Design, Fabrication, and Critical Current Testing of No-Insulation Superconducting Rotor Coils for NASA's High-Efficiency Megawatt Motor

Dr. Justin J. Scheidler, Thomas F. Tallerico

NASA Glenn Research Center
Materials and Structures Division
Rotating and Drive Systems Branch

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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

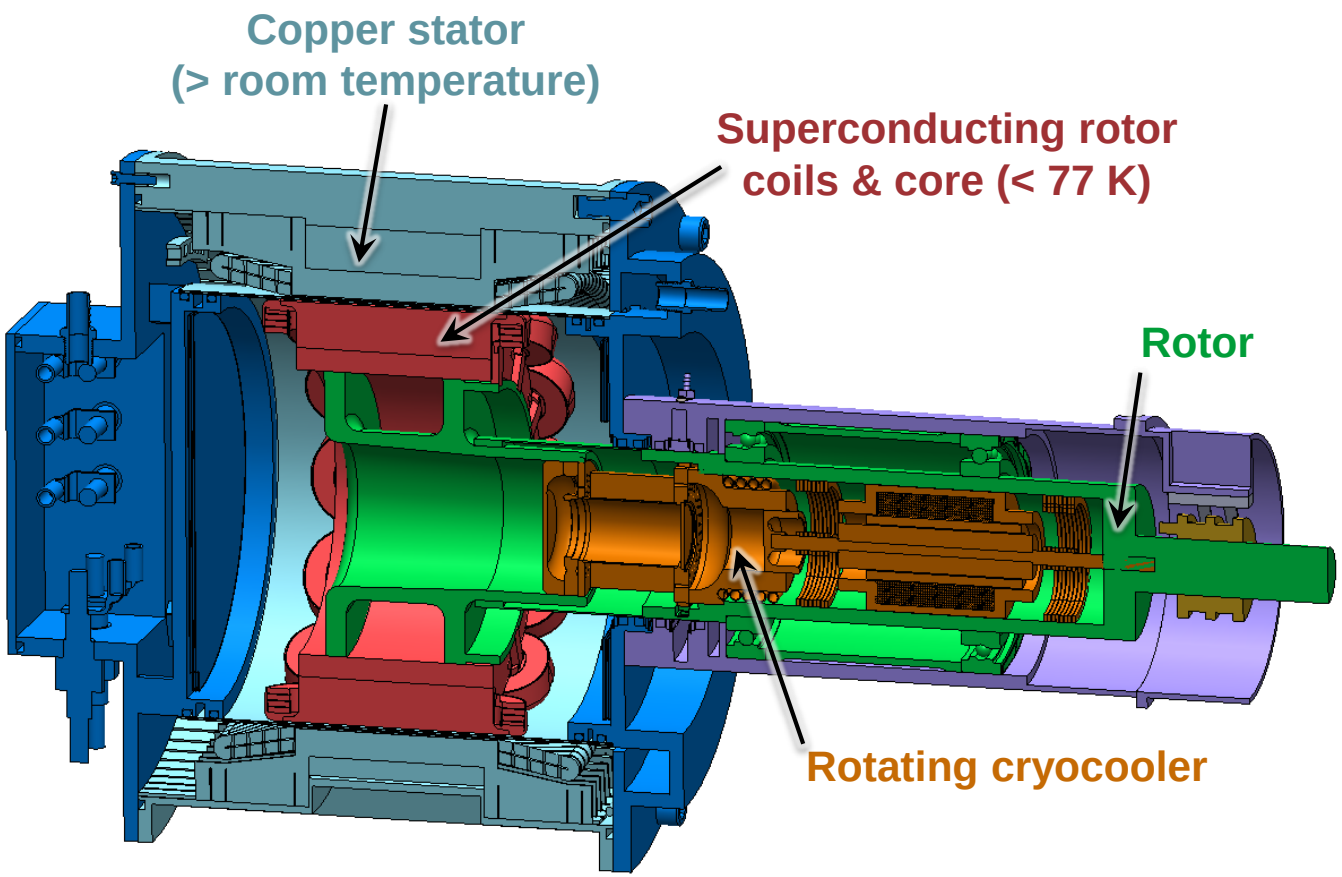
	STARC-ABL	
Electric machines	**Current design**	**With HEMM**
Specific power, kW/kg	13.2	16
Efficiency, %	96	98 to 99

Performance relative to STARC-ABL rev A	**With HEMM**
Fuel burn, %	–1 to –2
Waste heat in generator	½ to ¼ (–30 to –44 kW)

NASA's High-Efficiency Megawatt Motor (HEMM)

- Sized for generator of NASA's STARC-ABL concept
- Wound-field synchronous machine
  - Tolerant of stator fault
- Superconducting rotor
  - Negligible energy loss
  - Very strong magnetic excitation

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 %



Outline

Talk 1 (Scheidler, 2018 AIAA P&E)

- Complete preliminary design package for rotor
  - Electromagnetic design & optimization
  - Rotor containment design & stress analysis

This talk

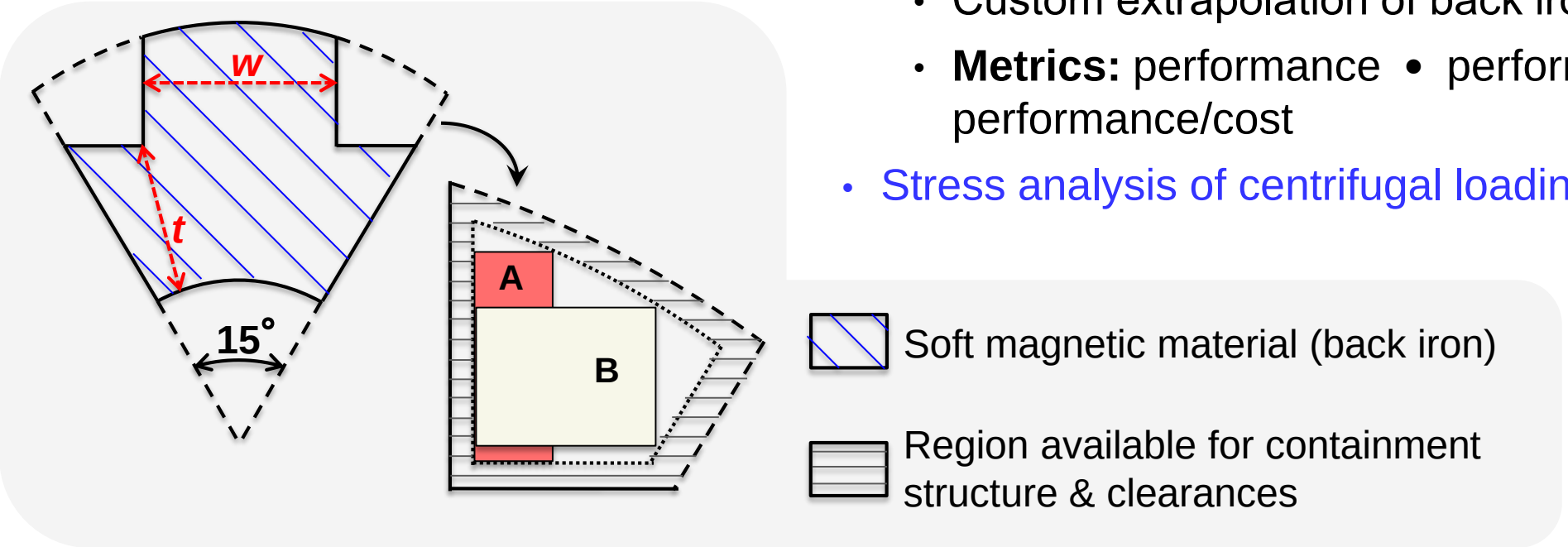
- Overview of current rotor design
- Fabrication & testing of sub-scale superconducting rotor coils

Outline

- Rotor & coil design
- Coil fabrication
- Critical current testing
- Conclusions

Rotor Design

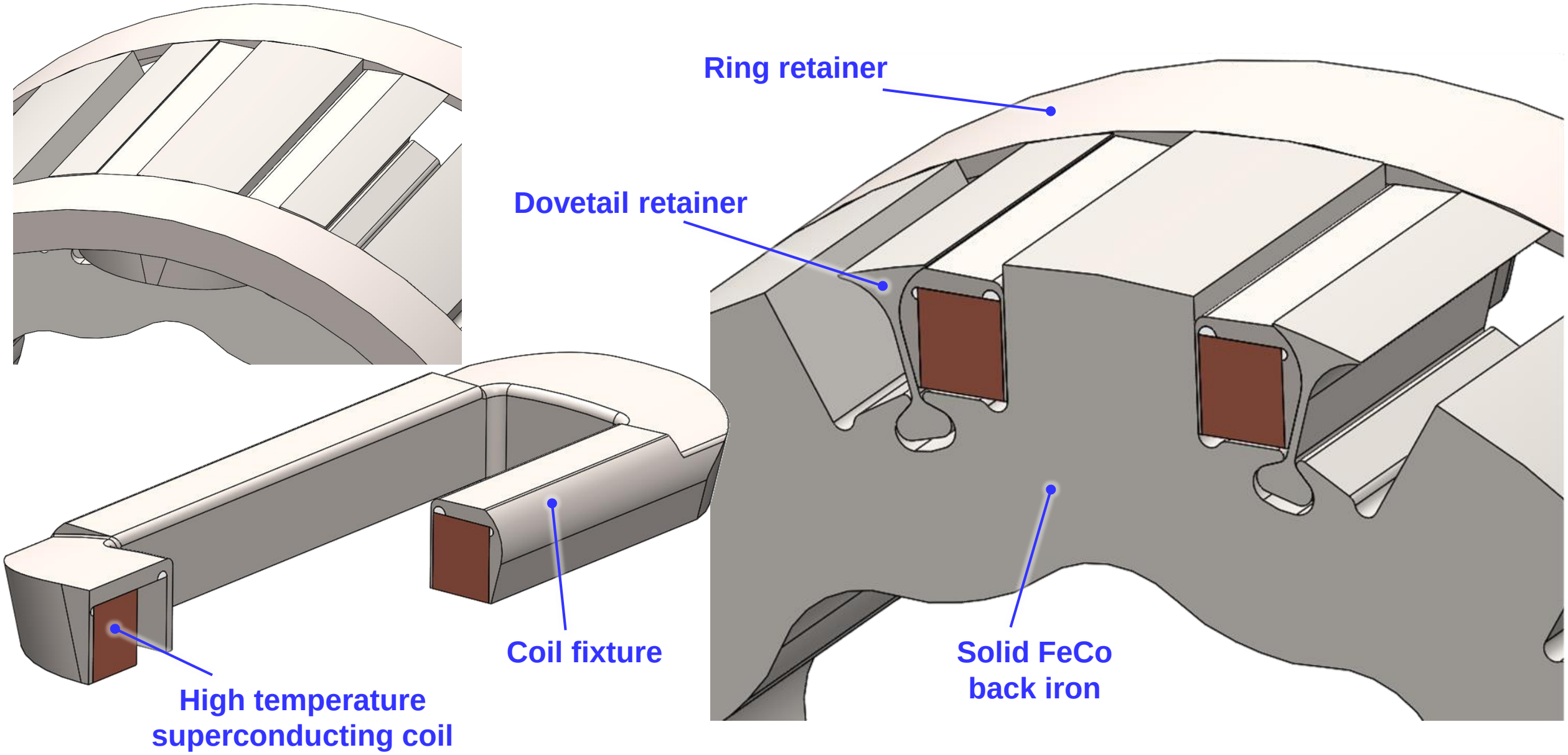
Parameter	Value
Electrical frequency	DC
Number of poles	12
Material	*Solid* $Fe_{49.15}Co_{48.75}V_2$
Outer diameter	30 cm
Inner diameter	18.9 to 20 cm
Axial length	12.5 cm



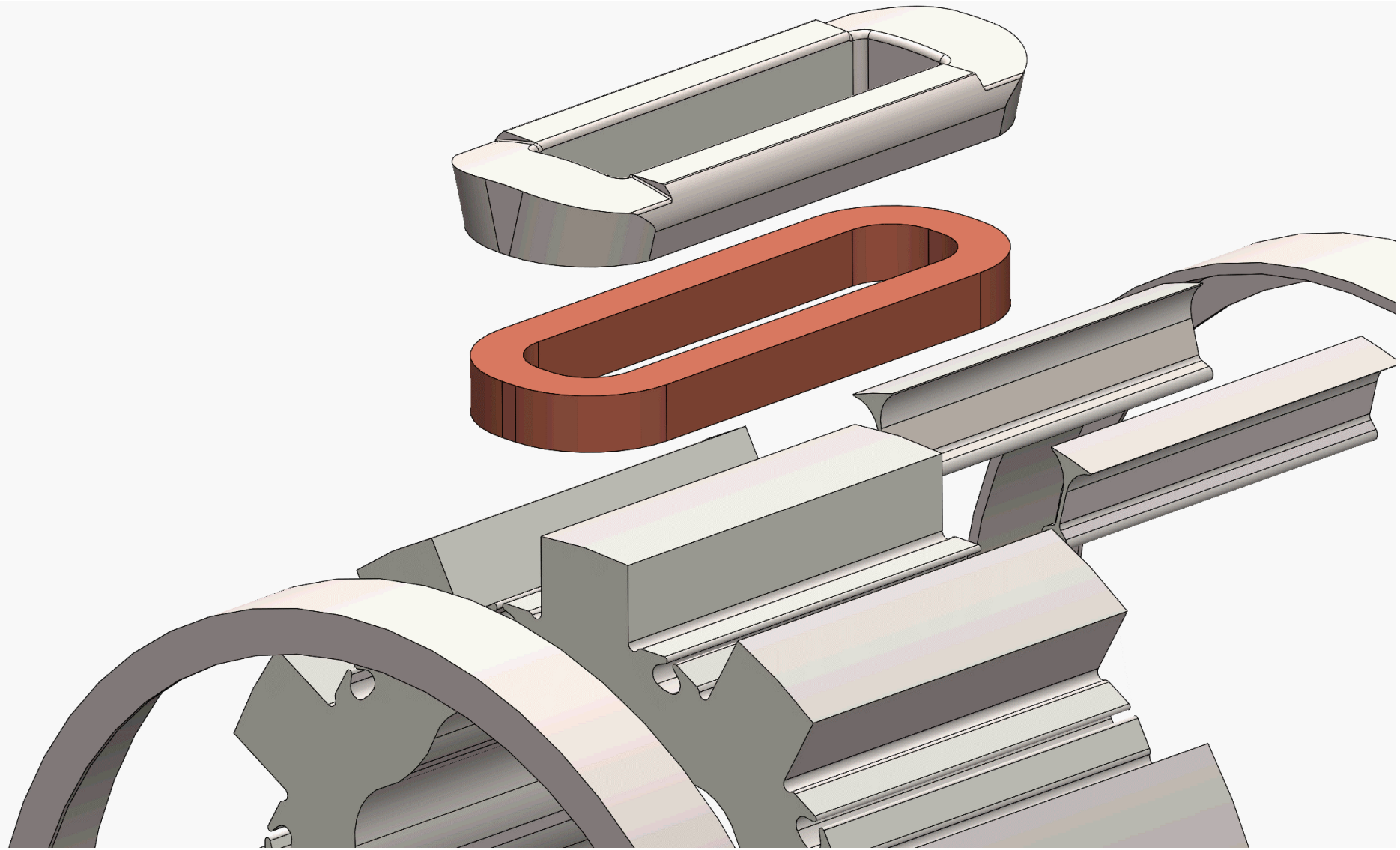
Design process (see 2018 AIAA P&E paper)

- 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)

Rotor Design



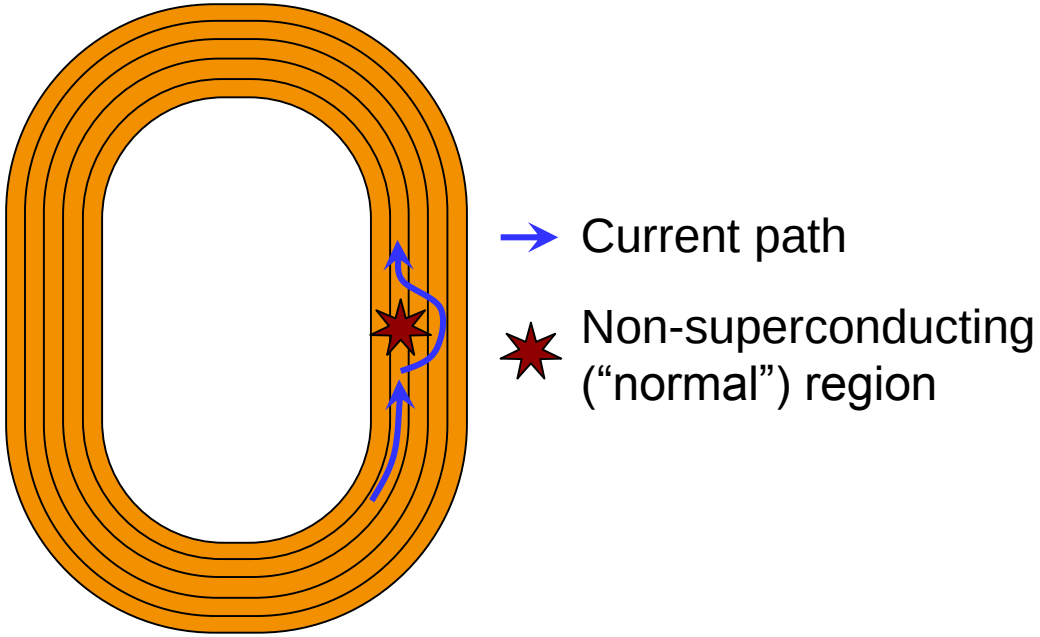
Rotor Design



Coil Design

- 2nd generation high temperature superconductor (REBCO) selected
  - Commercially available in long piece length
  - Sufficient performance at “high” temperatures in moderately strong magnetic environments
- REBCO is a composite conductor in the form of thin tape
  - AC losses will be negligible
- No-insulation (NI) coils selected [9-11]
  - **Fault tolerant**
  - **Higher *engineering* current density**
  - Higher mechanical strength

Self protection via no turn-to-turn insulation



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

Coil Design

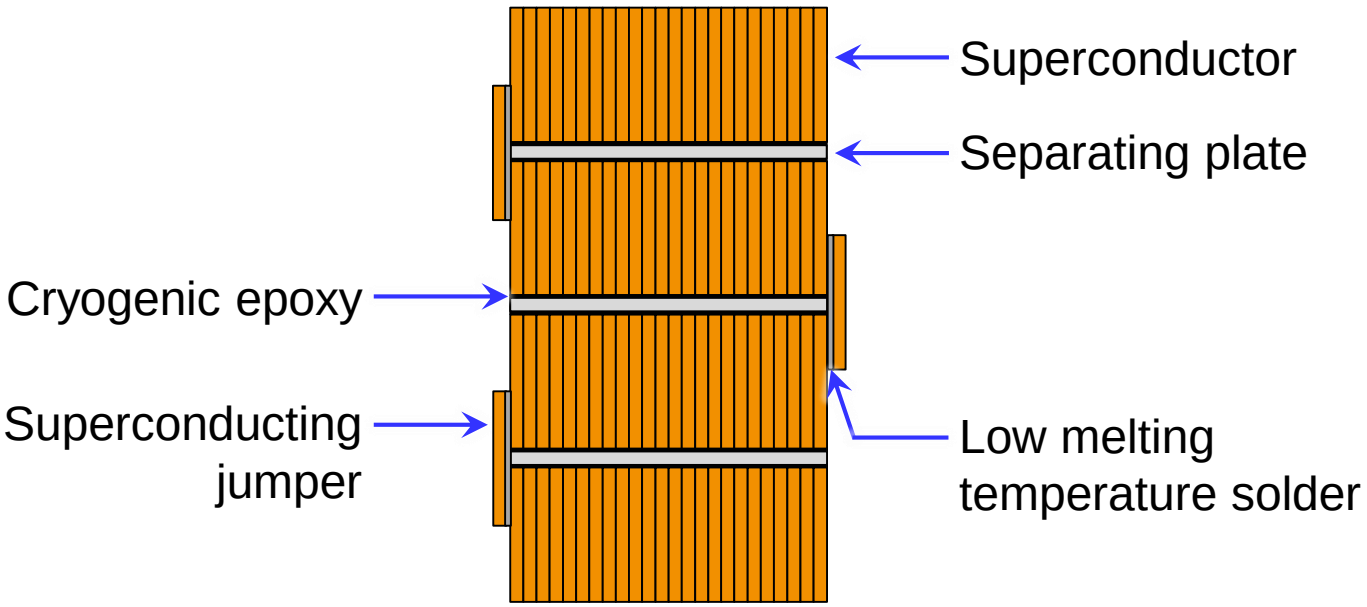
Coil characteristics

Parameter	Value
Turn-to-turn insulation	None
Operating temperature	62.8 K
Operating current	51.5 A
# of layers per coil	4
# of turns per layer	~ 230
Solder	52In 48Sn

Superconductor characteristics

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

Coil's cross-section



Risk reduction testing

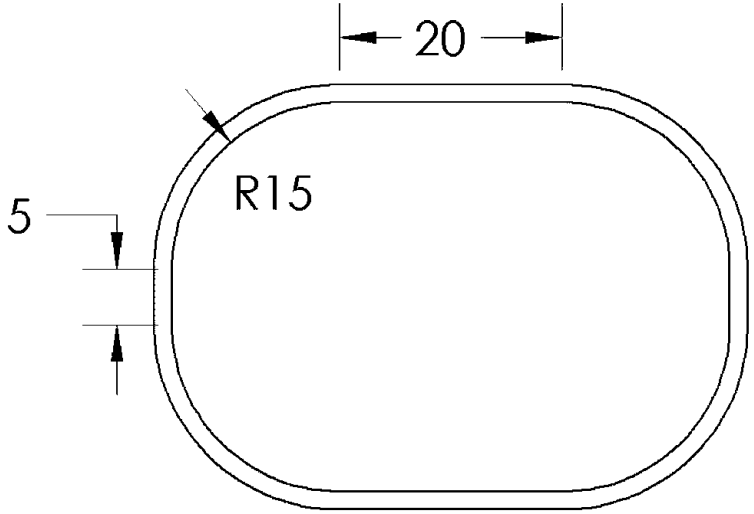
- Key risks of the superconducting coils
  - **Coils will fail when thermally cycled** due to thermal stresses
  - **Coils will fail when rotor is spun up** due to centrifugal stresses
- Risk reduction tests
  - **Thermal cycling**
    - Goal**:** demonstrate coils that are not degraded by thermal cycling
    - Approach**:** measure superconducting performance • subject to thermal shock • re-measure superconducting performance
    - Proof**:** negligible change in critical current & "n-value"
  - **Rotation** (future work)
    - Goal**:** demonstrate coils that are not degraded by high-speed rotation
    - Approach**:** measure superconducting performance • spin coils • re-measure superconducting performance
    - Proof**:** negligible change in critical current & "n-value"

Outline

- Rotor & coil design
- Coil fabrication
- Critical current testing
- Conclusions

Coil Fabrication

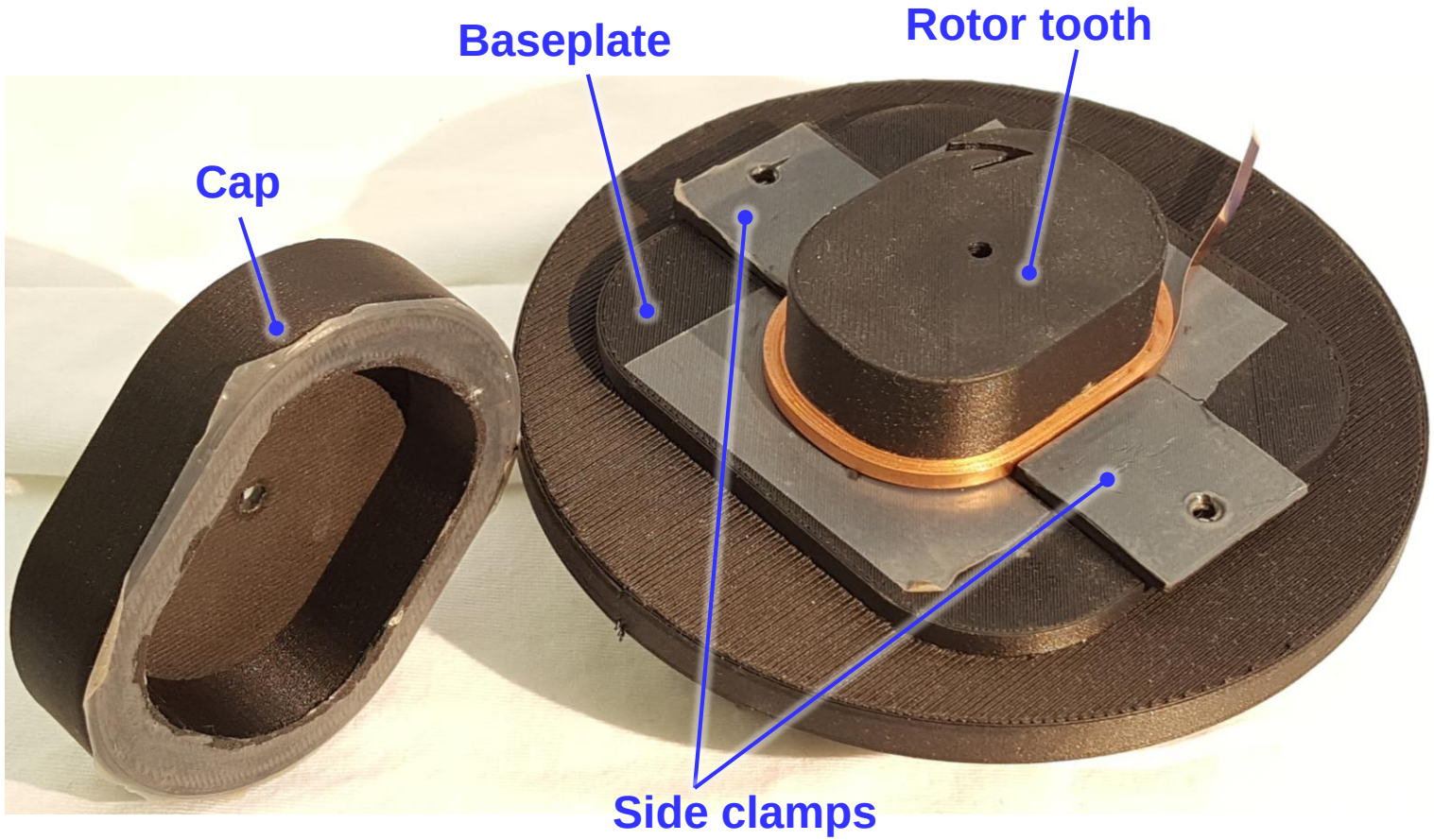
- Methodical development approach:
  simple, sub-scale → realistic, full-scale
- 25-turn sub-scale coils
  - Fewer turns & shorter



dimensions in mm

Coil Fabrication

- 3D printed nylon winding fixture
  - Reduced lead time & cost
  - But, limited temperature
- Accurately establishes width of active region & height
- Fixture inverted for epoxy application



Outline

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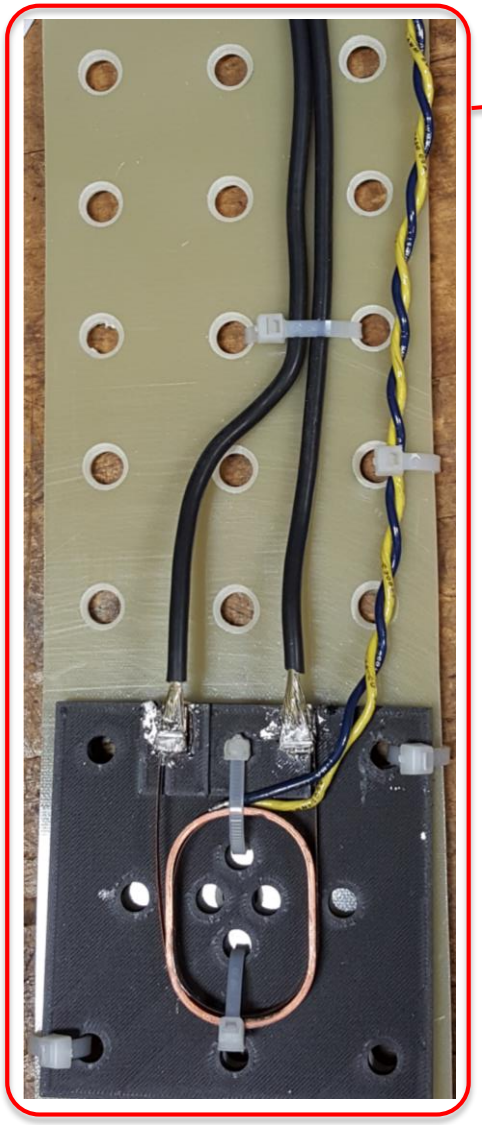
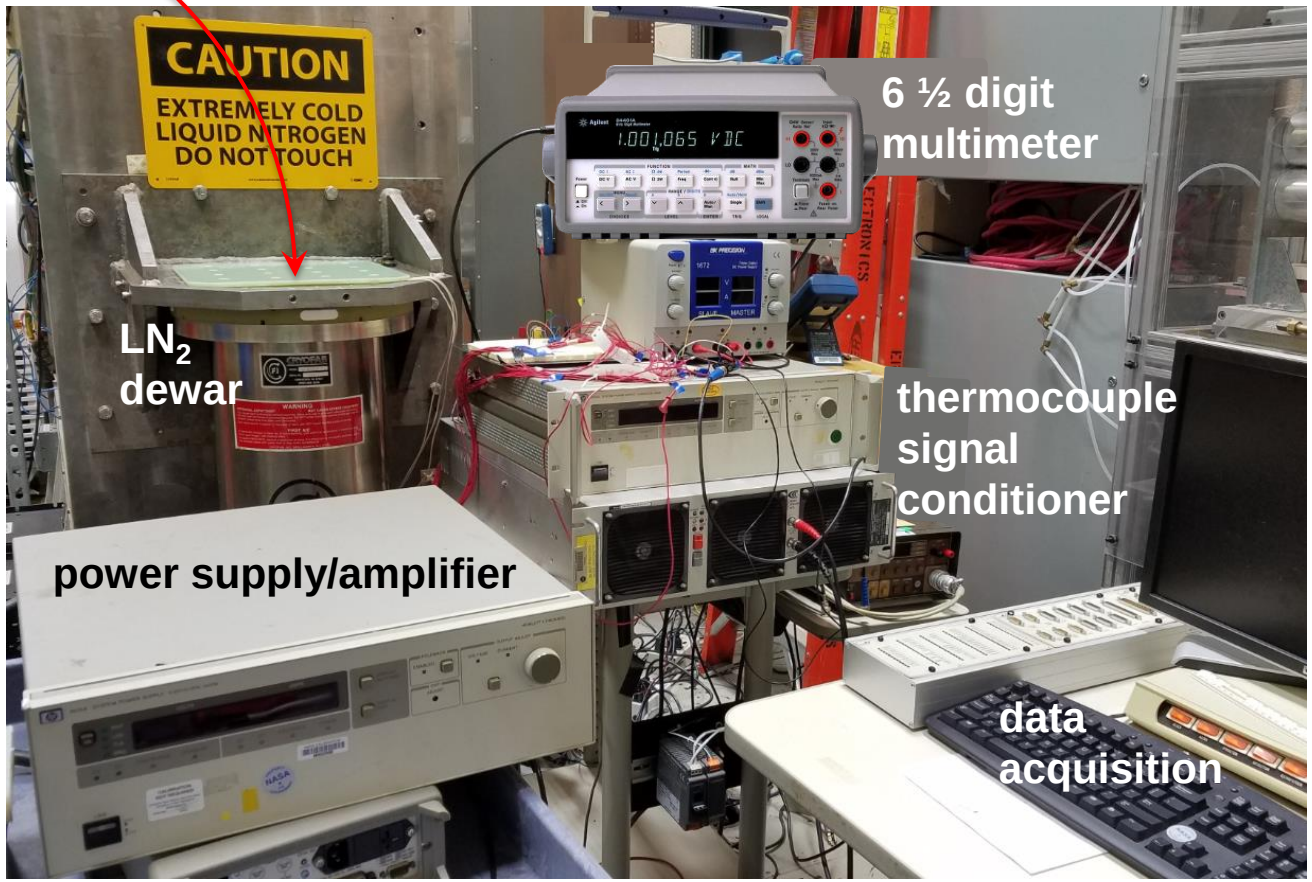
Critical Current Testing

- Critical current $(I_C) = I_C(T, B, \theta)$
- Coil mounted to G10 plate & suspended in liquid nitrogen
- **Measurements:** voltage & transport current





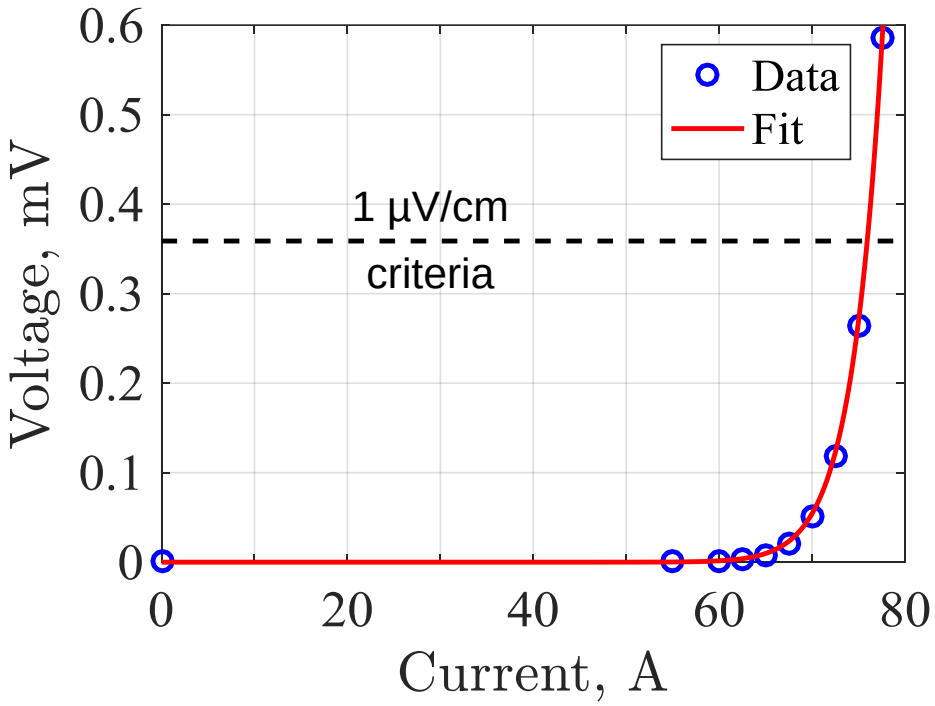
Critical Current Testing

- Voltage vs current response commonly described by

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

where the critical voltage $V_c = 1\,\frac{\mu\mathrm{V}}{\mathrm{cm}} * \text{superconductor length}$

- "n-value" indicates *combined* quality of superconductor & measurement
- Detect damage via changes in n and/or I_c

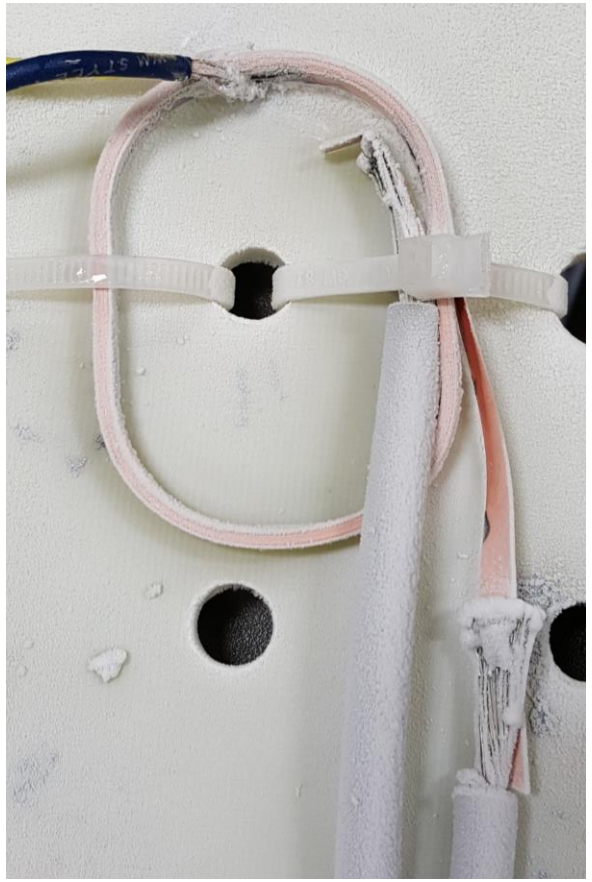


For this example

$V_c = 0.36\ \mathrm{mV}$

$I_c = 75.9\ \mathrm{A}$

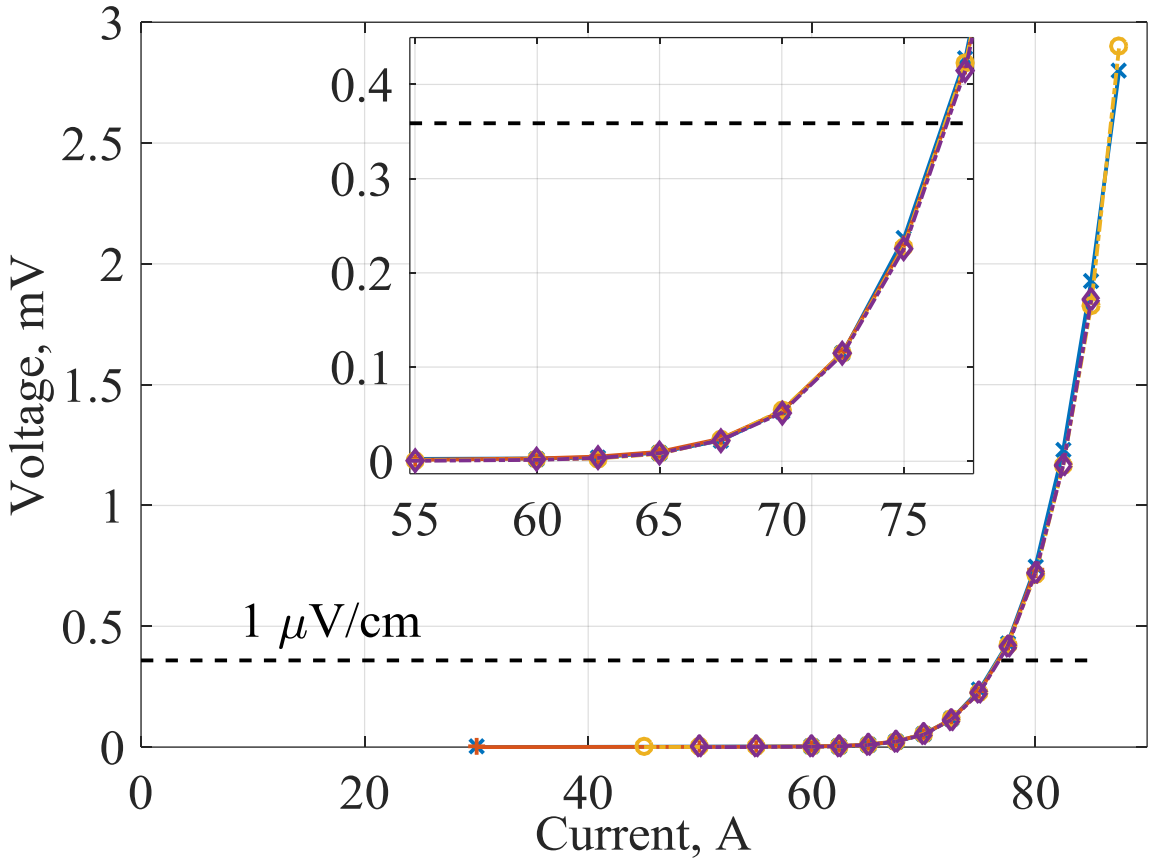
$n = 23.2$



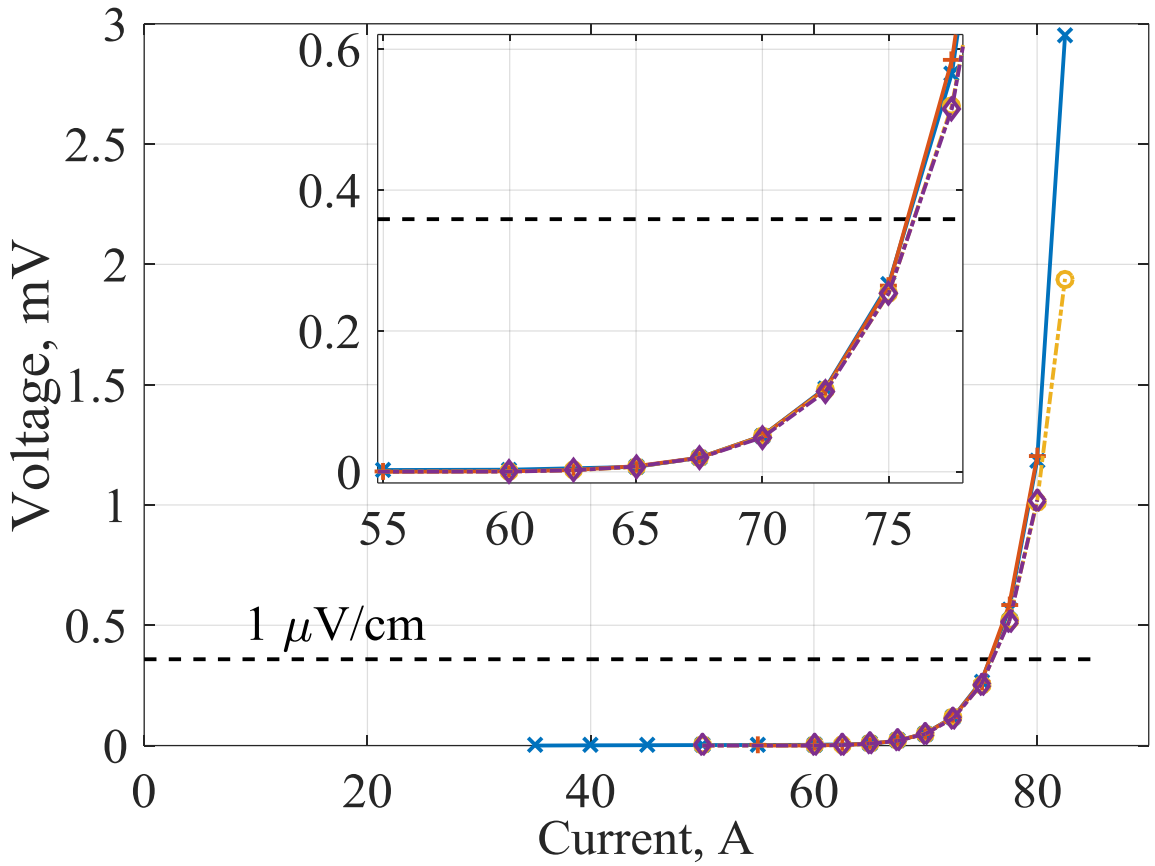
Critical Current Testing – 1-layer coils

- Two 1-layer coils tested: V vs I response at 77 K in "self field"
  - **Sanity check:** measure for increasing & decreasing I
  - **Thermal cycling tolerance:** measure before & after 2 or 4 thermal shock cycles

Coil 1 (2 thermal cycles)



Coil 2 (4 thermal cycles)



Critical Current Testing – 1-layer coils

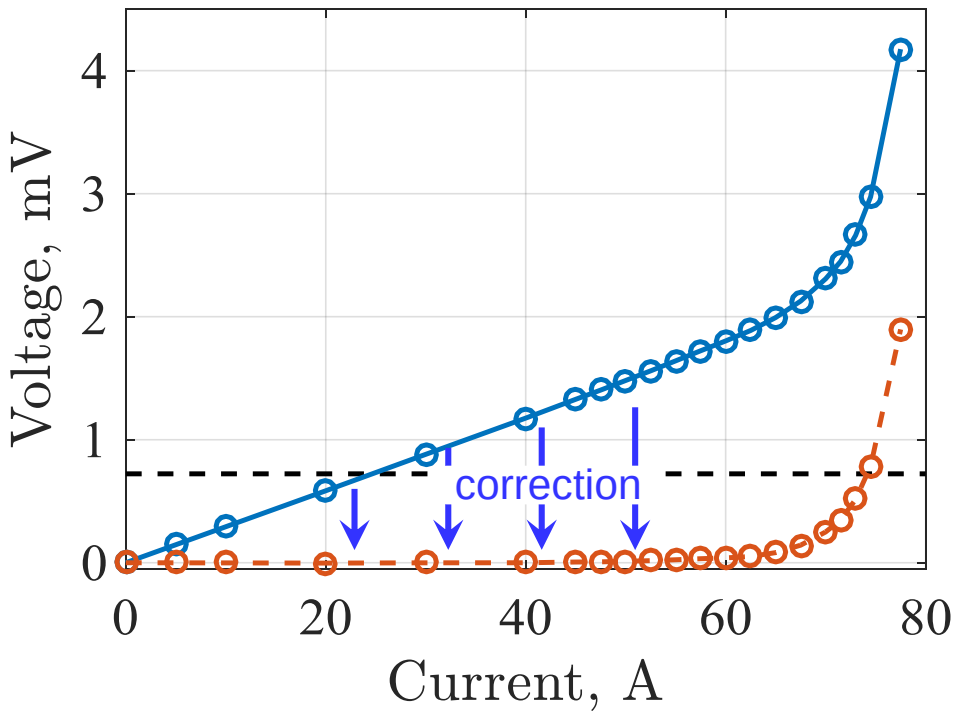
	Coil 1		Coil 2	
	I_c, A	n, –	I_c, A	n, –
Before thermal cycling	76.8	19.8	75.9	23.9
After thermal cycling	76.9	19.7	76.3	21.7

- Averaged results for increasing & decreasing I
- **Coil 1** (2 thermal cycles)
  - No detectable damage
- **Coil 2** (4 thermal cycles)
  - I_c increased by 1%, but n decreased by 9%
  - Inconclusive, but at worst only minor degradation of n

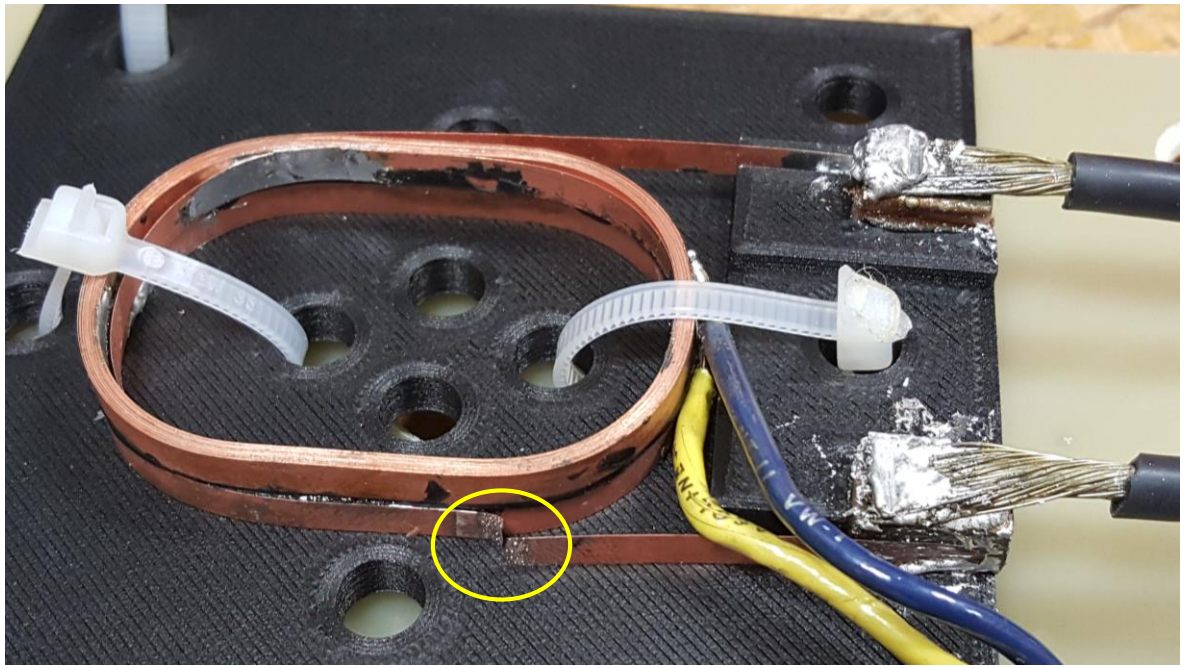
Critical Current Testing – 2-layer coils

- **2-layer coil requires superconducting joint** → solder introduces finite resistance
- After subtracting the linear trend, results analyzed as before
- Coil 3 broke while attempting to demonstrate self-protection feature
  - Damage occurred only in unprotected current lead

Coil 3



Coil 3

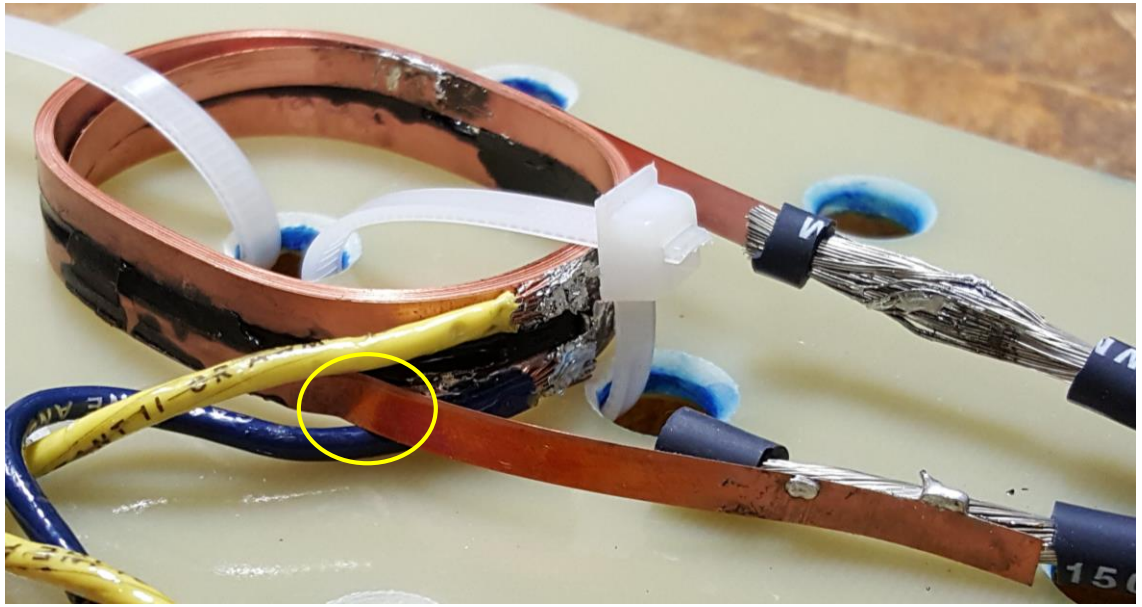


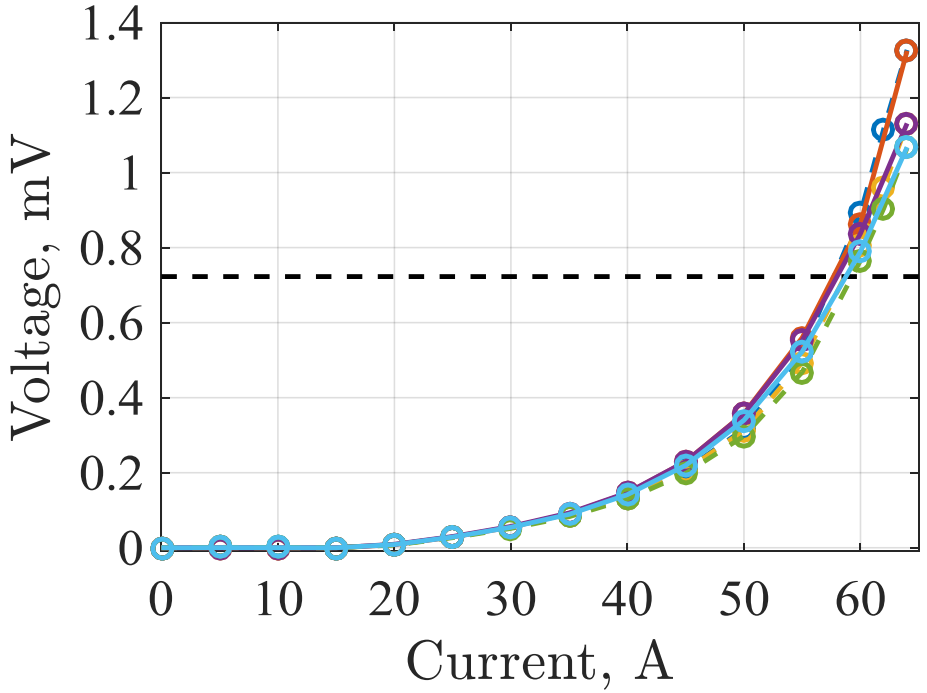
Critical Current Testing – 2-layer coils

Coil 4

- Current lead damaged during coil fabrication
  - I_c reduced and n-value significantly reduced
- I_c increased by 3%, but n decreased by 13%
- Inconclusive, but at worst only modest degradation of n

	Coil 4	
	I_c, A	n, –
Before thermal cycling	57.4	5.4
After 2 thermal cycles	58.3	4.7
After 6 thermal cycles	59.0	4.7





Outline

- Rotor & coil design
- Coil fabrication
- Critical current testing
- Conclusions

Conclusions

- Discussed the design of the superconducting rotor of NASA's 1.4 MW High Efficiency Megawatt Machine (HEMM)
  - Uninsulated superconducting coils selected to provide fault tolerance and significantly higher engineering current density
  - **2 key risks:** resilience to thermal cycling and rotation
- 3D printed winding fixtures work well & allow short lead time
  - But, they prevent the use of some solders while the coil is fixture
- **Initial thermal cycling measurements of 1-layer and 2-layer uninsulated coils**
  - Tested up to $1.15I_c$ • 2 to 6 thermal shock cycles
  - After thermal cycling, I_c increased but n-value decreased
    - Results inconclusive, but suggest little to no degradation

Acknowledgements

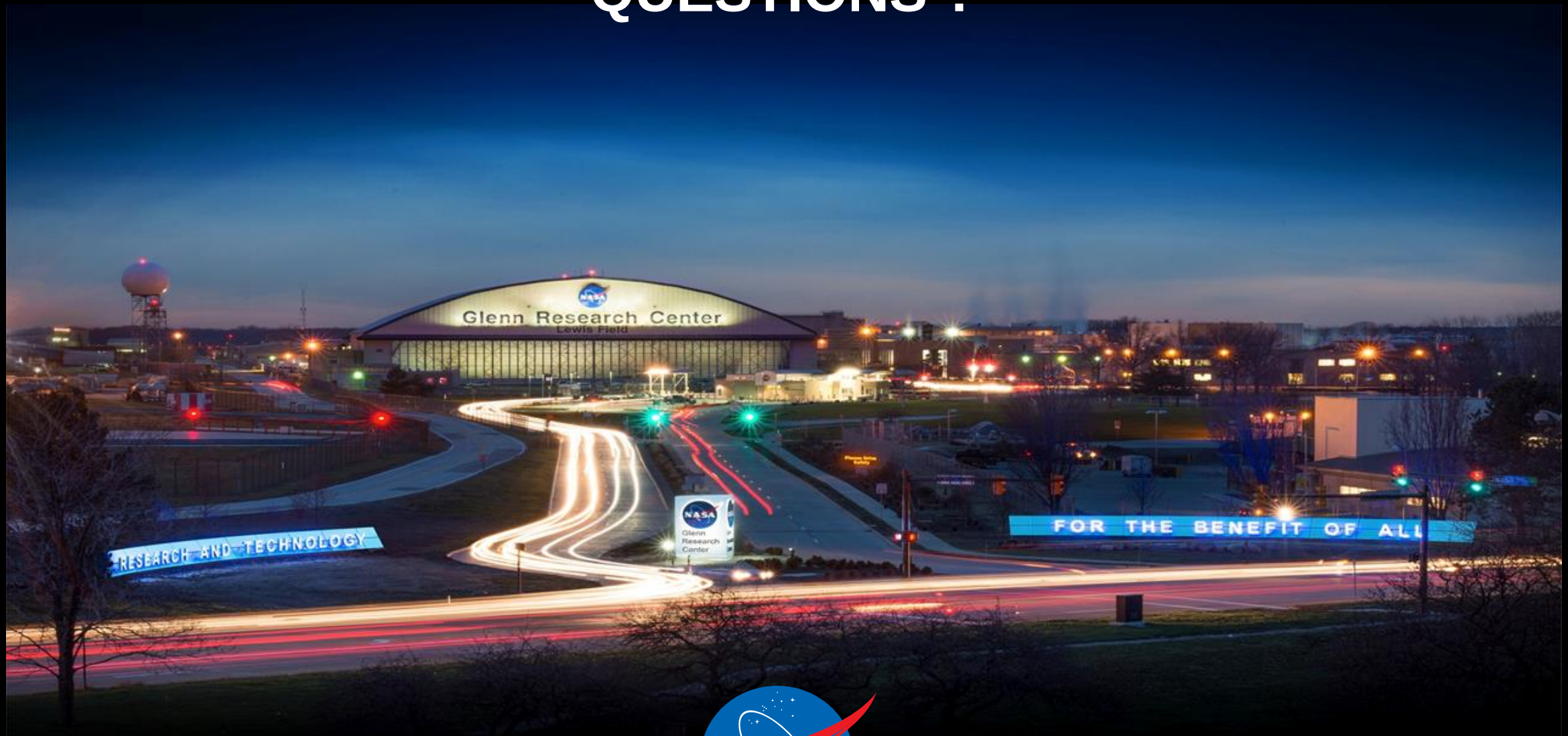
- Samuel Chung (summer intern)
- NASA Advanced Air Transport Technology (AATT) Project

References

[1] Jansen, R., Bowman, C., Jankovsky, A., Dyson, R., and Felder, J., "Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports," *53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, Atlanta, GA, AIAA 2017-4701*, 2017. doi:10.2514/6.2017-4701.

[7] Welstead, J., and Felder, J. L., "Conceptual design of a single-aisle turboelectric commercial transport with fuselage boundary layer ingestion," *54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, San Diego, CA, AIAA 2016-1027*, 2016. doi:10.2514/6.2016-1027.

QUESTIONS ?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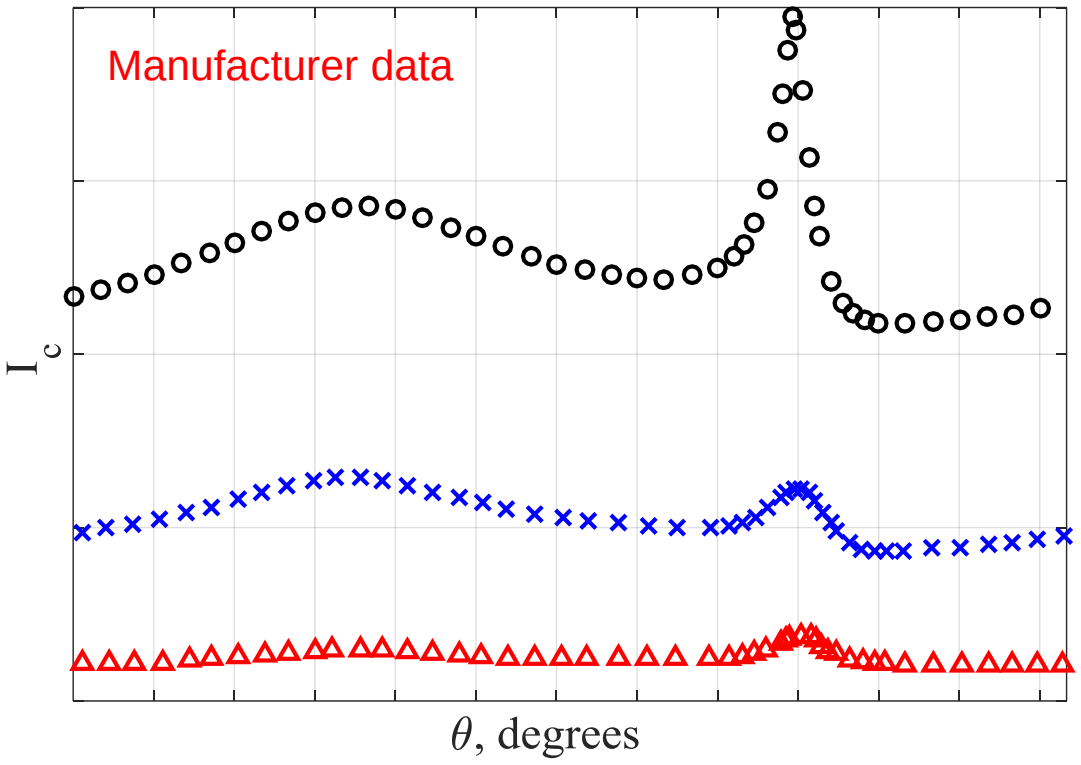
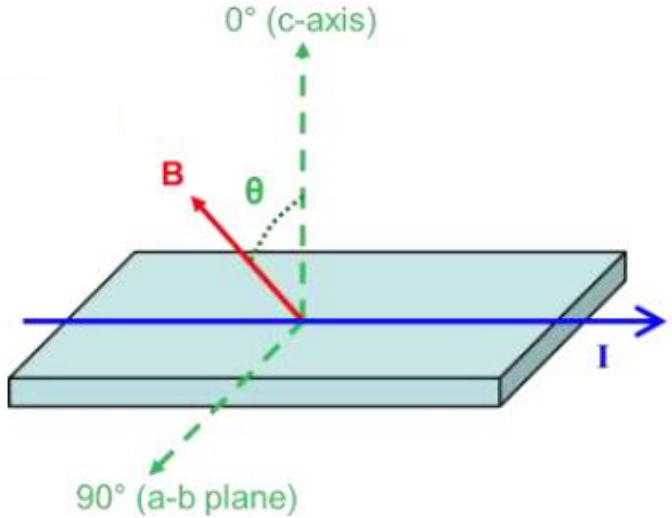
Superconductor current & thermal limits

- 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





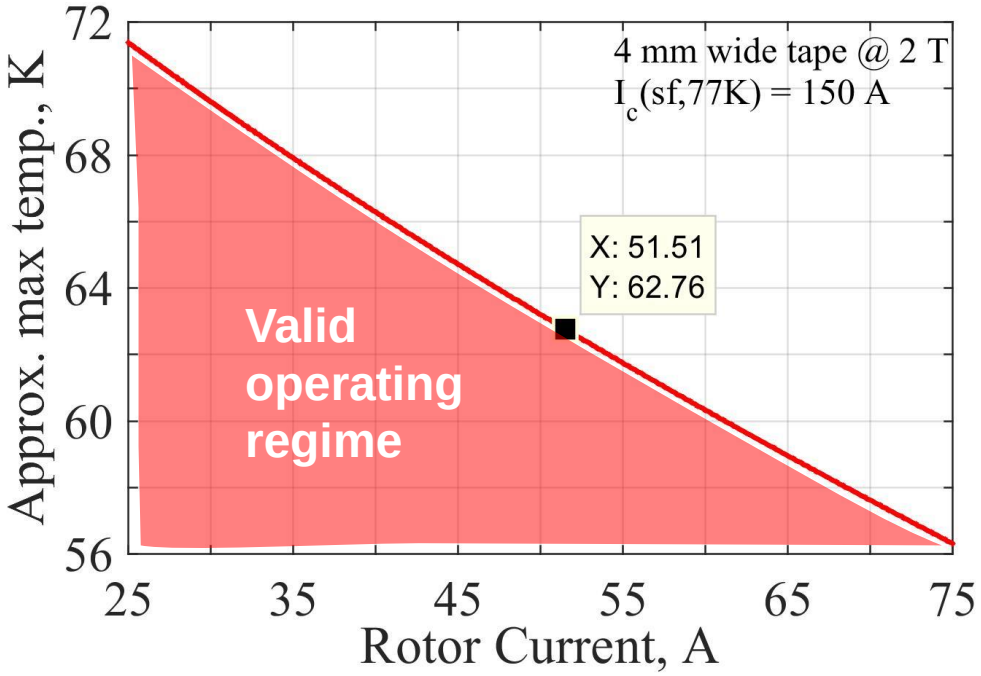
Safety factor

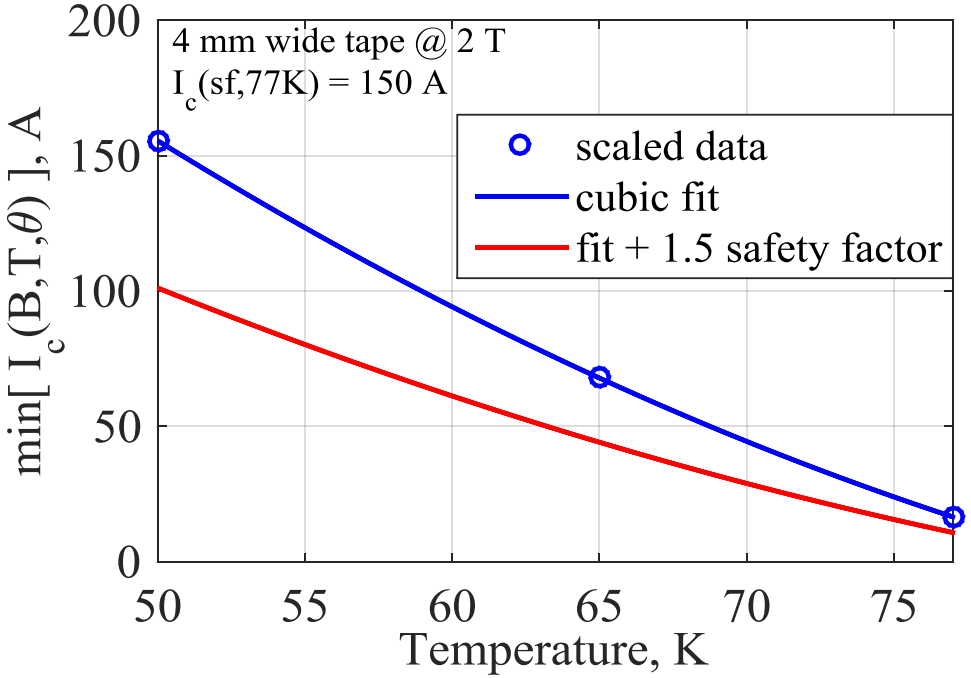
	±20%	Estimate of wire variation
+	±15%	Modeling inaccuracy
	±35% (≈1.5 safety factor)	

Superconductor current & thermal limits

- Measurements at B = 2 T obtained from manufacturer

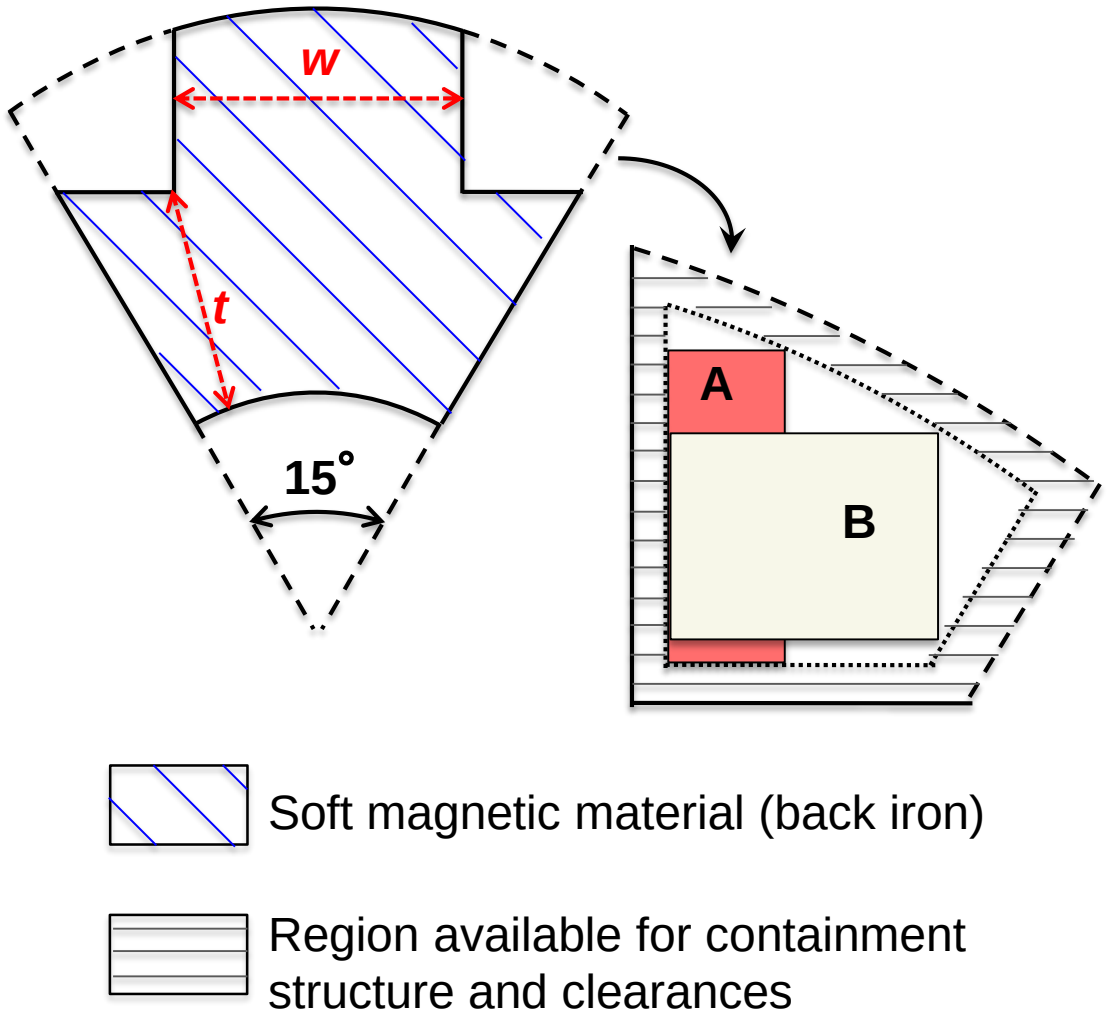
Design spec
current 51.5 A
temperature ≤ 62.8 K





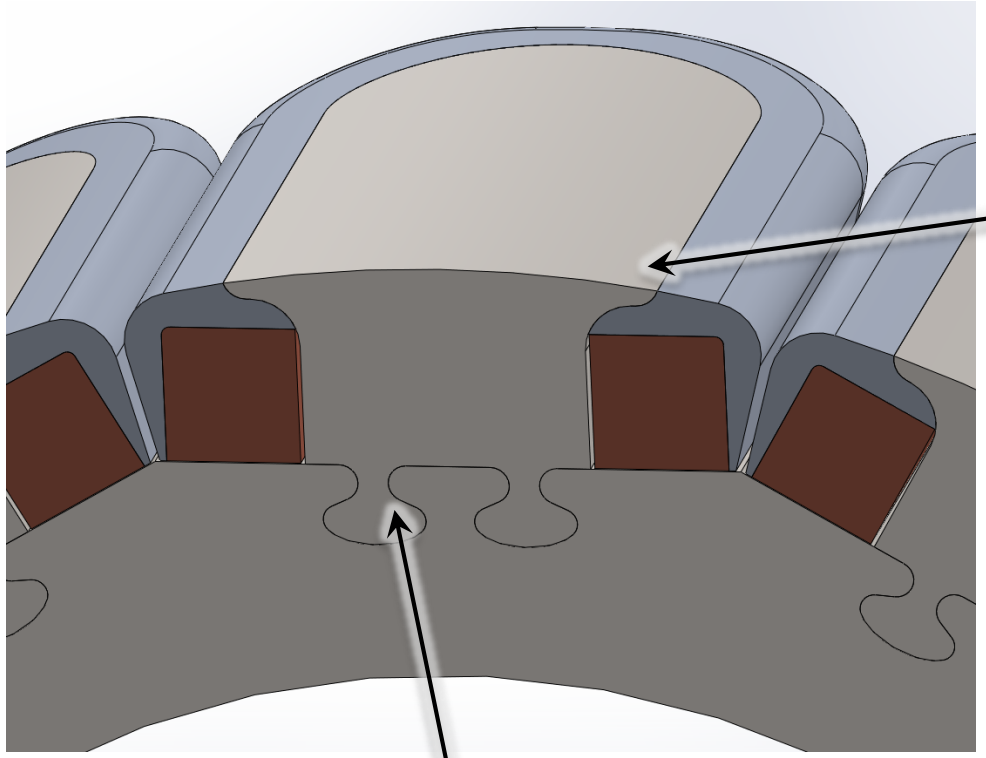
Optimization of rotor coil's geometry

- Optimized coil's geometry for given iron thickness & width by numerically maximizing # of turns
  - Rectangular coil cross section
  - Also outputs total length & cost of conductor, mass of iron+coil
  - 4 mm is optimal width of superconductor



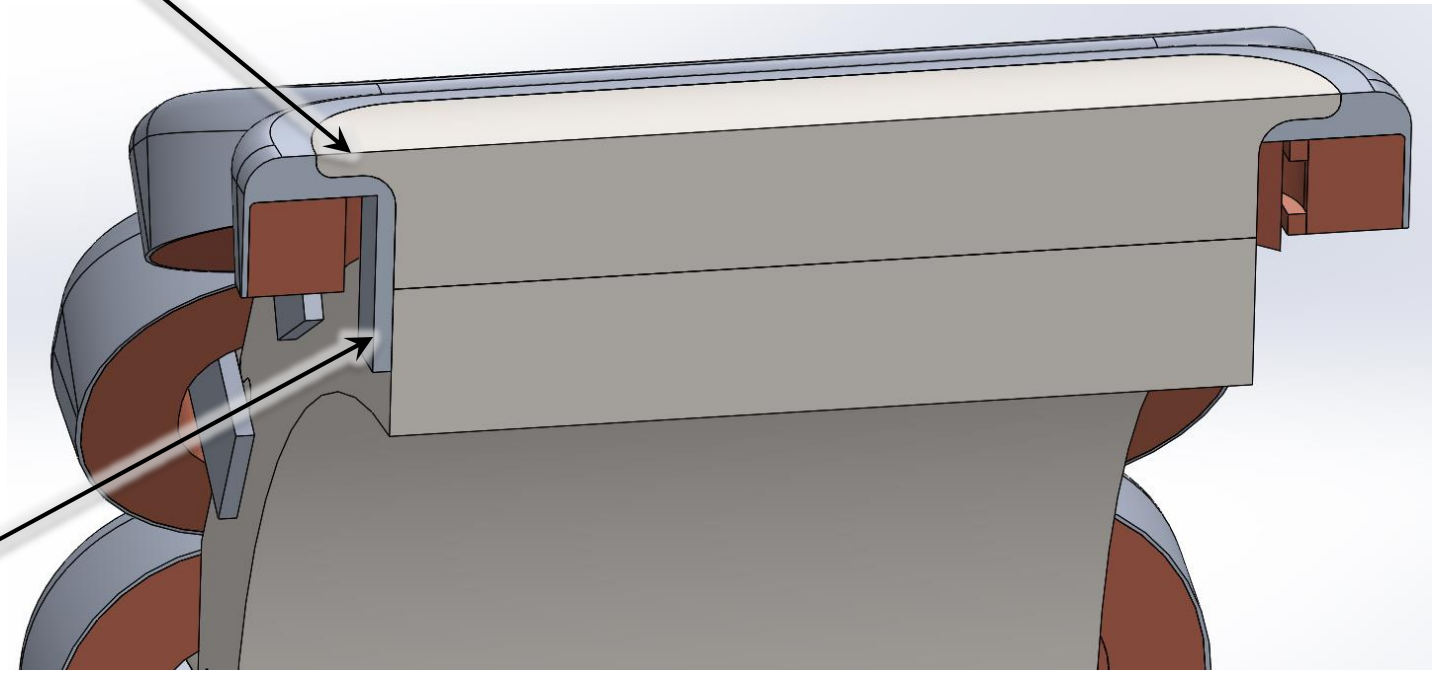
Preliminary design – double dovetail rotor teeth

Part	Material
back iron	Hiperco 50 A
Coil fixture	Sialon (SiN + Al_2O_3)
	SiC
	SupremEx 640XA (Al 6061 + SiC powder)
	Ti-6Al-6V-2Sn



continuous shoulder

double dovetail



heat extraction tab

Critical Current Testing – 1 layer coils

Test		Coil 1		Coil 2	
		I_c, A	n, –	I_c, A	n, –
Before thermal cycling	I increasing	76.9	18.5	75.8	24.6
	I decreasing	76.6	21.0	75.9	23.2
After thermal cycling	I increasing	76.8	19.7	76.2	21.6
	I decreasing	76.9	19.7	76.3	21.8