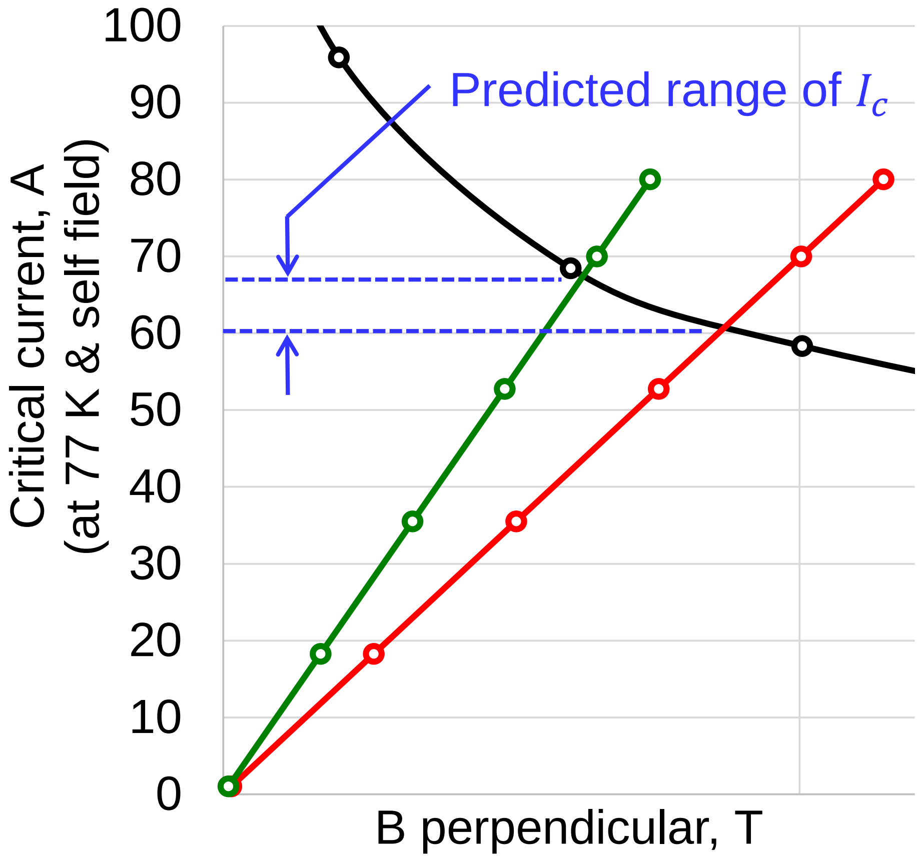
Manufacturer's I_c vs $B_\perp$

Finite element simulation

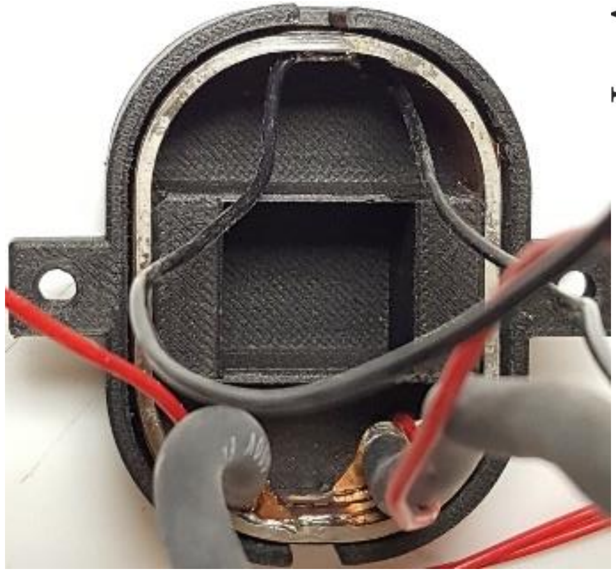


Simulated maximum $|B|$

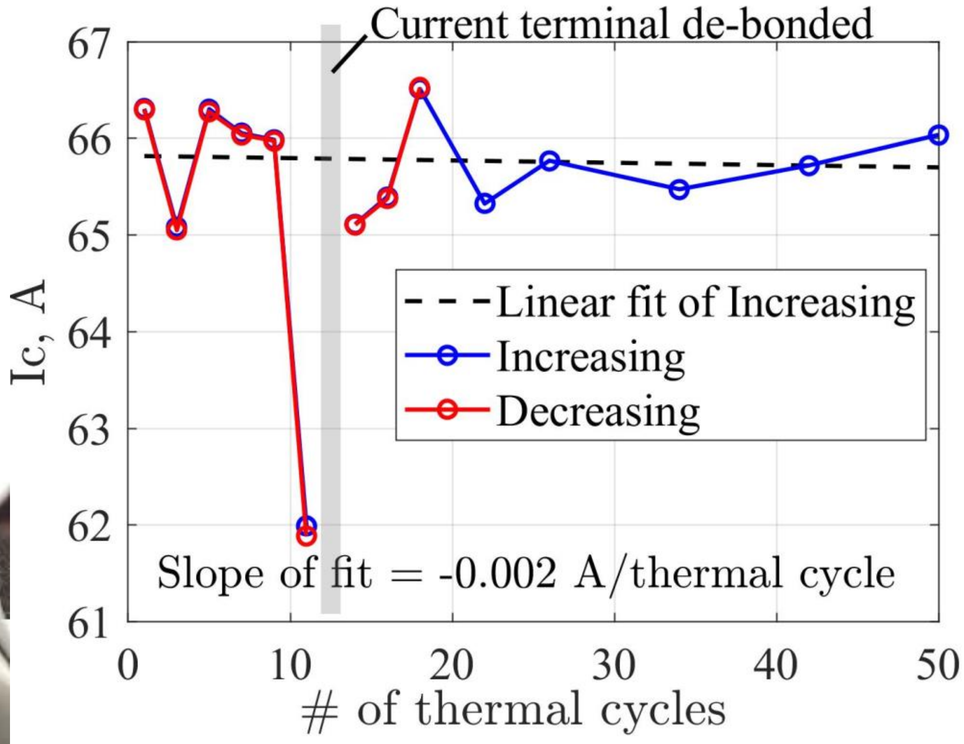
Simulated maximum $|B_\perp|$

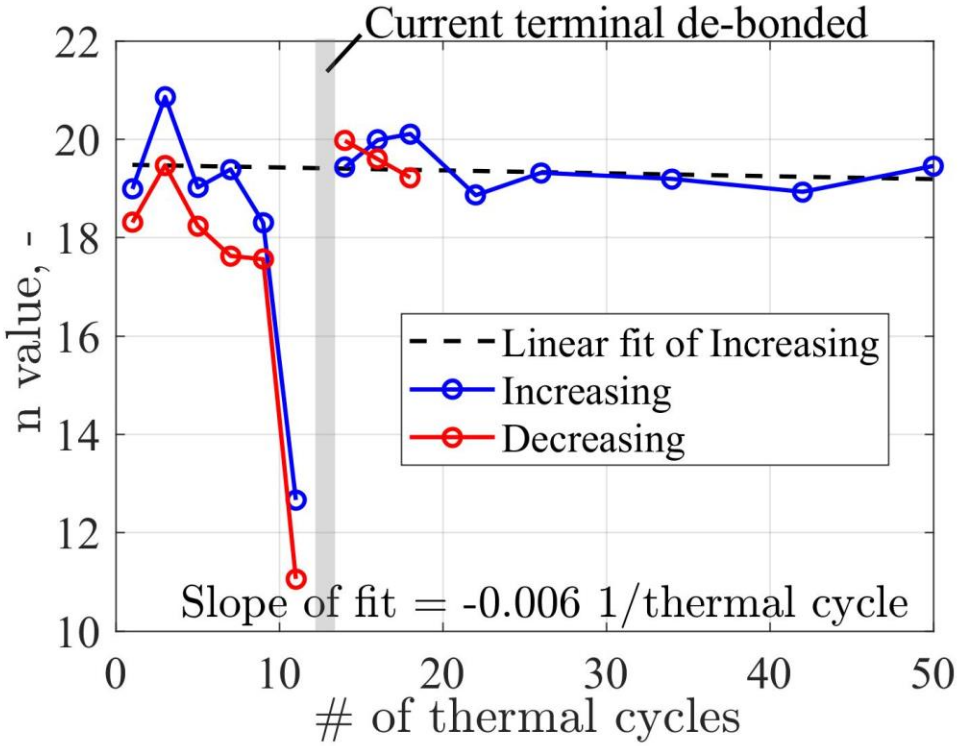


Thermal Cycling – Sub-scale, 4-layer coil

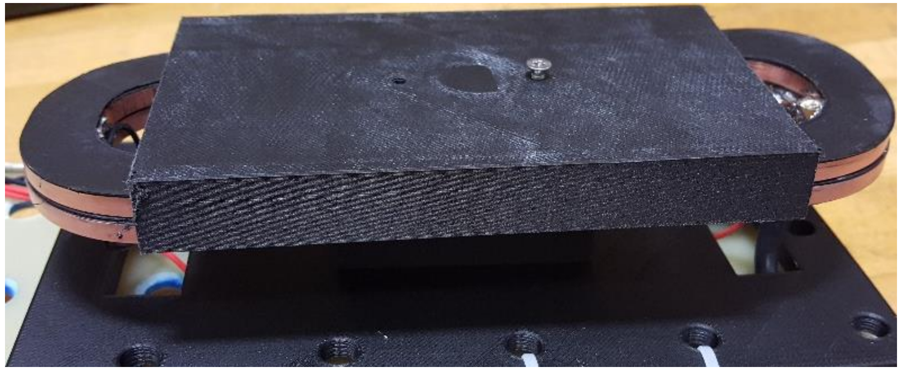


- **Critical current (Ic) prediction:** 60.5 A to 67.5 A
- Coil thermally cycled 50 times
- No clear trend in critical current or n-value
- Linear fit has nearly flat slope

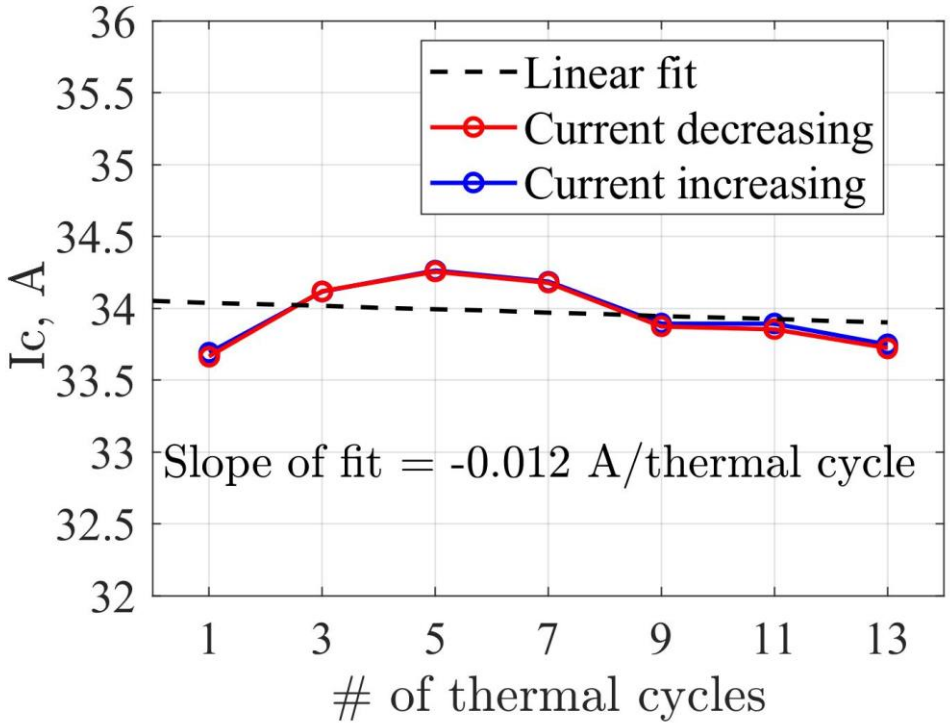


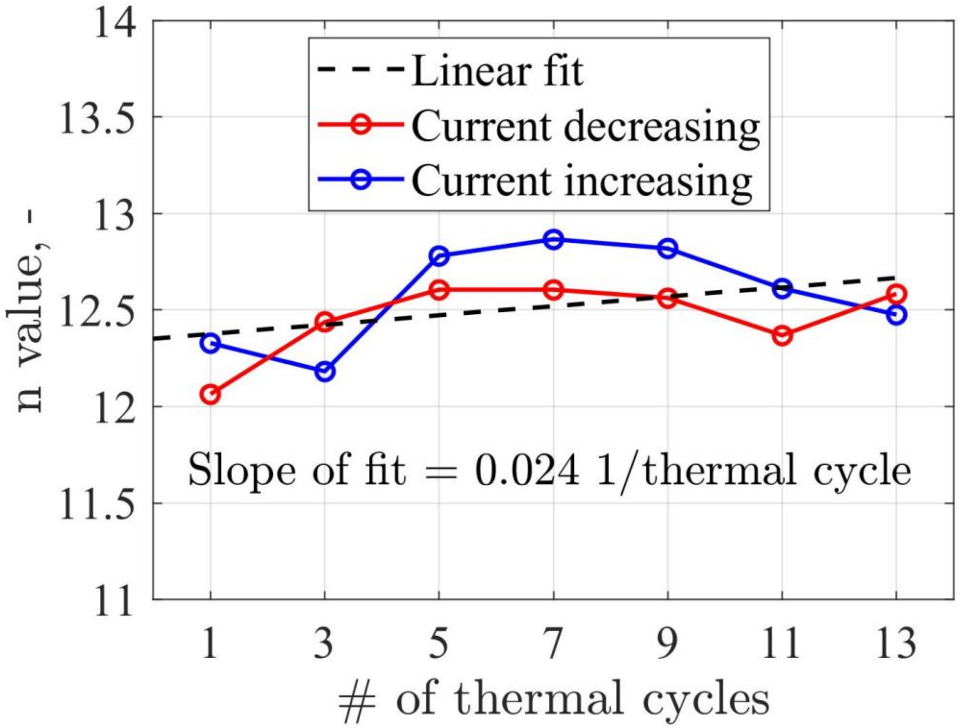


Thermal Cycling – Full-scale, 2-layer coil



- **Critical current (Ic) prediction:** 32 A to 38 A
- Coil thermally cycled 13 times
- No clear trend in critical current or n-value
- Slope of linear fits small & have opposite polarity





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Conclusions

Analysis

- Added fidelity to superconducting coil model
- Developed a multiphysics model that includes the thermal, centrifugal, and electromagnetic forces
  - Radial deflection calculated at each operating state → enables proper sizing or air gap
  - After fixing 1 stress concentration, structural components will have healthy margins
  - Superconductor’s stress components seem sufficiently low at each operating state

Testing

- Developed a fabrication process for no-insulation superconducting coils that can reliably survive thermal cycling
- Thermally cycled 9 superconducting coils up to 50 times from 293 K to 77 K
  - Need more repeatable solder joints between coil and copper terminals
  - Only very small and acceptable level of degradation

Future work

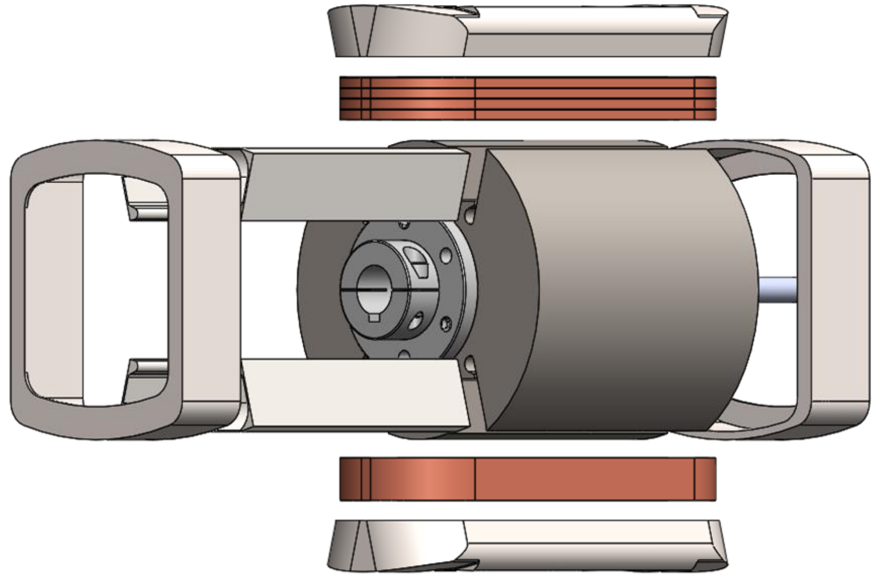
Analysis

- Refined optimization of geometry (2D model)
- Re-evaluate combined thermal, centrifugal, and electromagnetic loading (3D model)

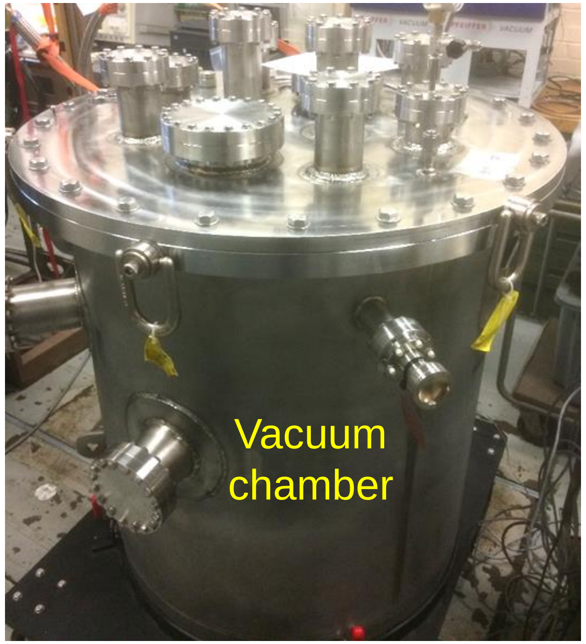
Testing

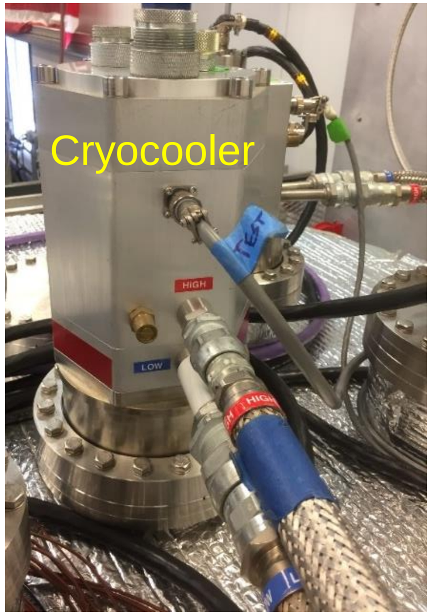
- Risk reduction testing – high speed rotation of superconducting coil & structural parts
    - Measure superconductor performance metrics before & after spinning on purpose-built rotor
- Stationary superconducting test at designed electrical, thermal, & magnetic operating point

Risk reduction test – purpose-built rotor



ICE-Box test rig at NASA GRC





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THANK YOU


Glenn Research Center
Lewis Field
RESEARCH AND TECHNOLOGY
FOR THE BENEFIT OF ALL
NASA
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Research
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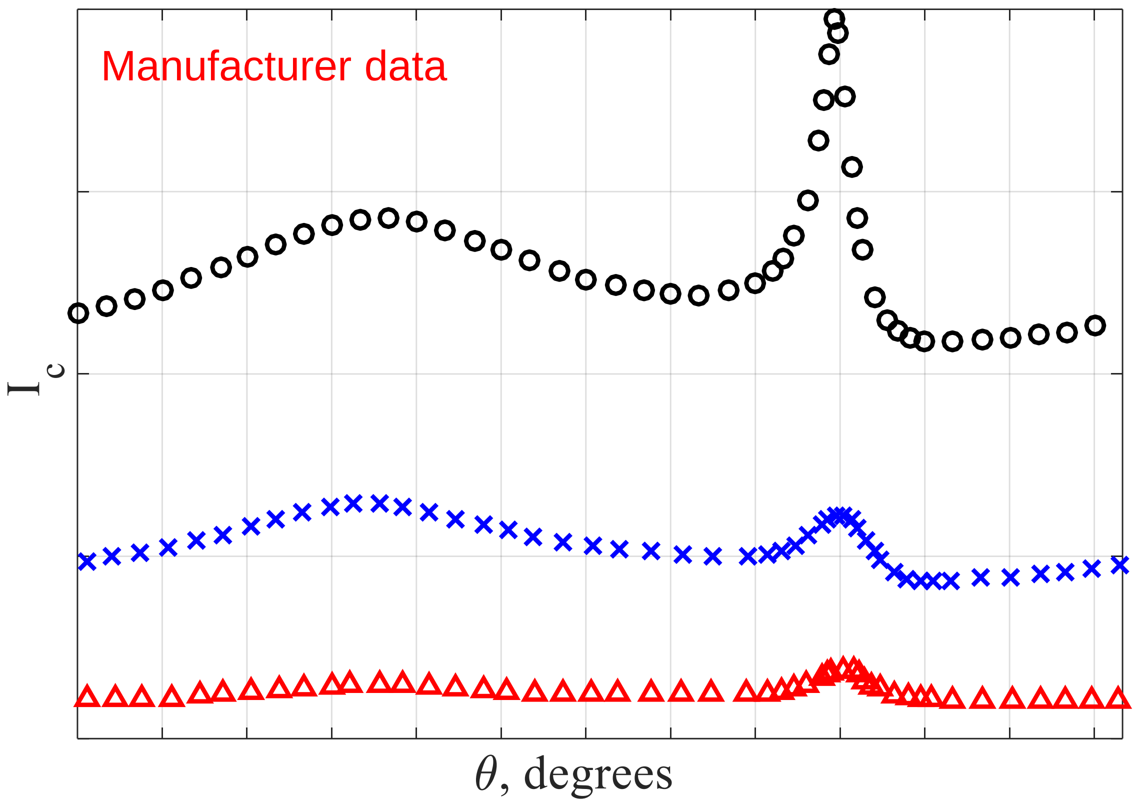
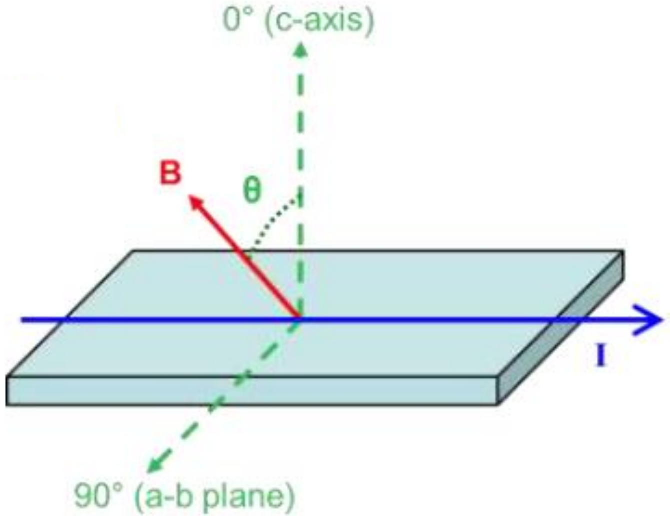
NASA

Superconductor current & thermal limits

- Critical current $(I_C) = I_C(T, B, \theta)$
  - Datasheet values $\theta = 0°$ and $90°$ are insufficient
- Datasheet specs de-rated twice: angular dependence & safety factor





Safety factor

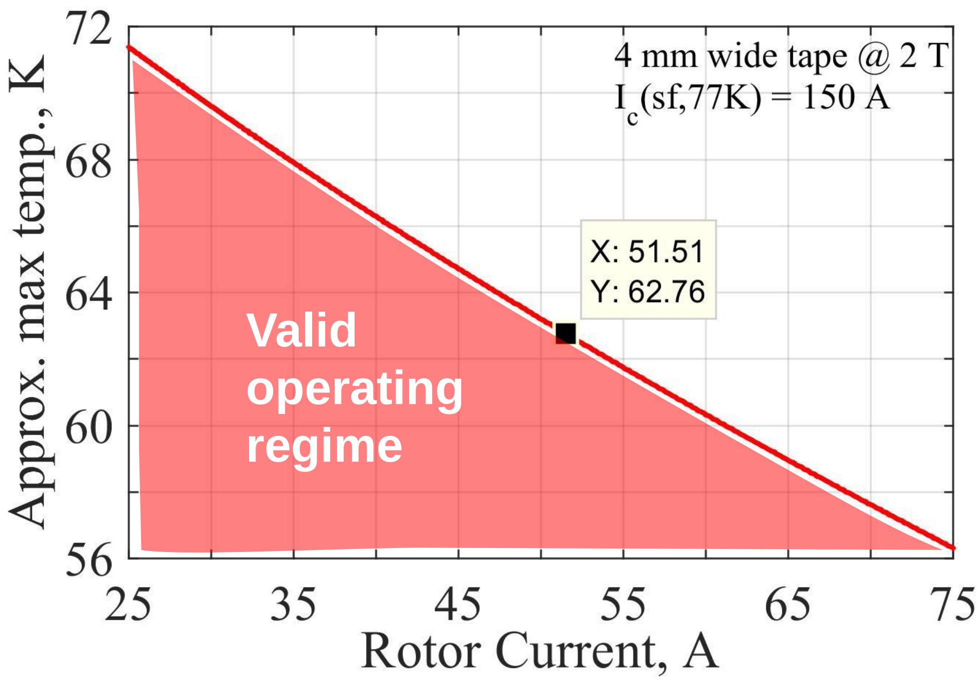
	±20%	Estimate of wire variation
+	±15%	Modeling inaccuracy
	±35% (≈1.5 safety factor)	

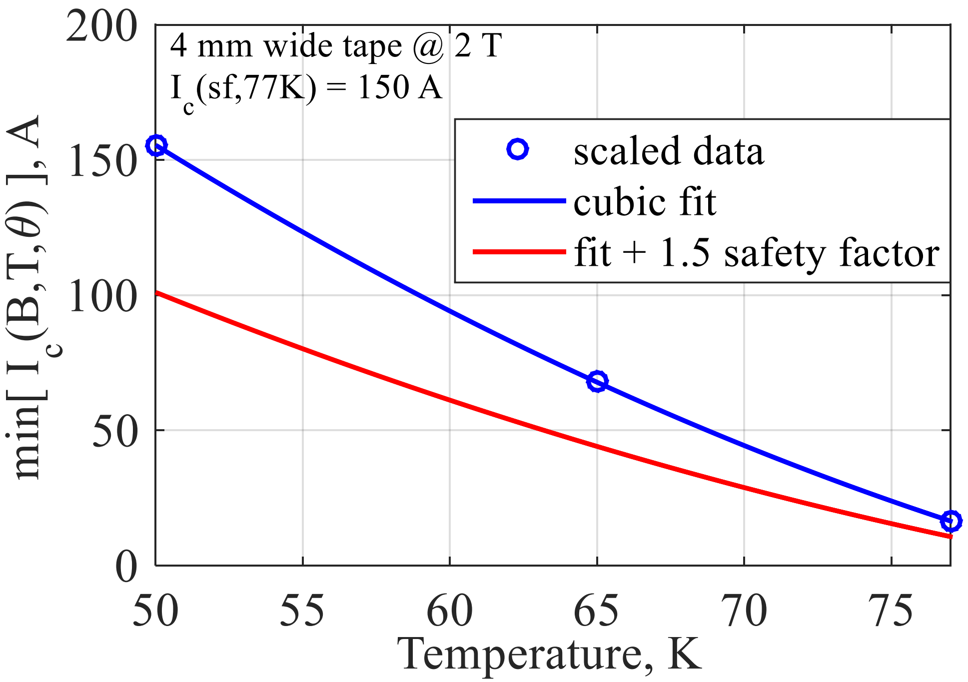
Superconductor current & thermal limits

- Measurements at B = 2 T obtained from manufacturer

Design spec

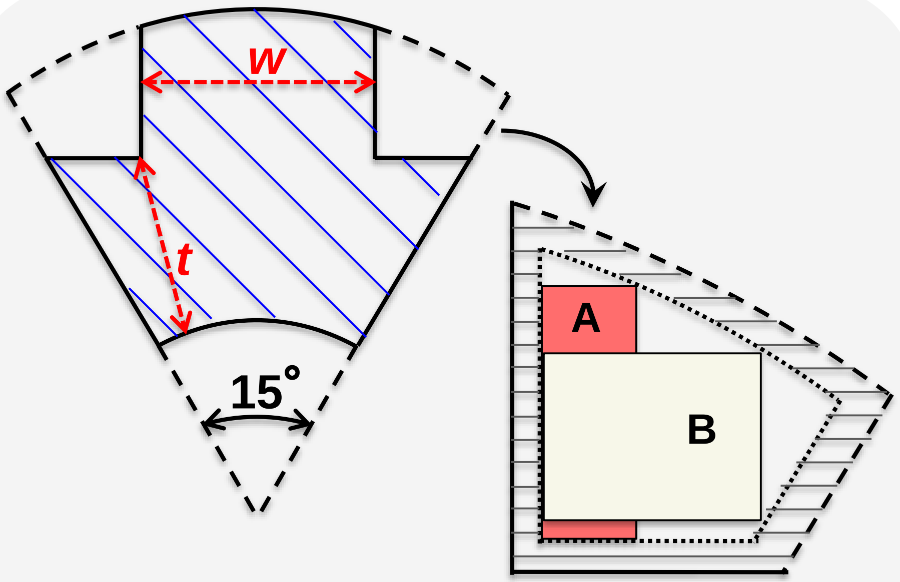
current 51.5 A
temperature ≤ 62.8 K





Rotor Design

Parameter	Value
Electrical frequency	DC
Number of poles	12
Material	*Solid* $Fe_{49.15}Co_{48.75}V_2$
Outer diameter	30 cm
Inner diameter	18.9 to 20 cm
Axial length	12.5 cm



Soft magnetic material (back iron)

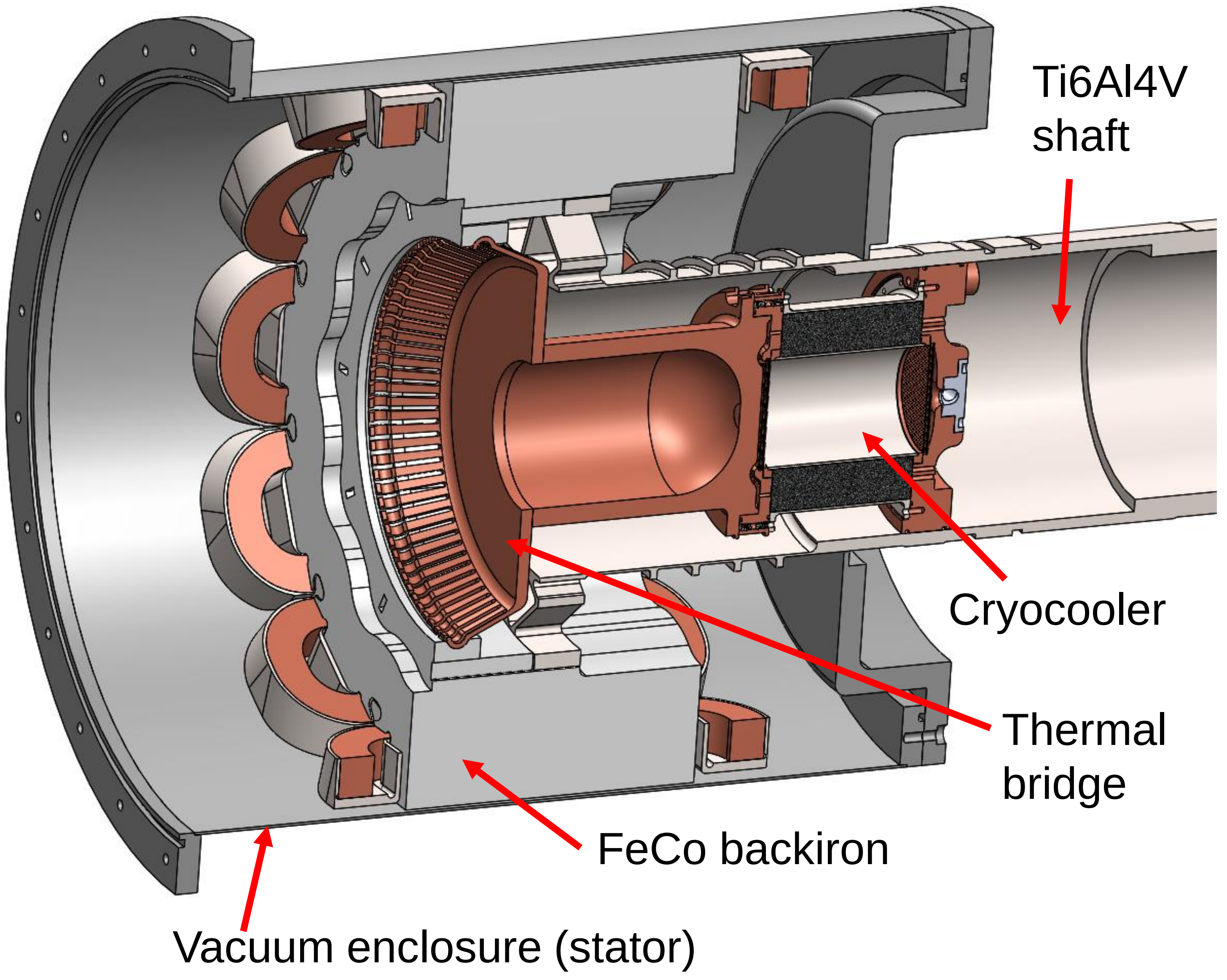
Region available for containment structure & clearances

Design process (see 2018 AIAA P&E paper)

- Defined current & thermal limits
  - Based on manufacturer data & safety factors
- Parametric studies of back iron's width w and thickness t (2D & 3D, nonlinear FEA)
  - Optimized coil's geometry by numerically maximizing # of turns in coil
  - Custom extrapolation of back iron's B vs H response
  - **Metrics:** performance • performance/mass • performance/cost
- Stress analysis of centrifugal loading (2D & 3D FEA)

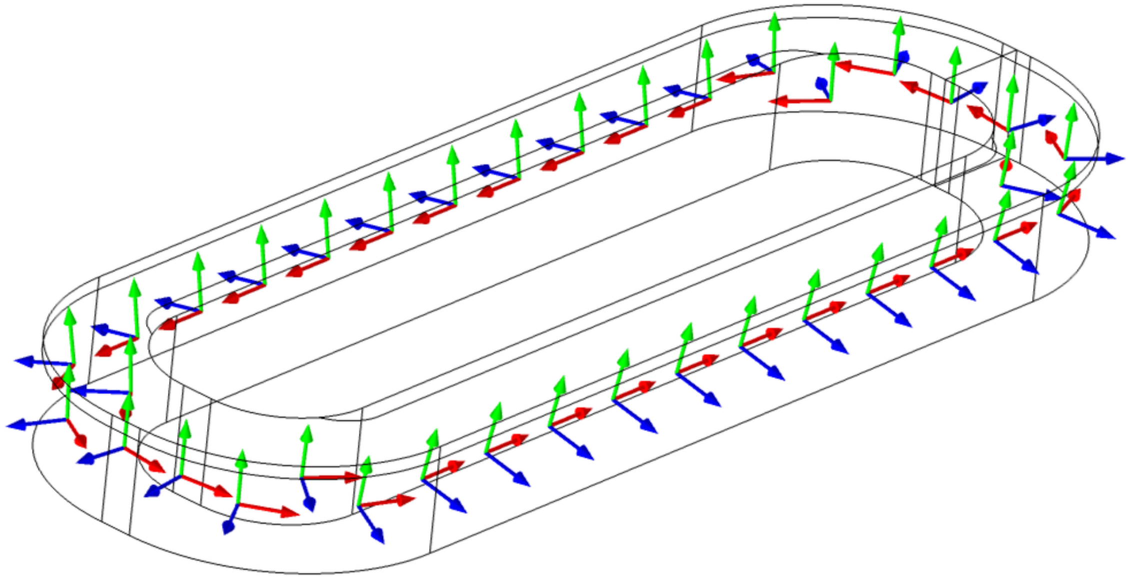
Thermal design

- Rotor is cooled by pulse-tube cryocooler which is connected to the backiron via a high thermal conductivity, low rigidity thermal bridge.
  - Cryocooler is designed to lift 55 W of heat with a 50 K cold end.
- Primary structural connection is high rigidity, low thermal conductivity Ti6Al4V shaft to reduce heat transfer from hot end.
- Other thermal design aspects
  - Rotor operates in vacuum to reduce convection and windage losses
  - Low emissivity coatings on rotor components and vacuum tube to reduce radiation heat transfer
  - Current lead (not shown) size and length optimized to minimize I^2R losses and conductive heat transfer



Thermal design (new design, no current lead heat loads)

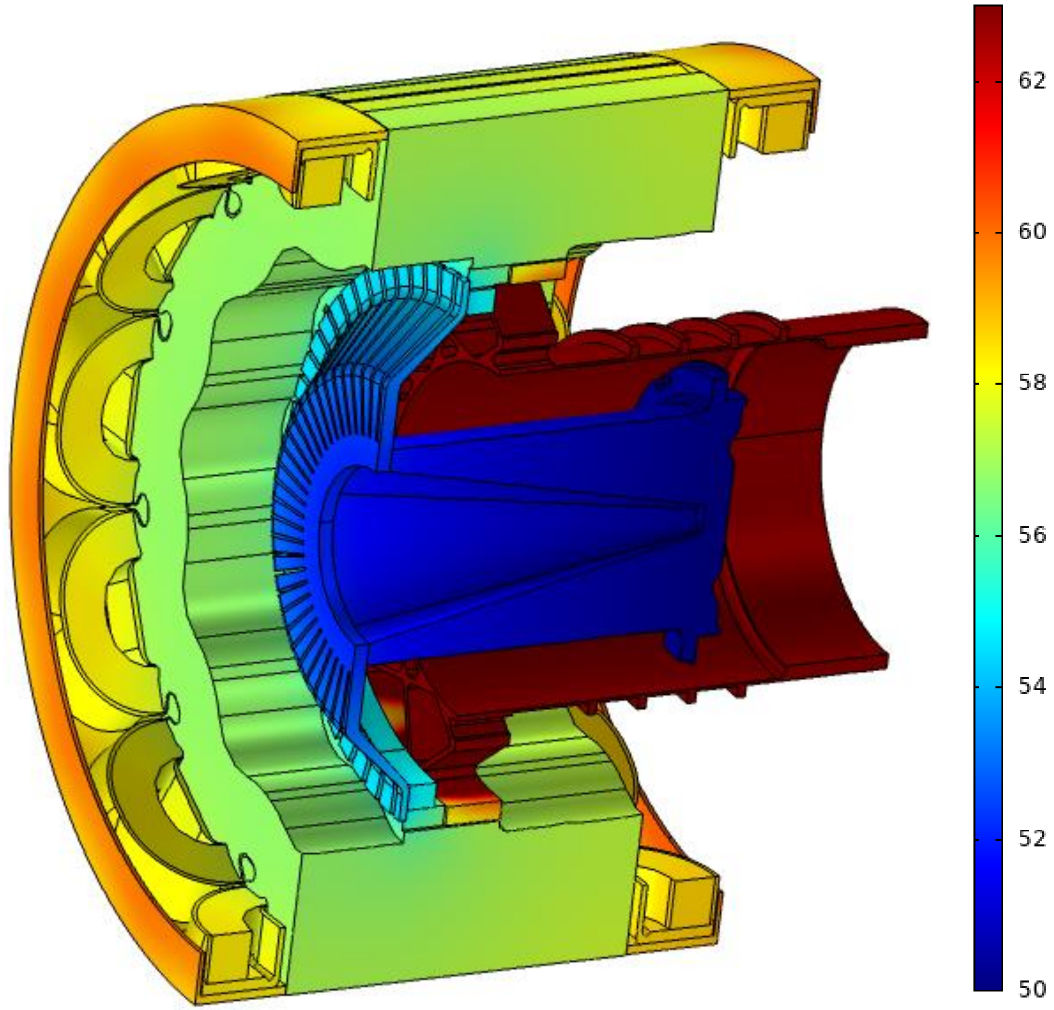
- Real coils have anisotropic thermal conductivity
  - → 121 W/m/K
  - → 121 W/m/K
  - → Up to 8.9 W/m/K depending on contact pressure
- Currently modeling using various isotropic thermal conductivities to determine effect on coil temperatures
- Anisotropic model in development



Thermal design (new design, no current lead heat loads)

Coil Thermal Conductivity (W/m/K)	0.1	1.0	5.0	8.9
Maximum Coil Temperature (K)	64.0	60.7	58.8	58.4

Results depicted use 5.0 W/m/K.

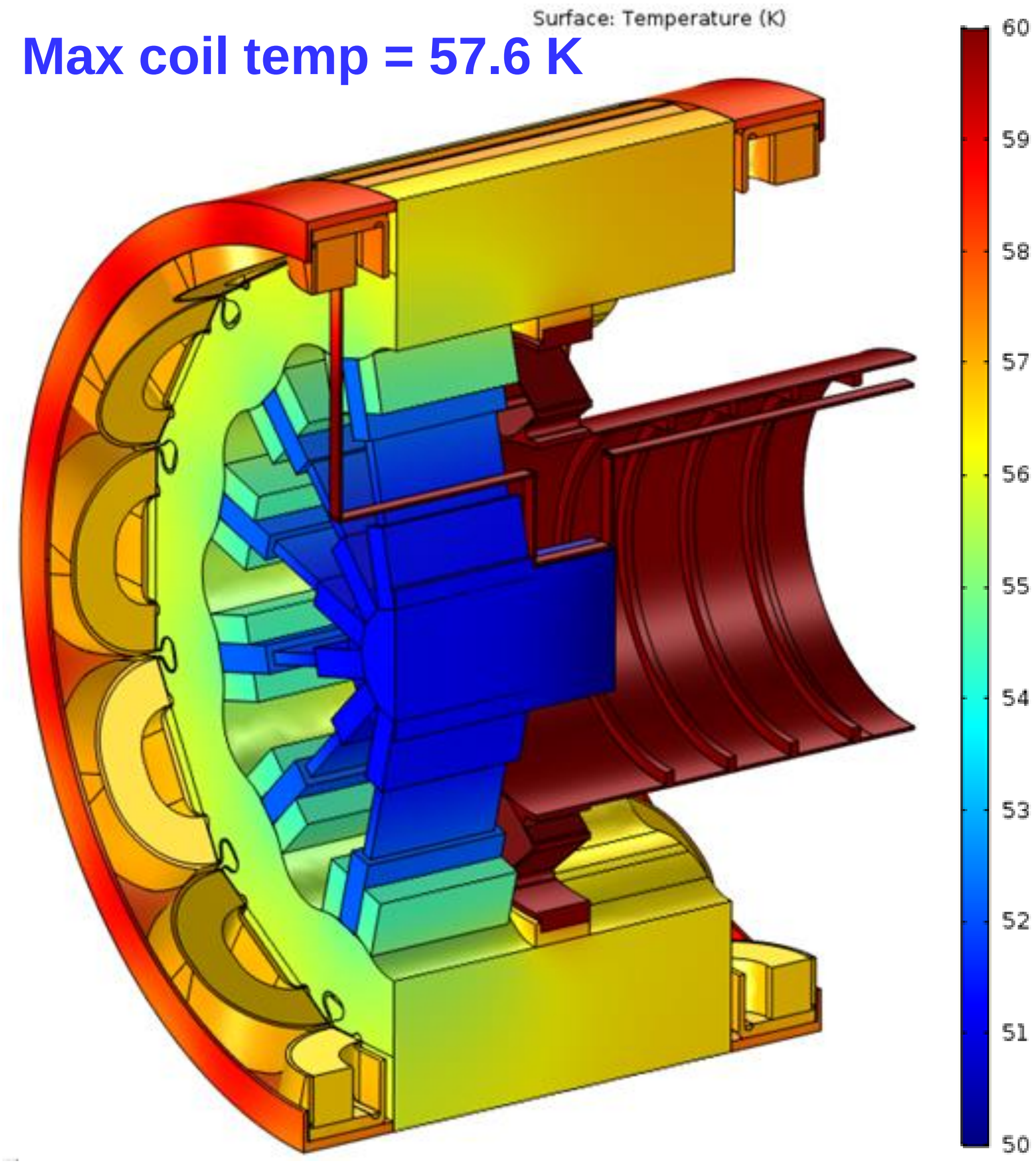


- Analysis includes temperature-dependent properties, contact pressure results from stress analysis, and the following heat loads:

Heat Source	Flux
Radiation	
Stator to Rotor Radiation	7.6 W
Convection	
Windage Losses	1 W
Stator to Rotor Convection	4 W
Conduction	
Shaft Conduction	8.3 W
Current Lead Conduction	0 W
I^2R Losses	0 W
	W

Thermal design (older design, all heat loads)

Max coil temp = 57.6 K



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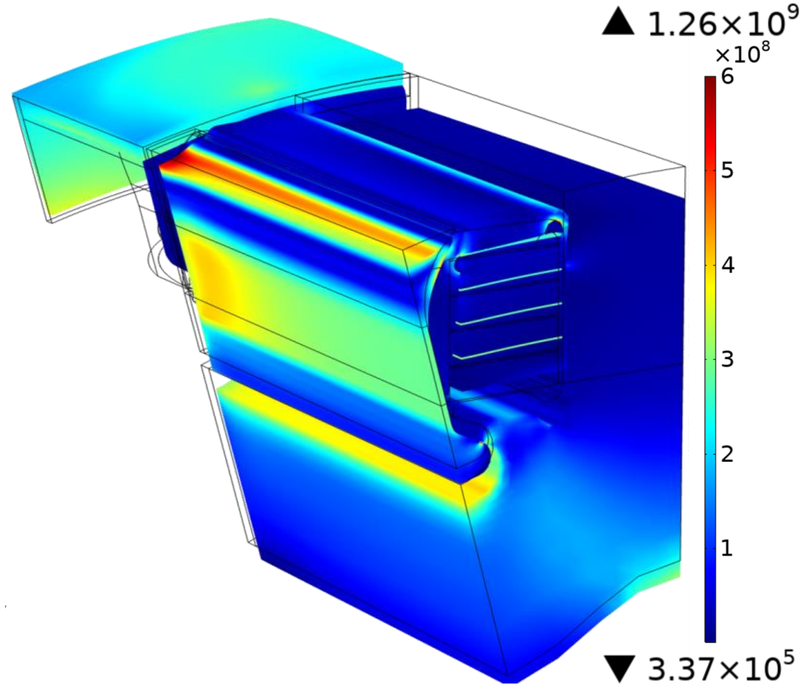
Conduction	
Shaft Conduction	8.3 W
Current Lead Conduction	6.2 W
I^2R Losses	2.0 W
	29.2 W

Combined Thermal, Centrifugal, and Electromagnetic Loading Model

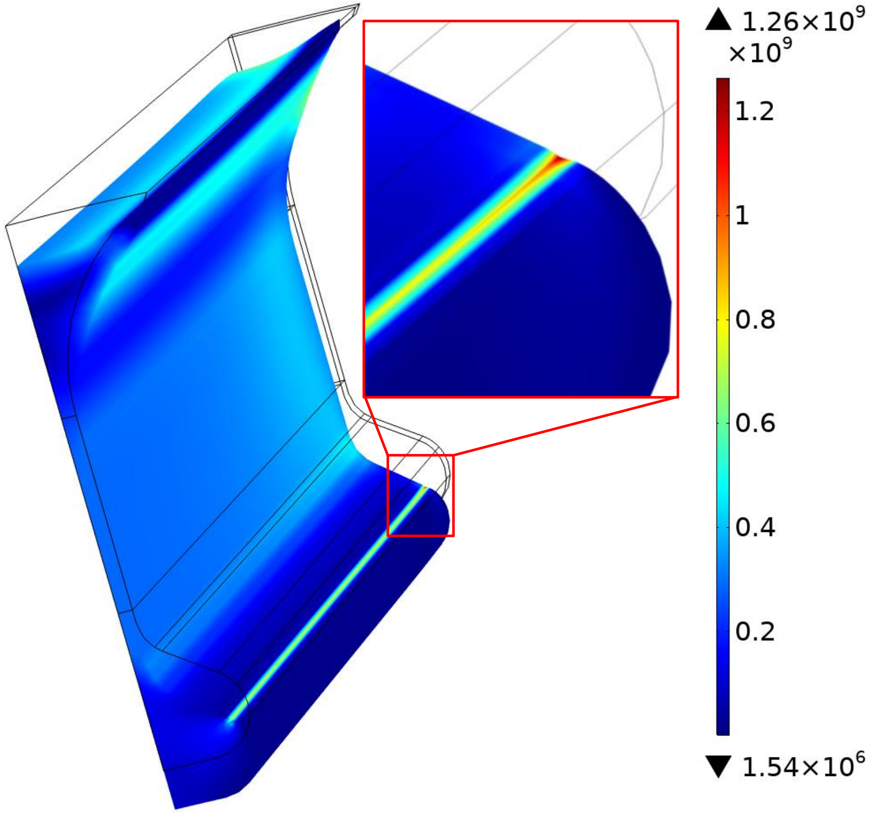
Von Mises stress (Pa) results

End of cold spin up to 6,800 rpm



Cannot rotate to full speed before cooling down

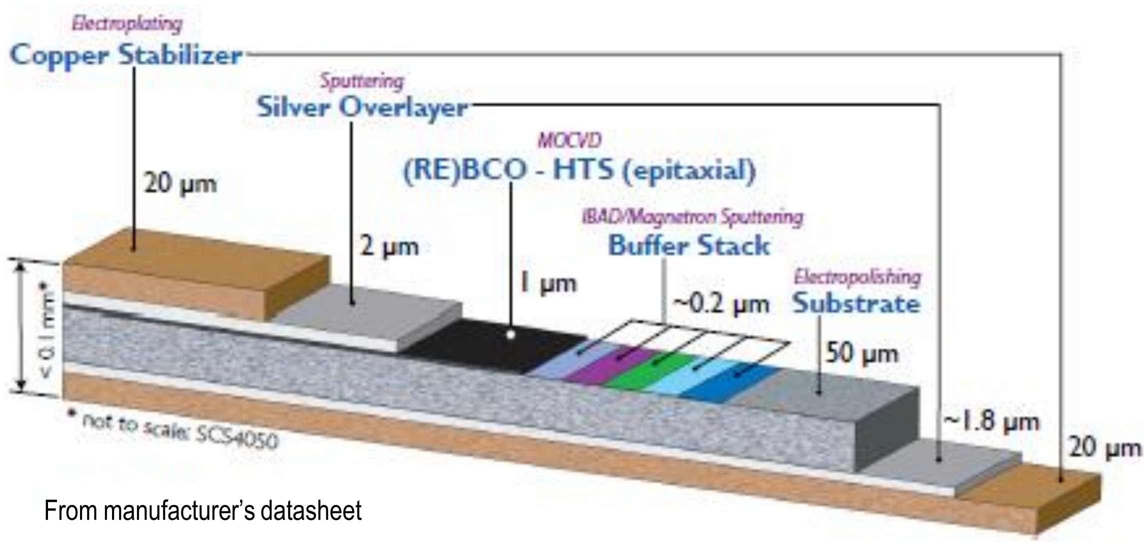
Stress concentration in dovetail part



Risk reduction testing

Superconductors produce much stronger magnetic fields, but they are…

- **Strongly temperature sensitive** -- superconductors must be kept below a critical temperature during their entire operation
- **Relatively fragile** – particularly to shear & transverse tensile loads
- **Difficult to accurately model** -- superconductors are anisotropic composite materials with stress/strain limits that are not well characterized
- **Significantly more expensive** -- $40 to $60 per meter



From manufacturer's datasheet

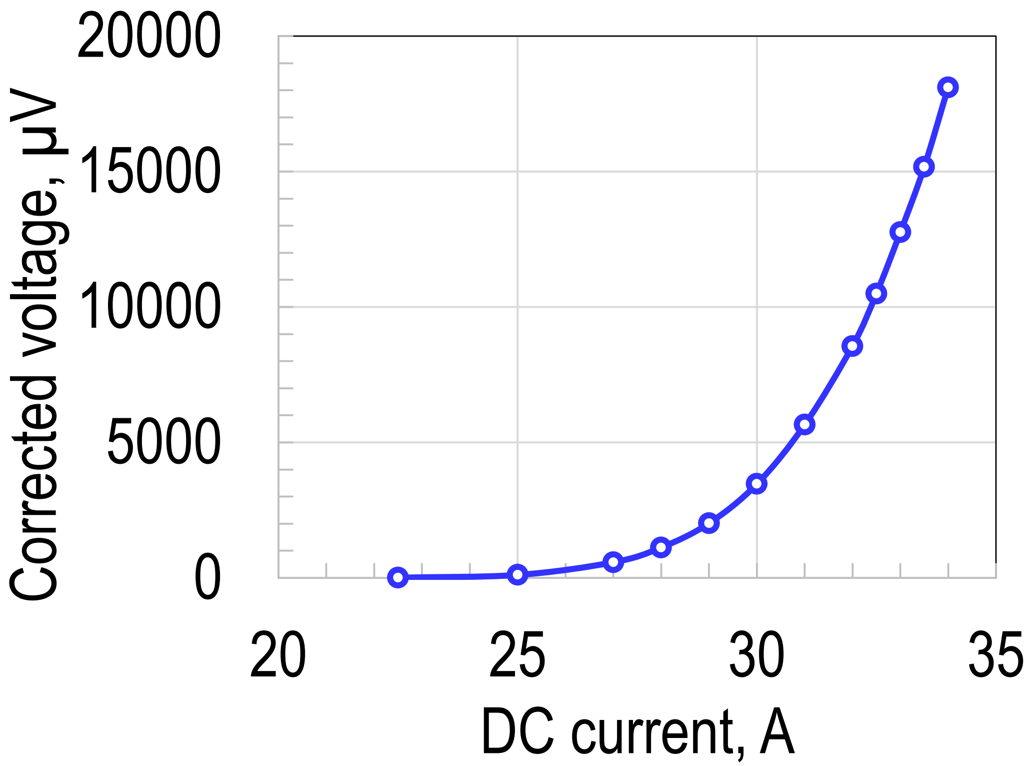
Thermal cycling

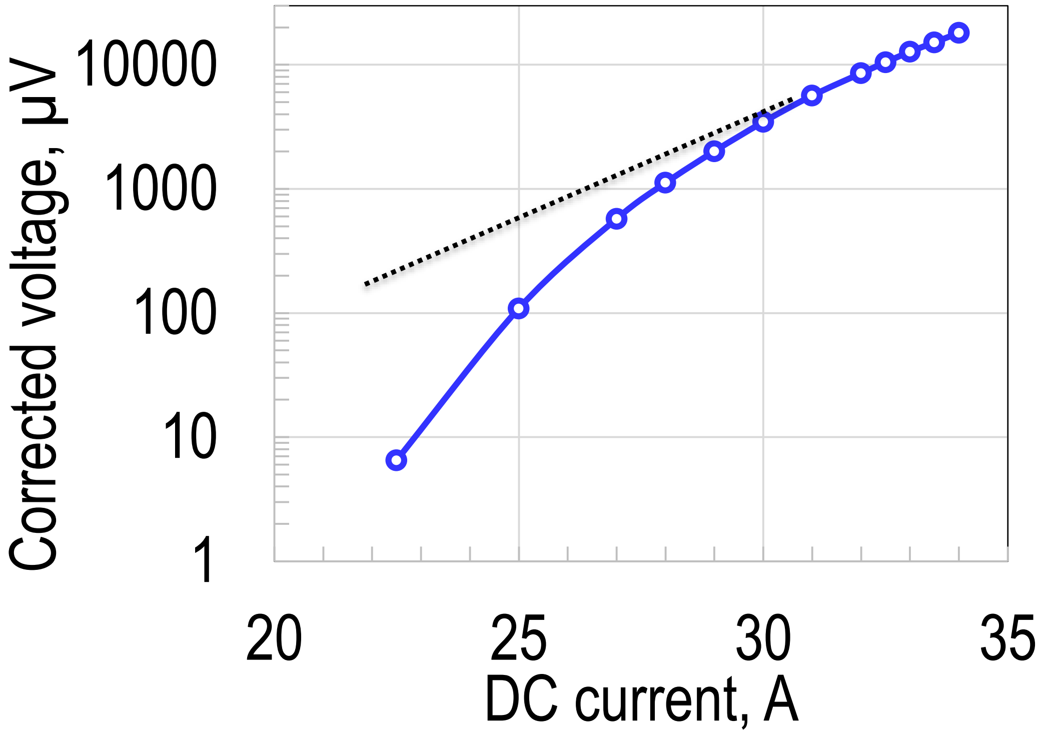
	Characteristic	HEMM coils	PTR-1 coils
Superconductor	Material	ReBCO (2nd gen high temperature superconductor)	**Same**
	Width, mm	4 mm	**Same**
	Thickness, micron	65 micron	**Same**
	Min. bend radius, mm	15 mm	**Same**
Coil	Turn-to-turn insulation	None	**Same**
	Operating temperature	62.8 K	77 K
	Cooling	Cryocooler (conductive)	**LN2 (nucleate boiling)**
	Operating current	51.5 A	Varies
	# of layers per coil	4	**Up to 4**
	# of turns per layer	about 230	**Up to 221**
	Magnetic excitation	Up to 2 T	Up to about 0.9 T
	Cryogenic epoxy	Stycast 2850 FT black	**Same**

Thermal Cycling – Performance Metrics

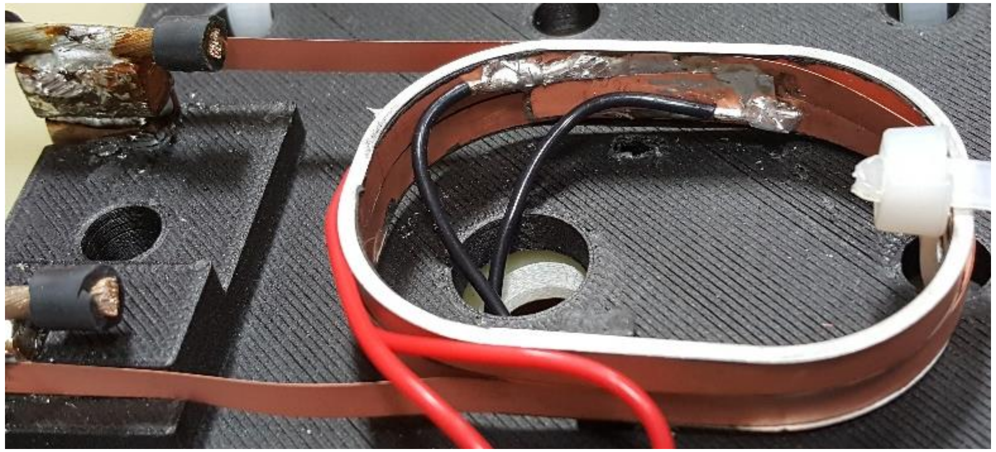
- Performance metrics: critical current (I_c) and n
- Detect damage via changes in n and/or I_c
- Lesson learned: data more easily evaluated with logarithmic y-axis scale
  - Equation only fit to data above a current threshold

$$V = V_c \left(\frac{I}{I_c} \right)^n$$

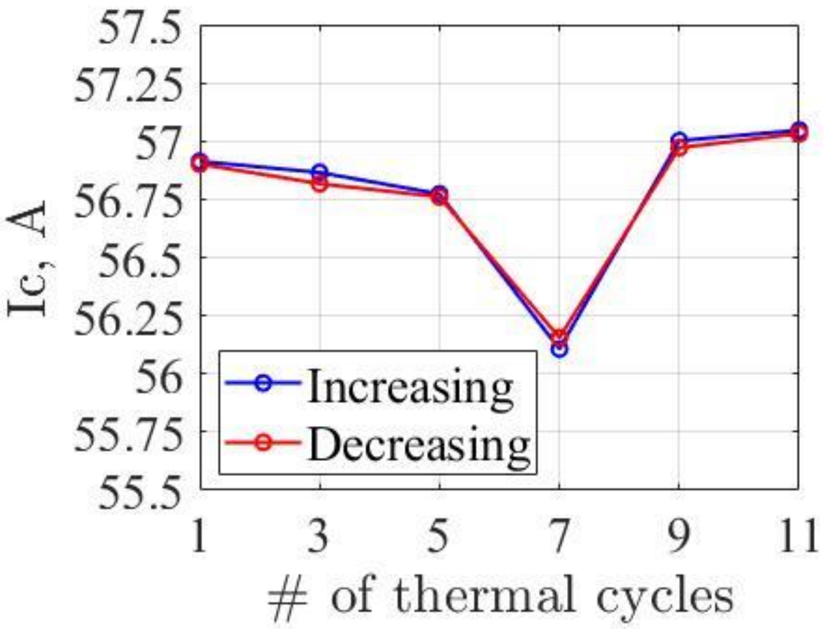


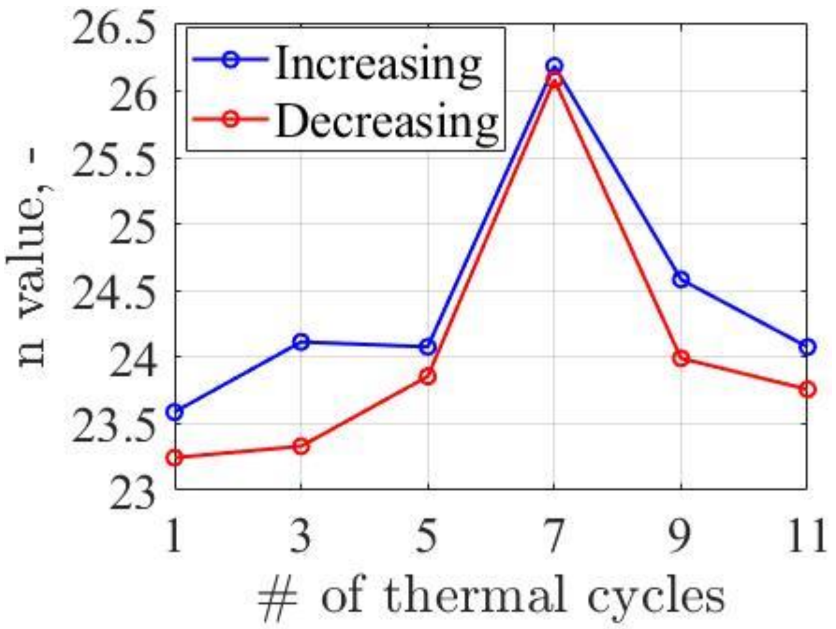


Thermal Cycling – Sub-scale, 2-layer coil



- Coil thermally cycled 11 times
- No clear trend in critical current or n-value
- n-value close but lower than that of as-delivered superconductor (about n = 32)
  - No-insulation coil type
  - Appreciable uncertainty in n-value





No detectable degradation