Preliminary Design of the Superconducting Rotor for NASA's High-Efficiency Megawatt Motor

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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

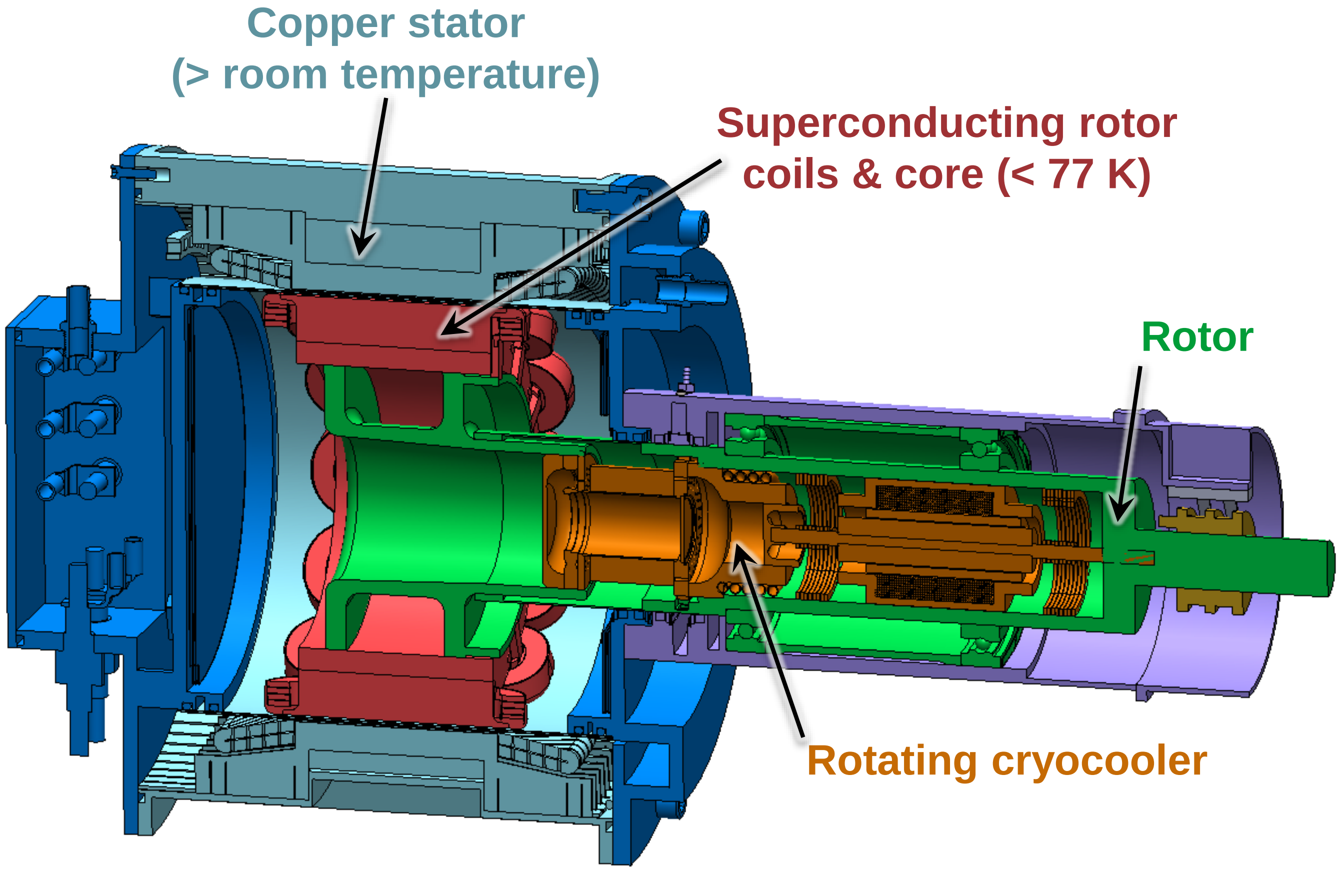
	STARC-ABL	
Electric machines	**Current design**	**With HEMM**
Specific power, kW/kg	13.2	16
Efficiency, %	96	98 to 99

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

This talk

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

Talk 2 (Scheidler & Tallerico, 2018 EATS)

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

Outline

- Electromagnetic design & optimization
  - Thermal requirements
  - Optimization of rotor coil's geometry
  - Optimization of back iron geometry
- Rotor containment design & stress analysis
- Conclusions

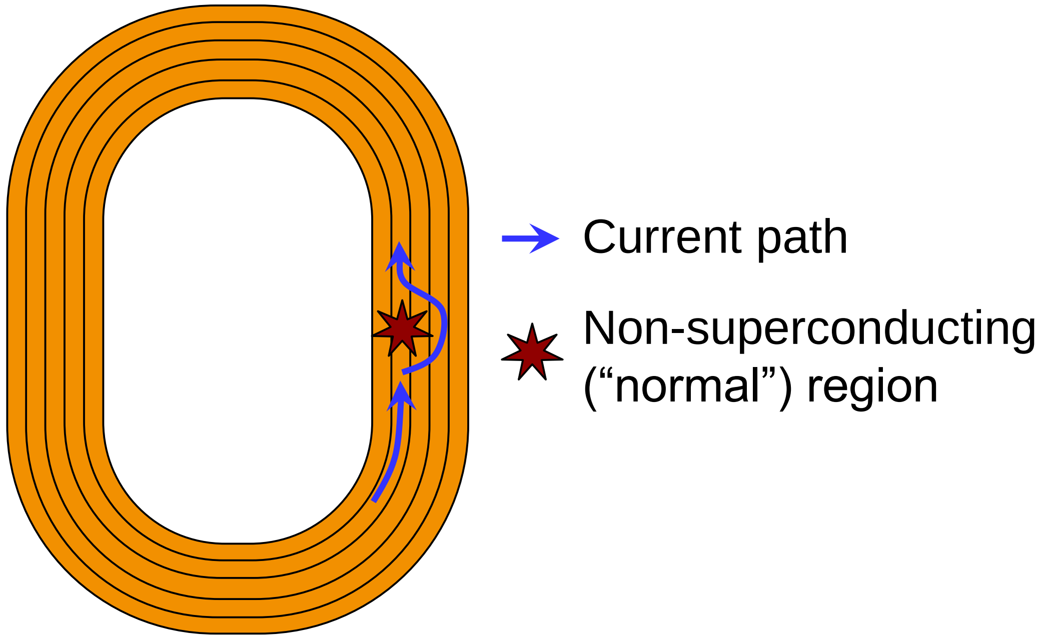
Superconductor selection & form factor

Parameter	Value
Electrical frequency	DC
Number of poles	12
Stator configuration	Slotless
Rotor outer diameter	30 cm
Air gap	4 cm
Axial length	12.5 cm

- REBCO is a composite conductor in the form of Cu-coated thin tape
- No-insulation (NI) coils selected [9-11]
  - **Fault tolerant**
  - **Higher engineering current density**
  - Higher mechanical strength

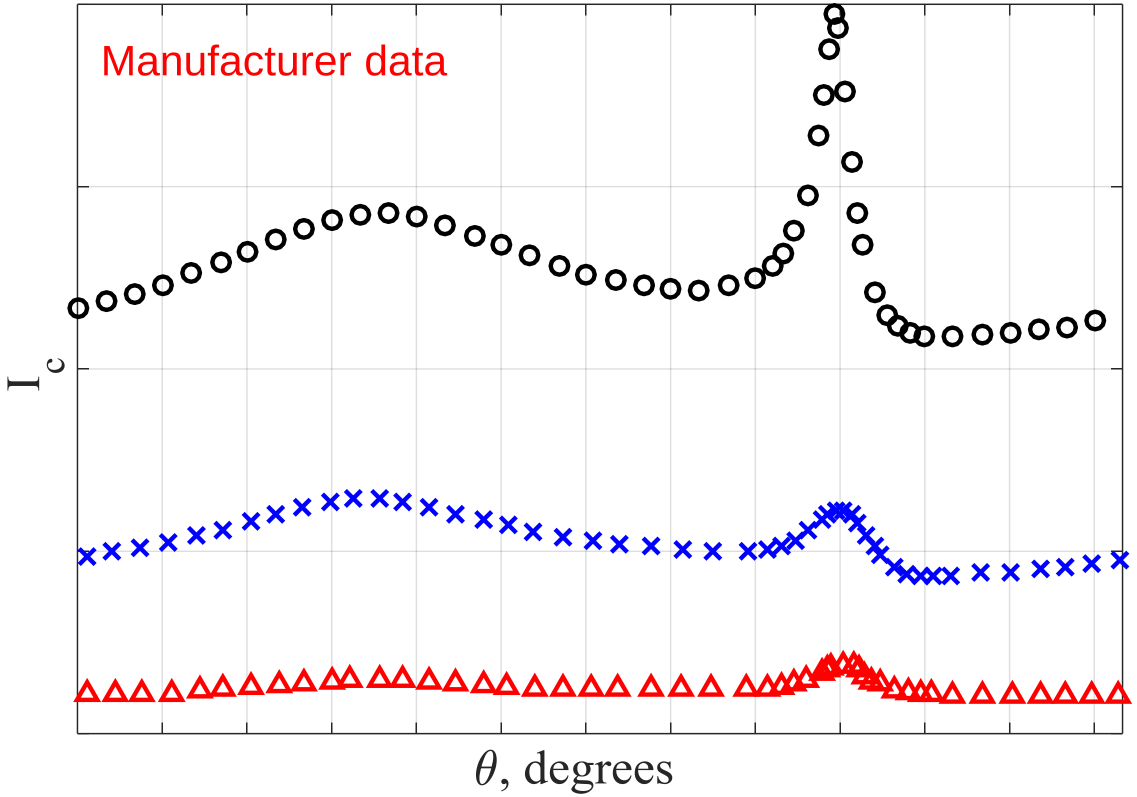
- 2nd generation high temperature superconductor (REBCO) selected
  - Commercially available in long piece length
  - Sufficient performance at “high” temperatures in moderately strong magnetic environments

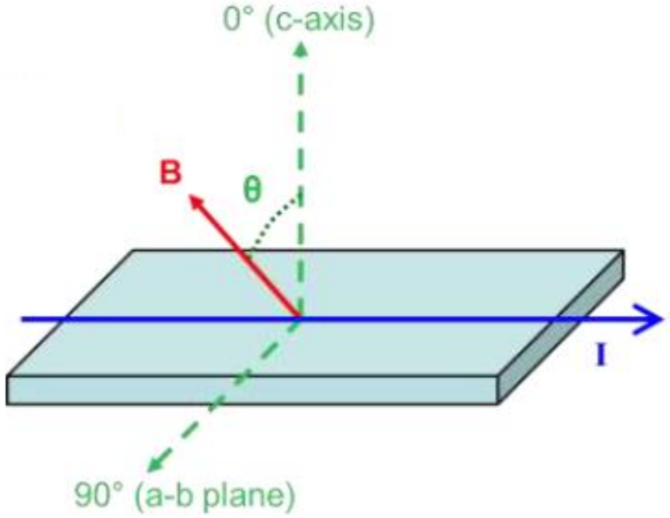
Self protection via no turn-to-turn insulation



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

$\boxed{\pm 35\% \ (\approx 1.5 \text{ safety factor})}$

Superconductor current & thermal limits

- Measurements at our operating condition obtained from manufacturer

Temperature	High performance tape (191 A @ ~0 T)		Standard tape (150 A @ ~0 T), *calculated*
	nominal I_c, A	$\min[I_c(\theta)]$, A	$\min[I_c(\theta)]$, A
50 K	249.4	x	155.0
65 K	127.1	x	67.8
77 K	28.9	x	16.5

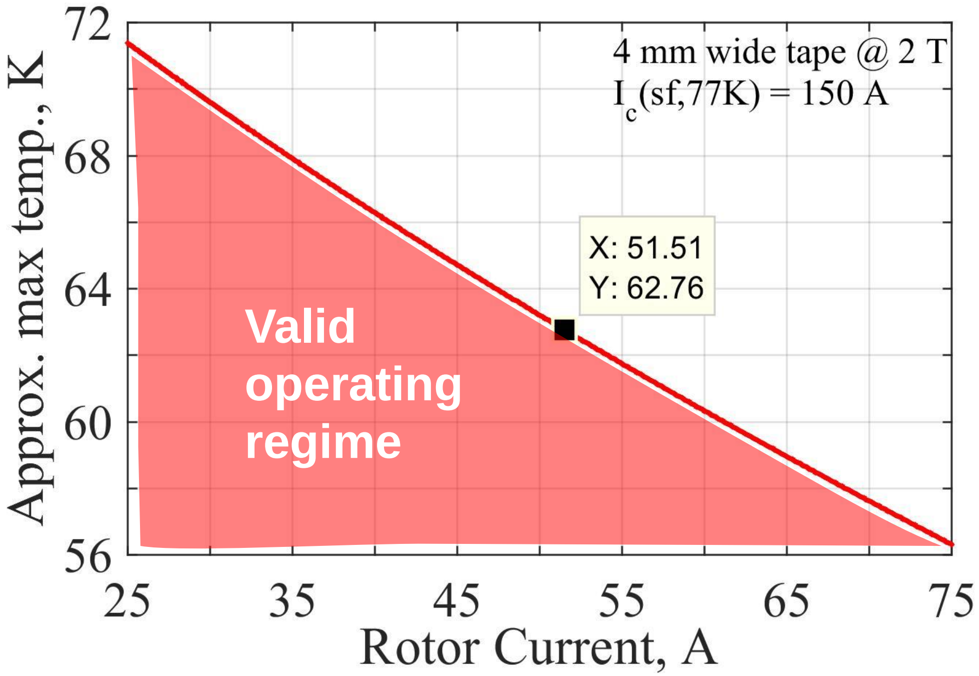
Avg. ↓ of 27%

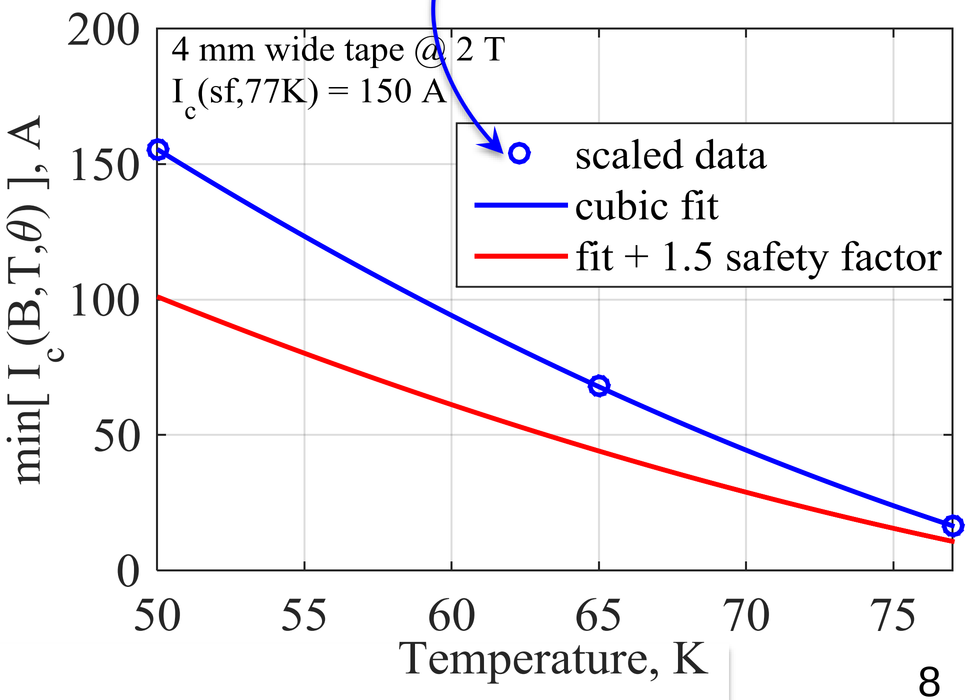
lift factor

Design spec

current 51.5 A

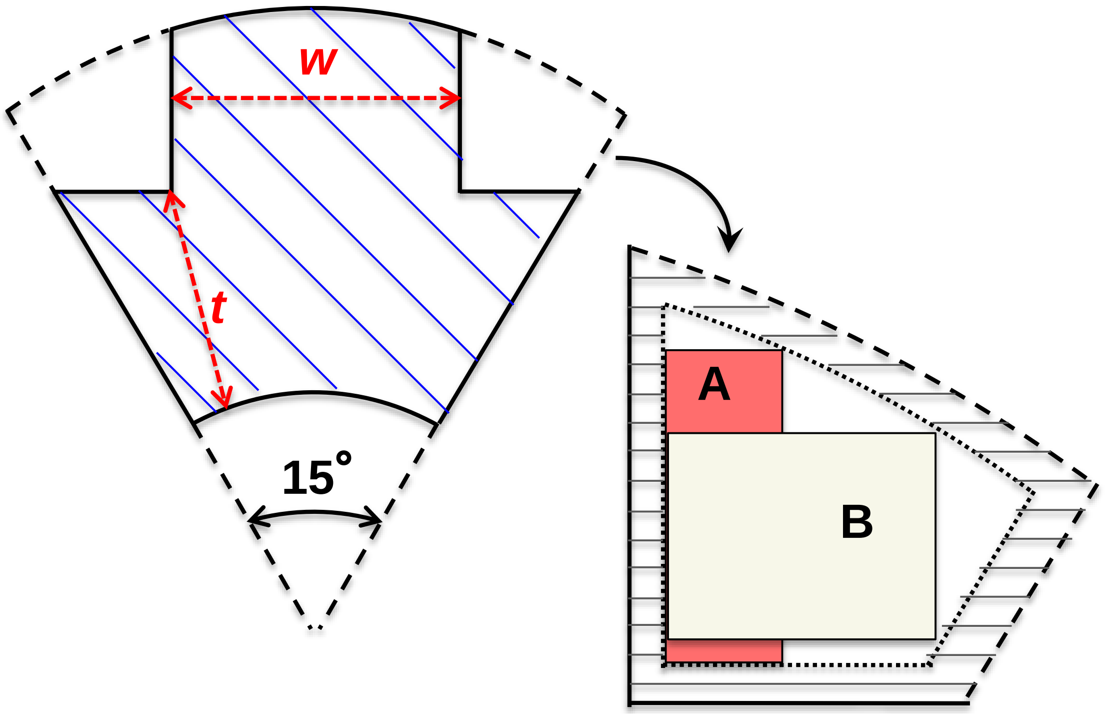
temperature ≤ 62.8 K





Optimization of rotor coil's geometry

- Optimized coil's geometry for a 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

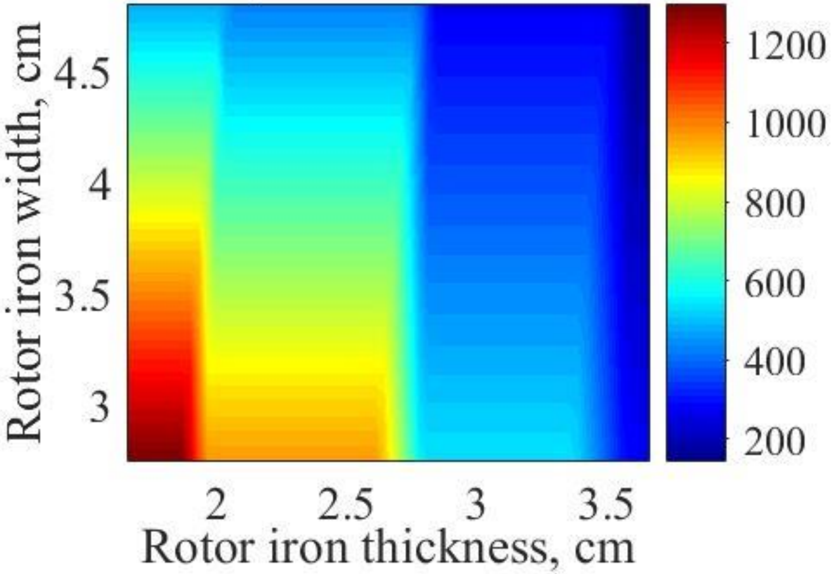


▨ Soft magnetic material (back iron)

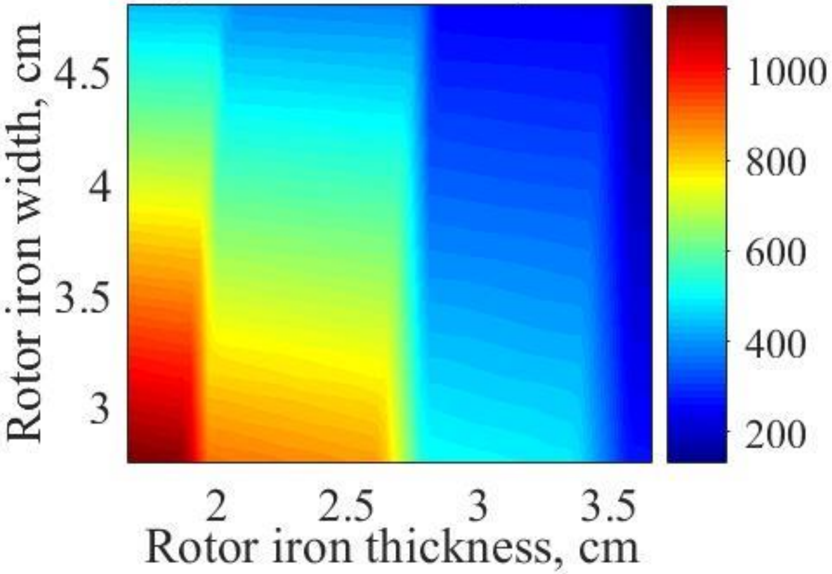
▤ Region available for containment structure & clearances

Optimization of rotor coil’s geometry

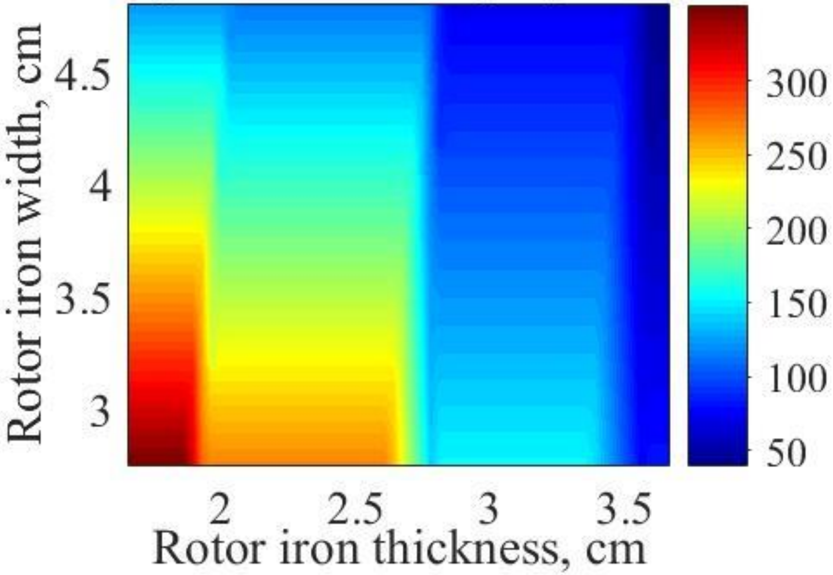
Optimal # of turns



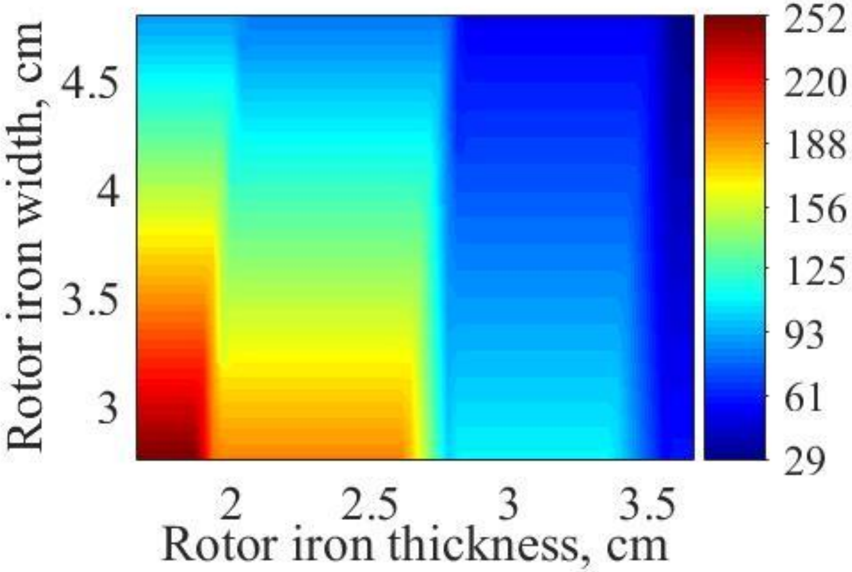
Magnetomotive force per mass



Superconductor length per coil



Total cost

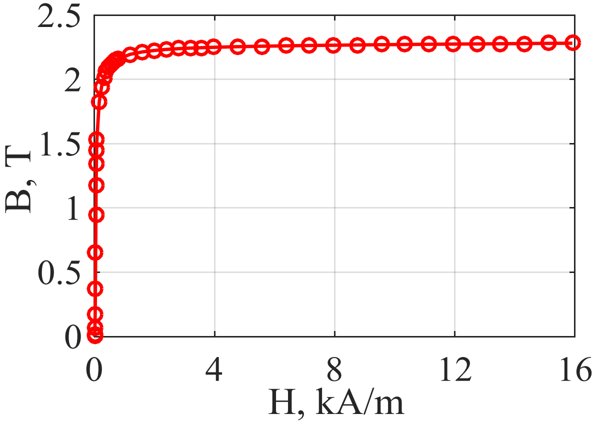


Optimization of back iron geometry

- Custom extrapolation derived for Hiperco 50A's B vs H response
- Mesh refinement study completed
- Results consistent with 2D MotorSolve

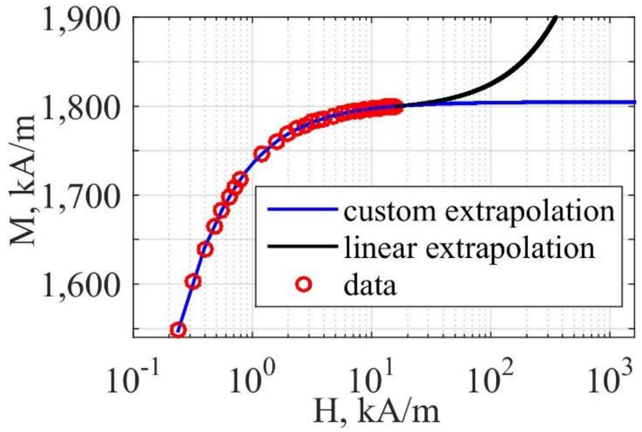
		MotorSolve	COMSOL	% difference
	Current, A	75	75	-
	A-Turns in coil	37500	37500	-
Avg. radial flux density	Rotor surface, T	1.999	1.9729	1.31%
	Stator surface, T	0.9028	0.8620	4.62%
	Max. flux density, T	4.14	4.04	2.44%

Data from manufacturer



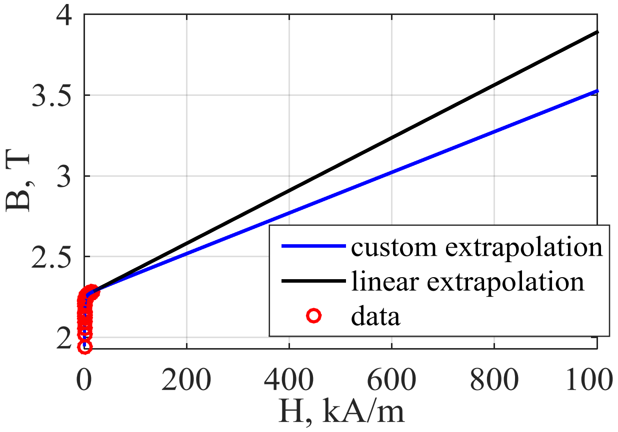
$$M = \frac{B}{\mu_0} - H$$

Curve fit, extrapolate



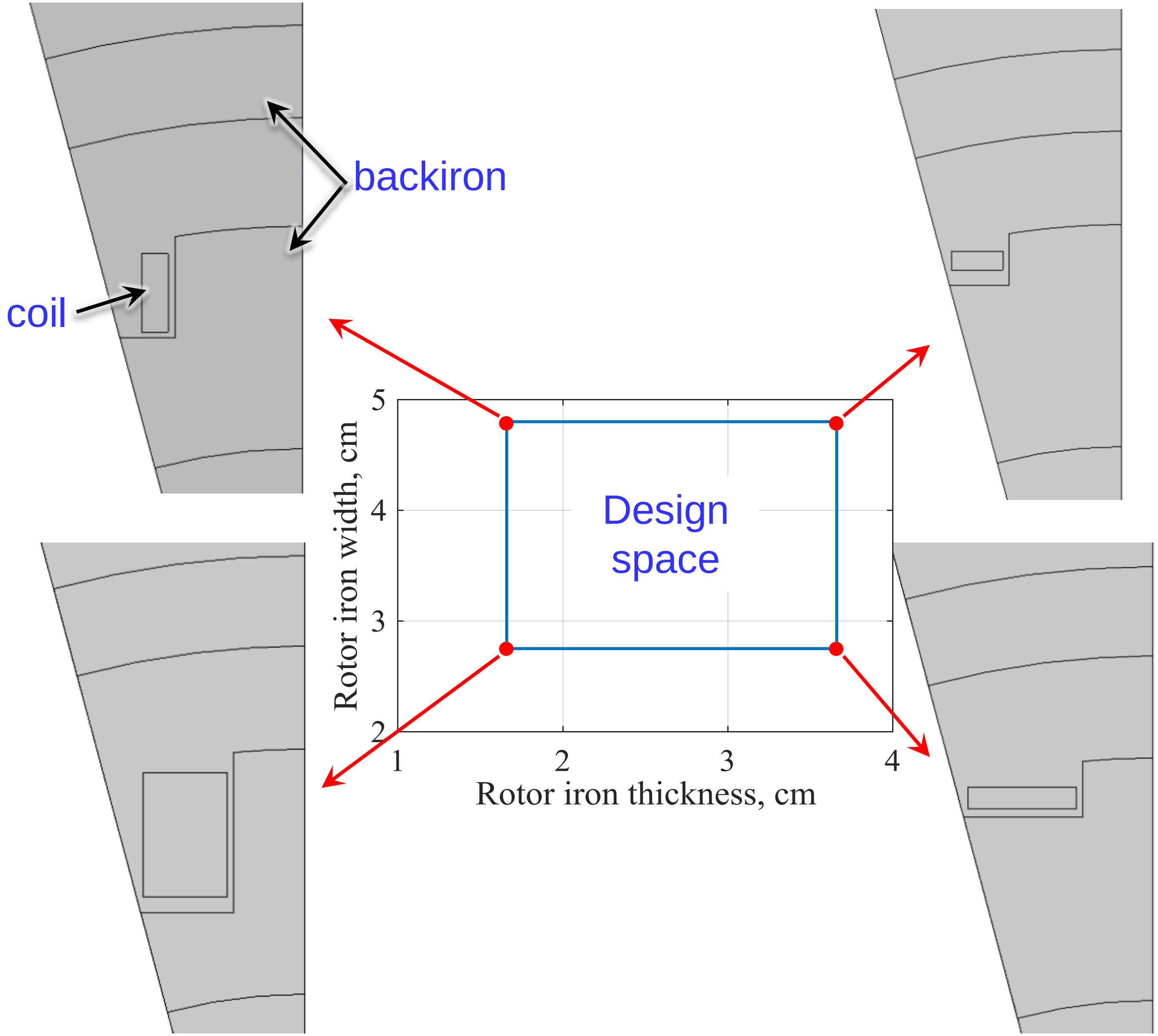
$$B = \mu_0(H + M)$$

Calculate from extrapolation



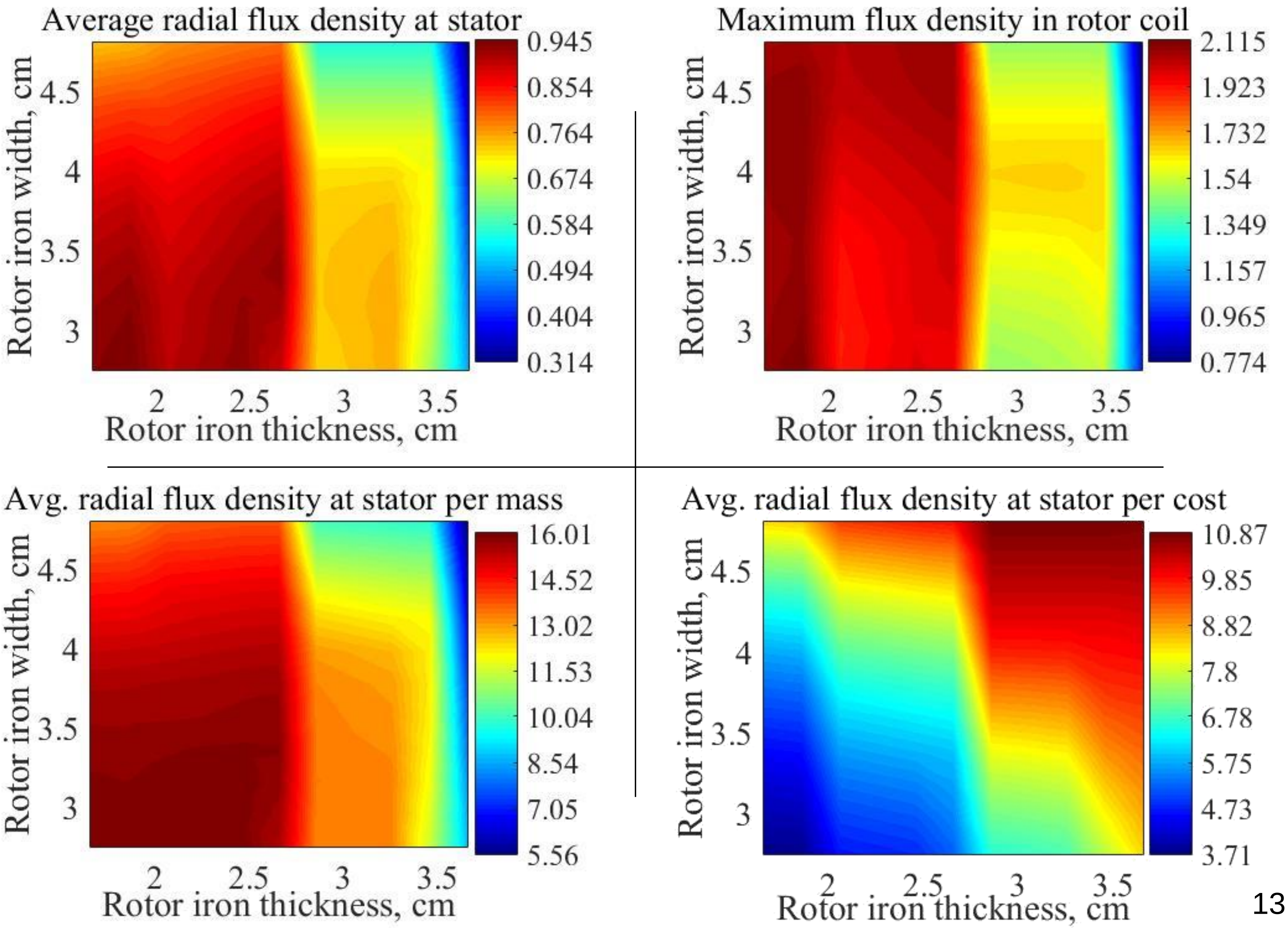
Optimization of back iron geometry – 2D FEA

- Parametric study of iron and coil geometry
- COMSOL electromagnetic simulation
  - 2D and 3D
  - Nonlinear, static
  - No stator current



Optimization of back iron geometry – 2D FEA

- Trends nearly mirror coil's A-turns
- Minimize rotor iron width & thickness (maximize A-Turns)
  - Diminishing returns due to magnetic saturation
- Constrained by max *B* in coil
- Performance & performance per mass have opposite trends than performance per cost

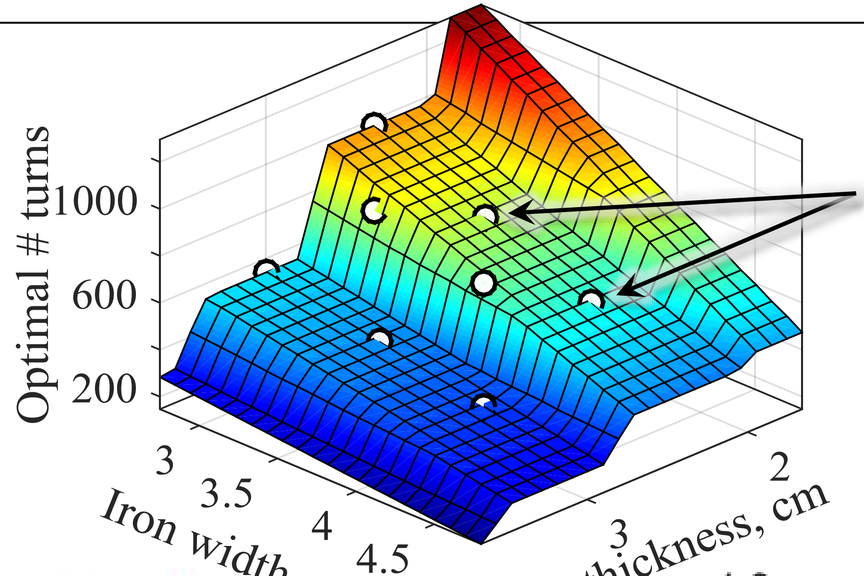

Average radial flux density at stator

Maximum flux density in rotor coil

Avg. radial flux density at stator per mass

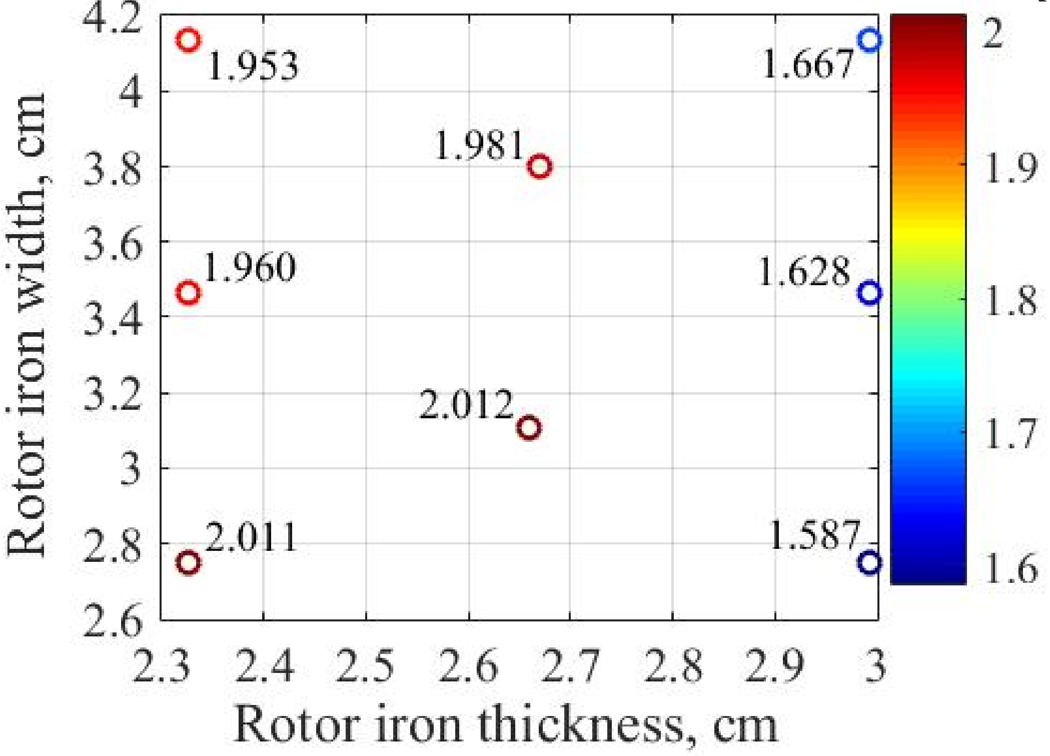
Avg. radial flux density at stator per cost

Optimization of back iron geometry – 3D FEA

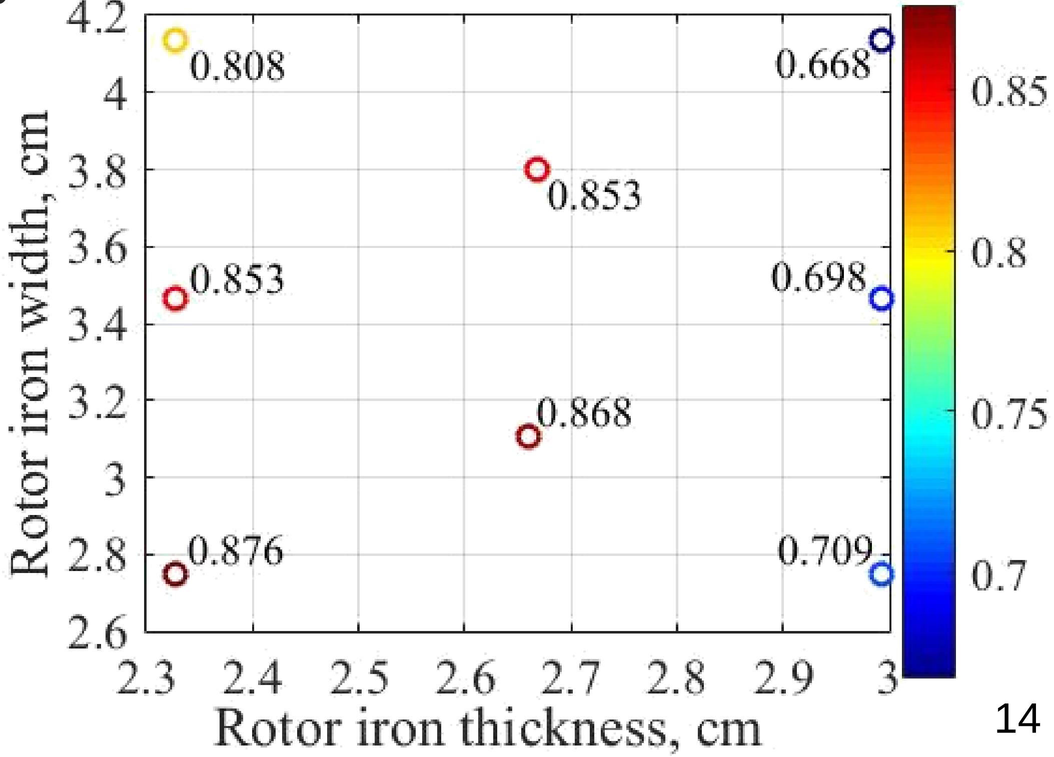


3D parametric study points

Avg. radial flux density at stator



Max. flux density in rotor coil



Optimization of back iron geometry – 3D FEA

- Preliminary design
  - Max rotor temp. = 62.8 K
  - HTS tape = 4 mm x 65 micron
  - Rotor thickness = ~2.6 cm
  - Rotor tooth width = ~3.3 cm
- Length of HTS wire needed
  - Each coil: ~250 m
  - Total wire length: 3150 m
- Estimated total cost of HTS wire
  - $200K = 3150 m * $60/m
    + 5% margin

v1 design	**v2 (preliminary) design**	**% change**
75 A	51.5 A	– 31%
60 K	62.8 K	+ 5%
0.94 T @ air gap	0.96 T @ air gap	+ 2%
346 A-turns/kg	738 A-turns/kg	+ 113%
2.0 T in HTS	1.99 T in HTS	0%

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- Electromagnetic design & optimization
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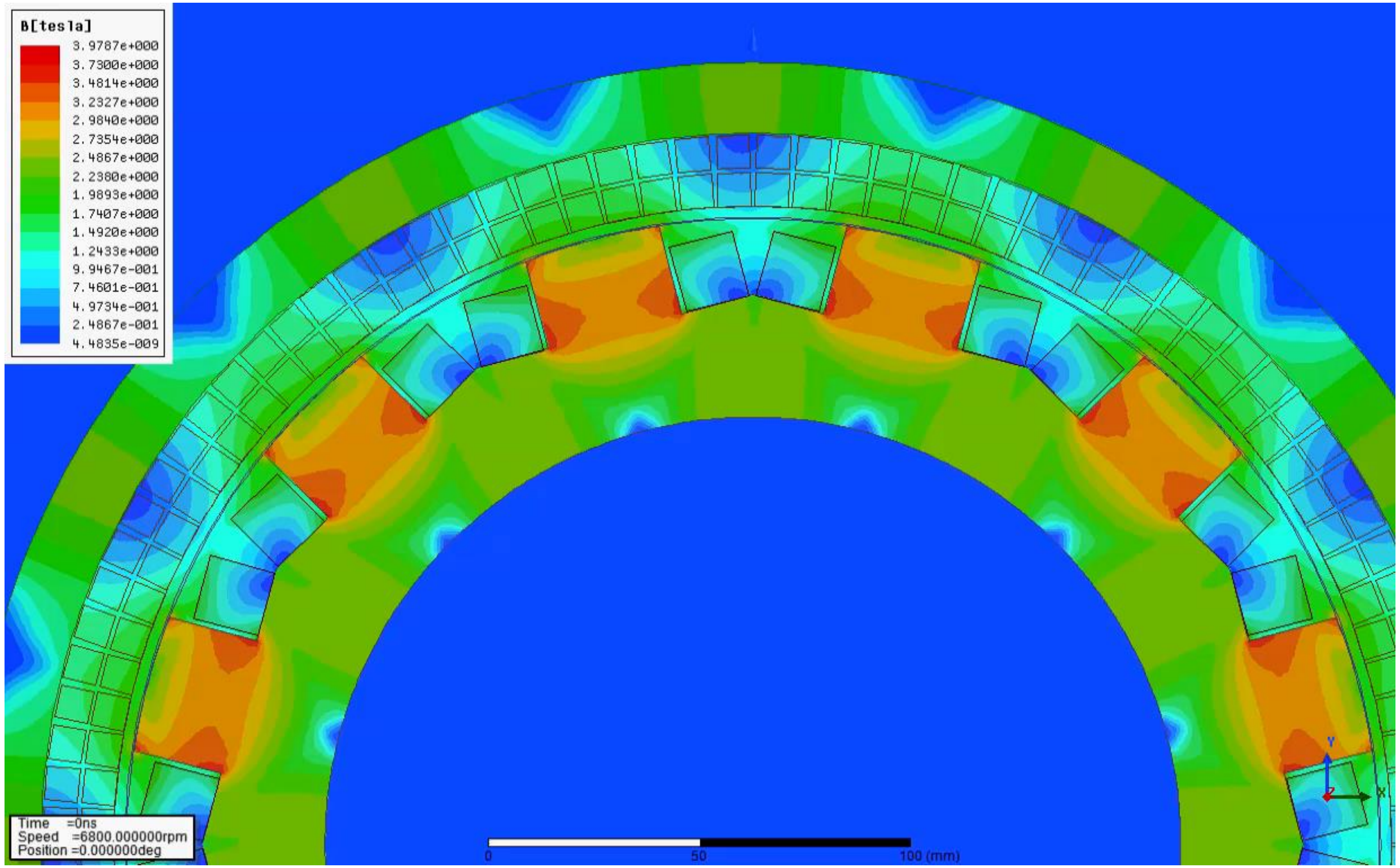
- Conclusions

Rotor containment design & stress analysis

- Only centrifugal force considered for preliminary design
  - Neglected forces: thermal, magnetostrictive, electromagnetic
- Rotor B variation minimal

  → magnetostriction < 6e-6 m/m

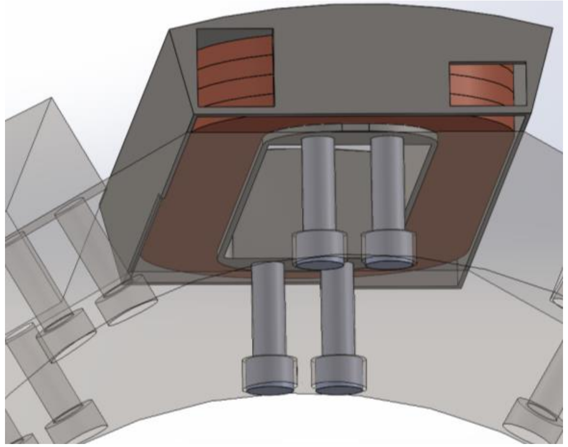
  → magnetostrictive forces are negligible
- Mechanical contact modeling is critical



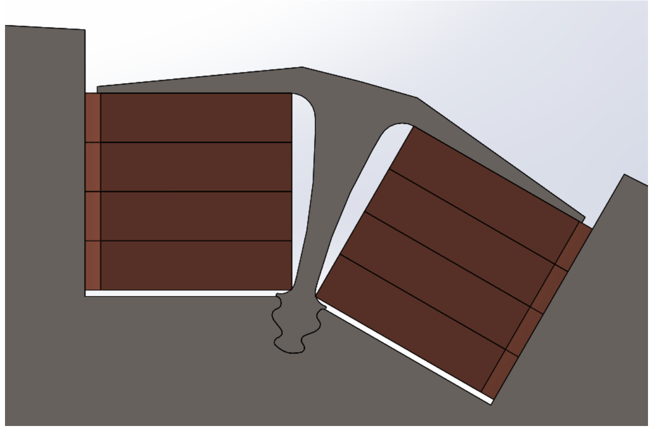
Rotor containment design & stress analysis

- Wide range of fixture designs considered

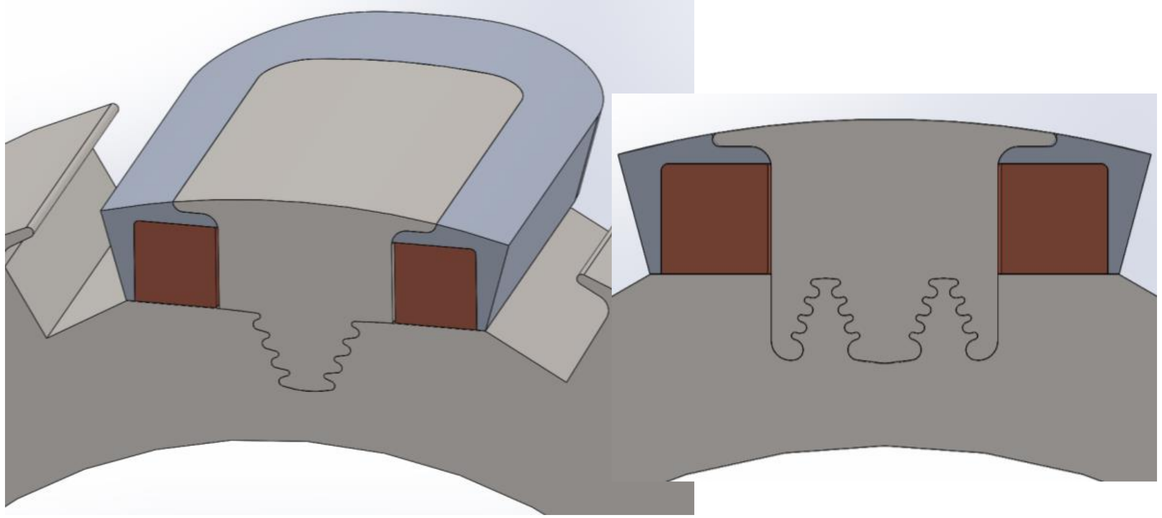
bolted fixtures

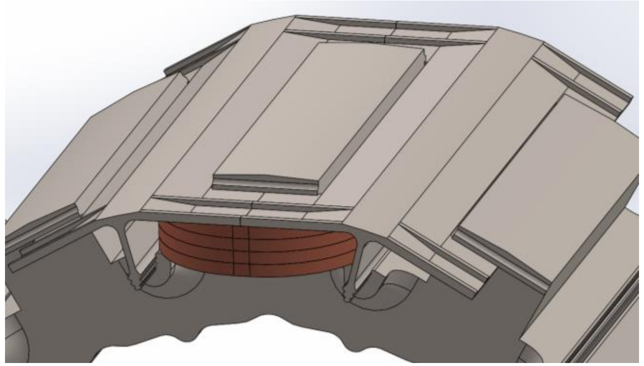


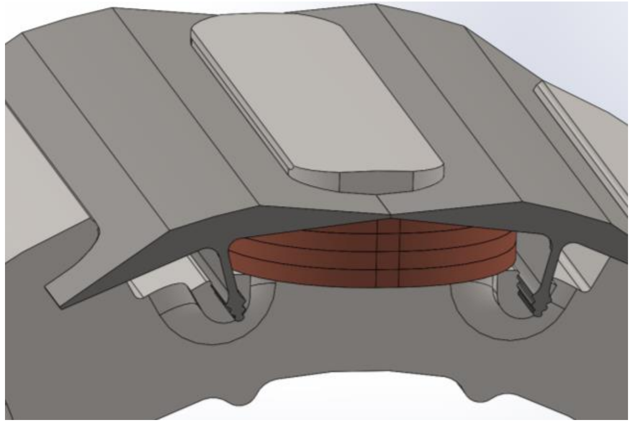
‘fir tree’ fixtures

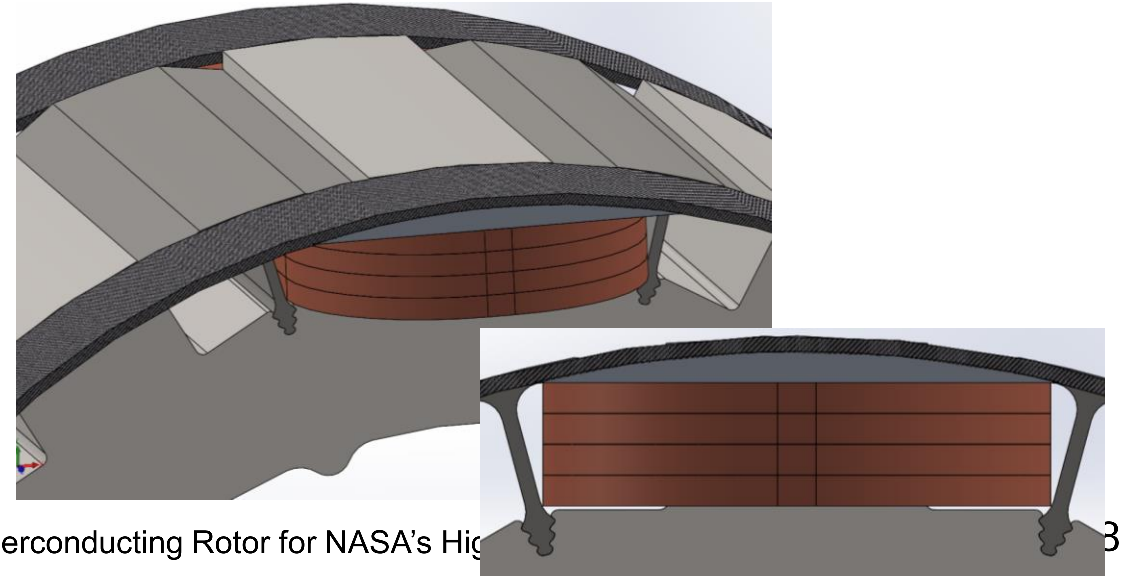


‘fir tree’ teeth



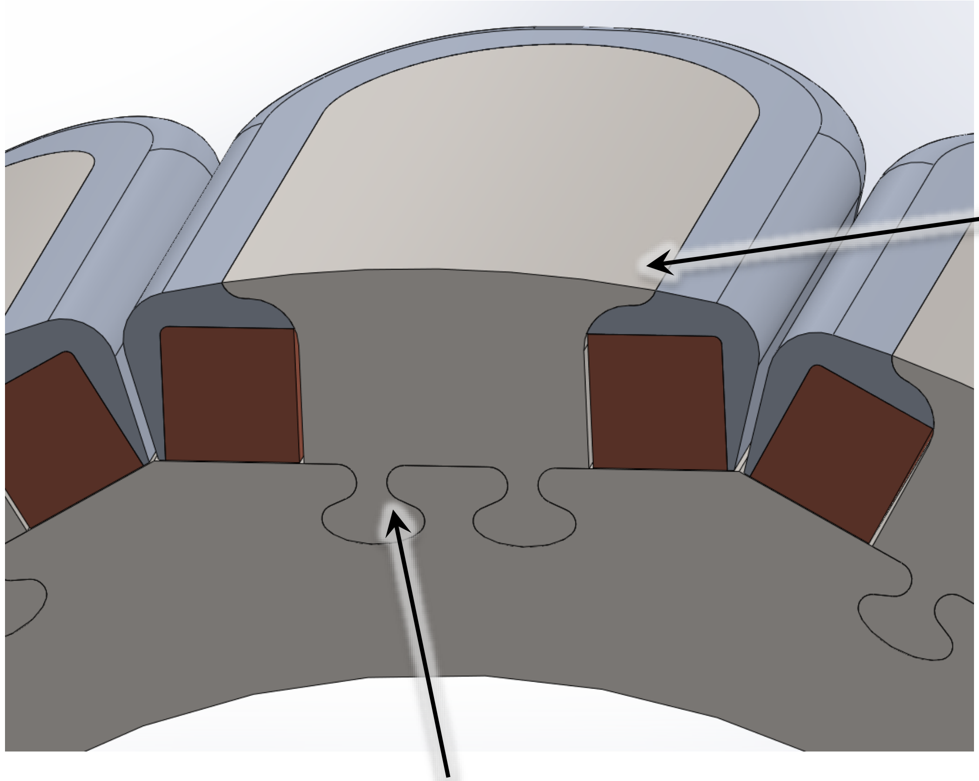






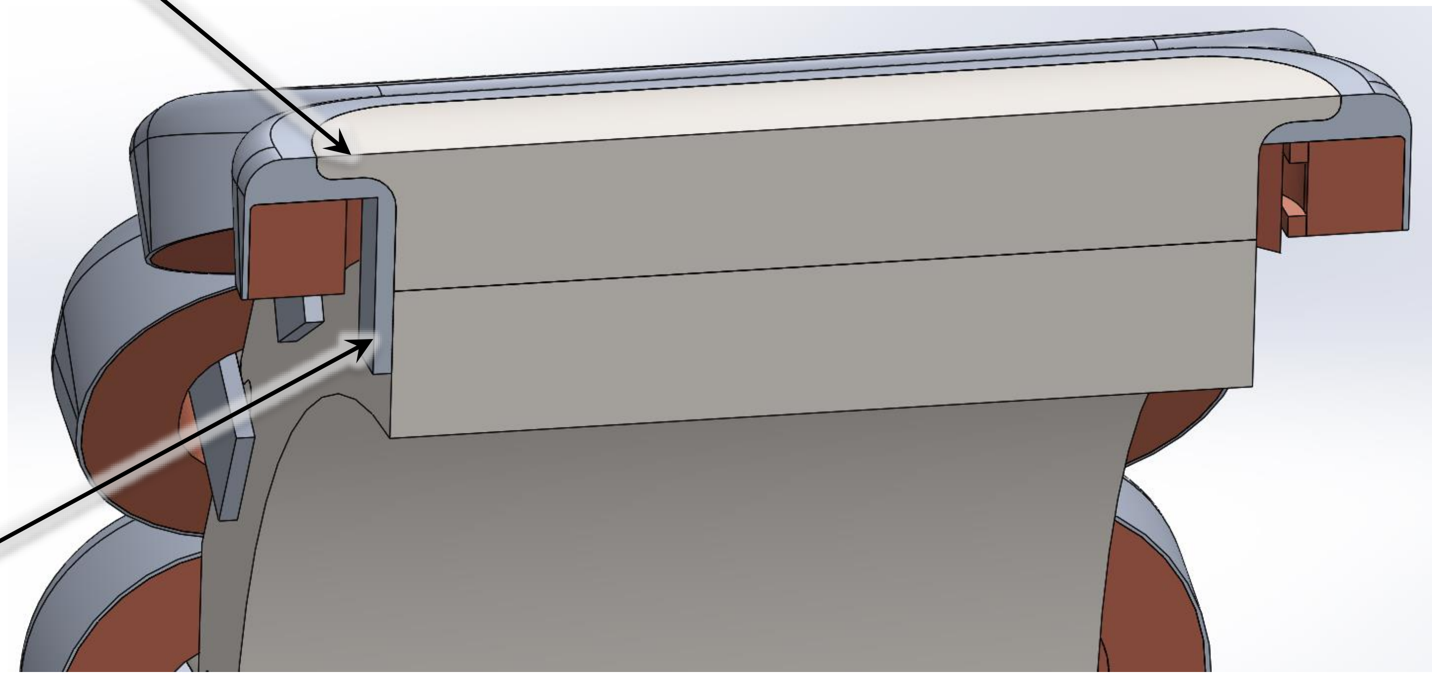
Preliminary design – double dovetail rotor teeth

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



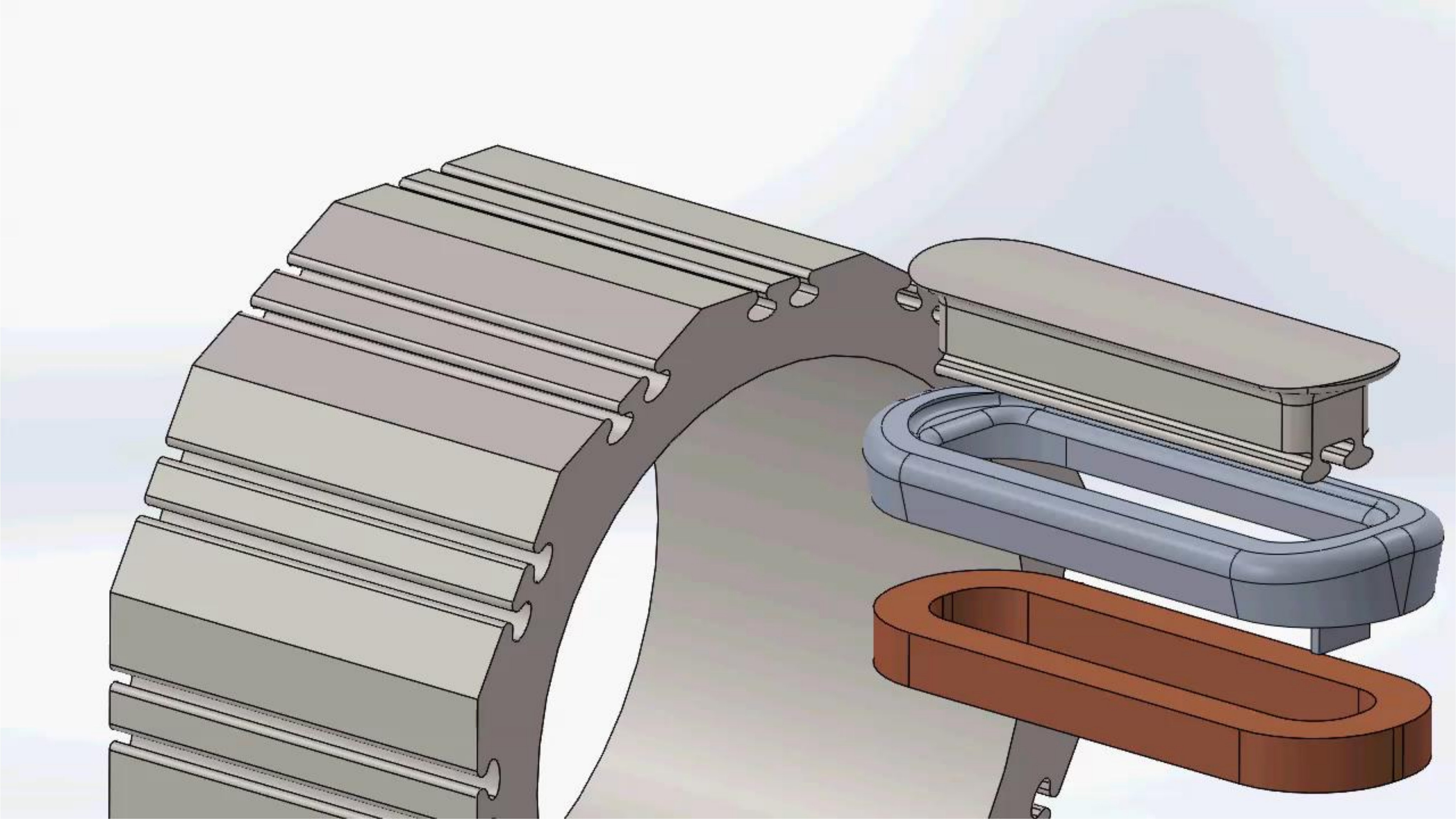
continuous shoulder

double dovetail

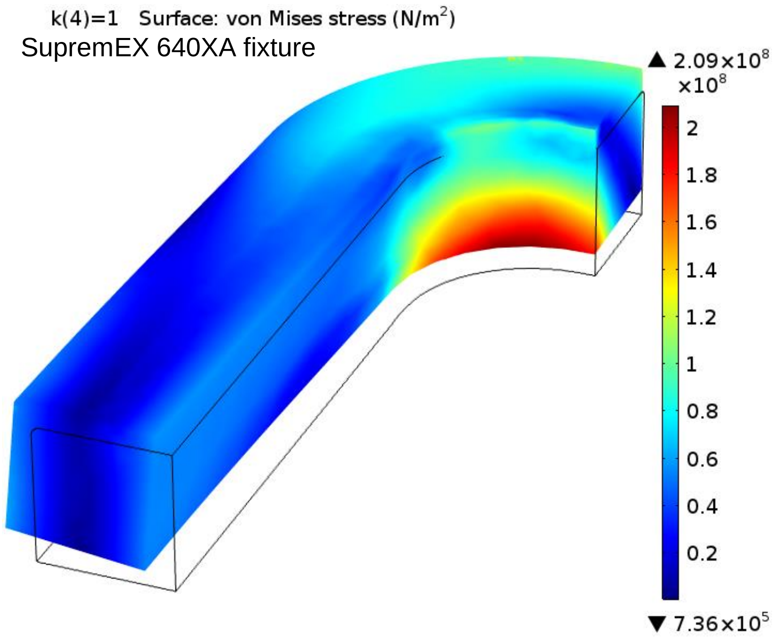


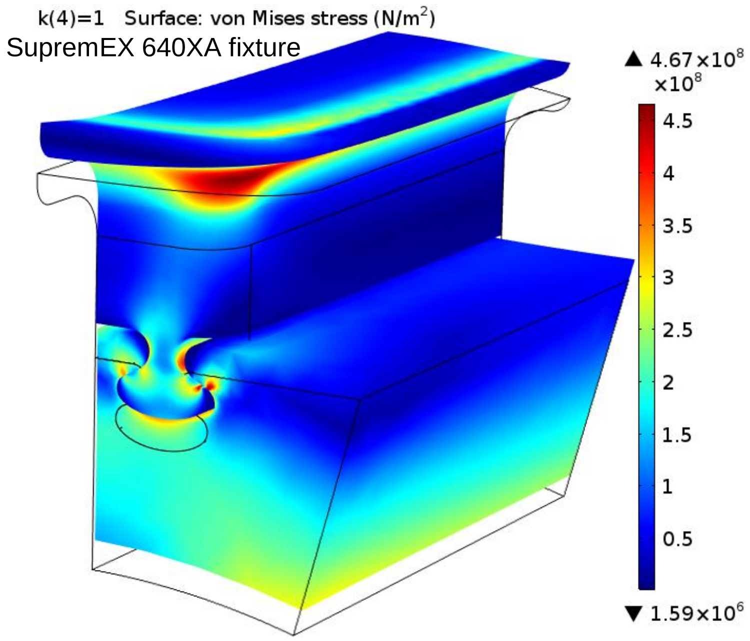
heat extraction tab

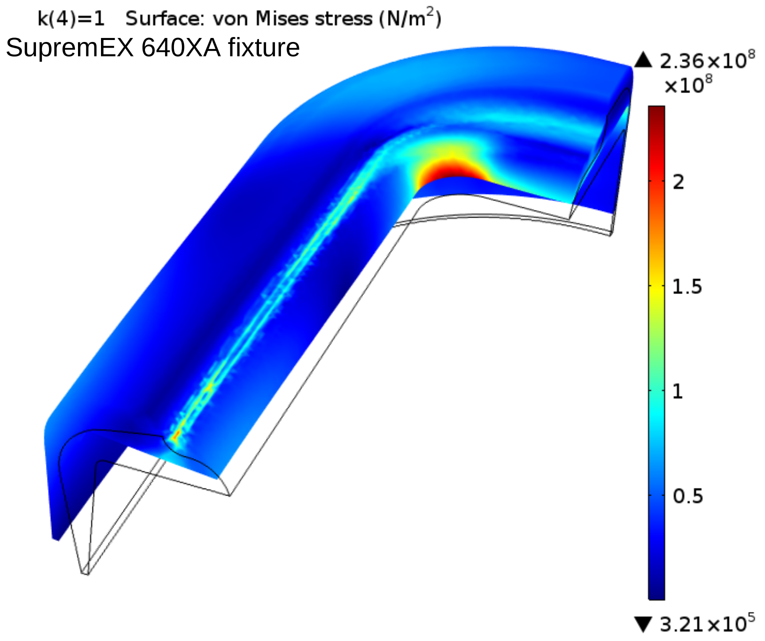
Assembly of the rotor



Preliminary design – stress analysis


SupremEX 640XA fixture


SupremEX 640XA fixture


SupremEX 640XA fixture

Fixture material	Superconductor			Hiperco 50 A			Fixture		
	'Failure' strength, MPa	Max von Mises stress, MPa	Margin	'Failure' strength, MPa	Max von Mises stress, MPa	Margin	'Failure' strength, MPa	Max von Mises stress, MPa	Margin
SiC	>550	183	2.01	694 (@ 77 K, approx.)	480	0.45	550	462	0.19
Sialon (SiN + Al2O3)		191	1.88		483	0.44	760	391	0.94
SupremEX 640XA (Al 6061 + SiC powder)		209	1.63		467	0.49	560	236	1.37
Ti-6Al-6V-2Sn		239	1.30		516	0.34	1210	338	2.58

Outline

- Electromagnetic design & optimization
  - Thermal requirements
  - Optimization of rotor coil’s geometry
  - Optimization of back iron geometry
- Rotor containment design & stress analysis
- Conclusions

Conclusions

- Uninsulated superconducting coils offer significant benefits, but are unproven in rotor applications

Electromagnetic design & optimization

- 2D FEA trends nearly mirror coil's A-turns until back iron is magnetically saturated
- Performance & performance per mass have opposite trends than performance per cost
- 3D FEA performance ~7% lower than 2D, but max flux density in coil approx. the same

Rotor containment design & stress analysis

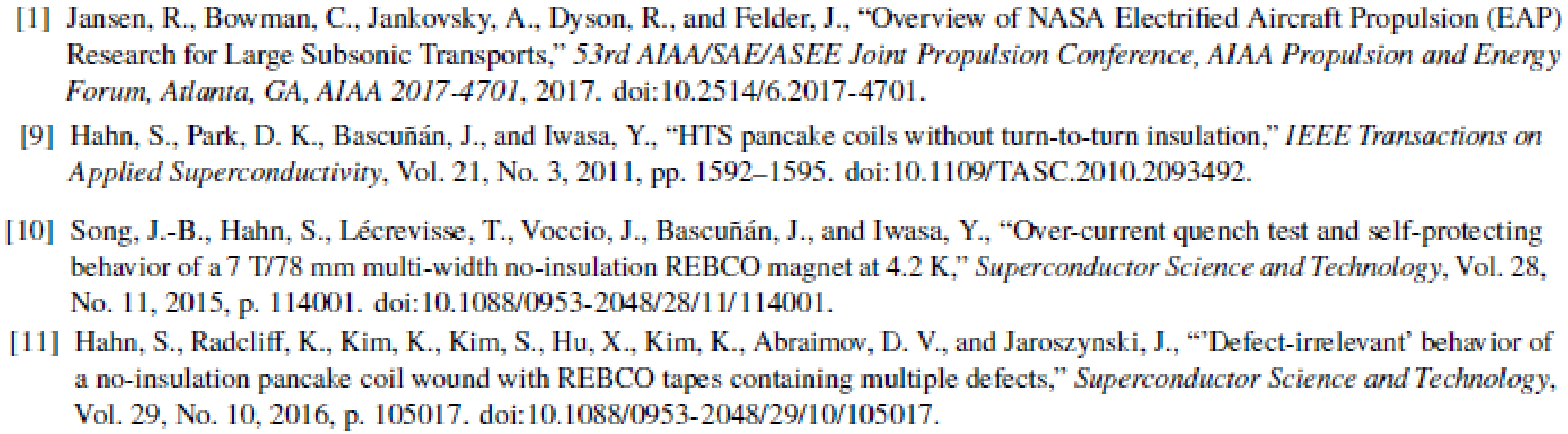
- Containment design is very challenging when pole count is relatively high & structure cannot reside in the air gap
- Double dovetail rotor teeth provide satisfactory stress margin, but may not have adequate thermal conductance

Considerable risks remain – further analysis & sub-scale testing is needed

Acknowledgements

- NASA Advanced Air Transport Technology (AATT) Project
  - Hybrid Gas-Electric Propulsion Sub-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.

[9] Hahn, S., Park, D. K., Bascuñán, J., and Iwasa, Y., "HTS pancake coils without turn-to-turn insulation," *IEEE Transactions on Applied Superconductivity*, Vol. 21, No. 3, 2011, pp. 1592–1595. doi:10.1109/TASC.2010.2093492.

[10] Song, J.-B., Hahn, S., Lécrevisse, T., Voccio, J., Bascuñán, J., and Iwasa, Y., "Over-current quench test and self-protecting behavior of a 7 T/78 mm multi-width no-insulation REBCO magnet at 4.2 K," *Superconductor Science and Technology*, Vol. 28, No. 11, 2015, p. 114001. doi:10.1088/0953-2048/28/11/114001.

[11] Hahn, S., Radcliff, K., Kim, K., Kim, S., Hu, X., Kim, K., Abraimov, D. V., and Jaroszynski, J., "'Defect-irrelevant' behavior of a no-insulation pancake coil wound with REBCO tapes containing multiple defects," *Superconductor Science and Technology*, Vol. 29, No. 10, 2016, p. 105017. doi:10.1088/0953-2048/29/10/105017.

QUESTIONS ?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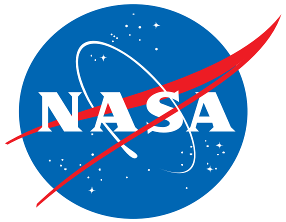
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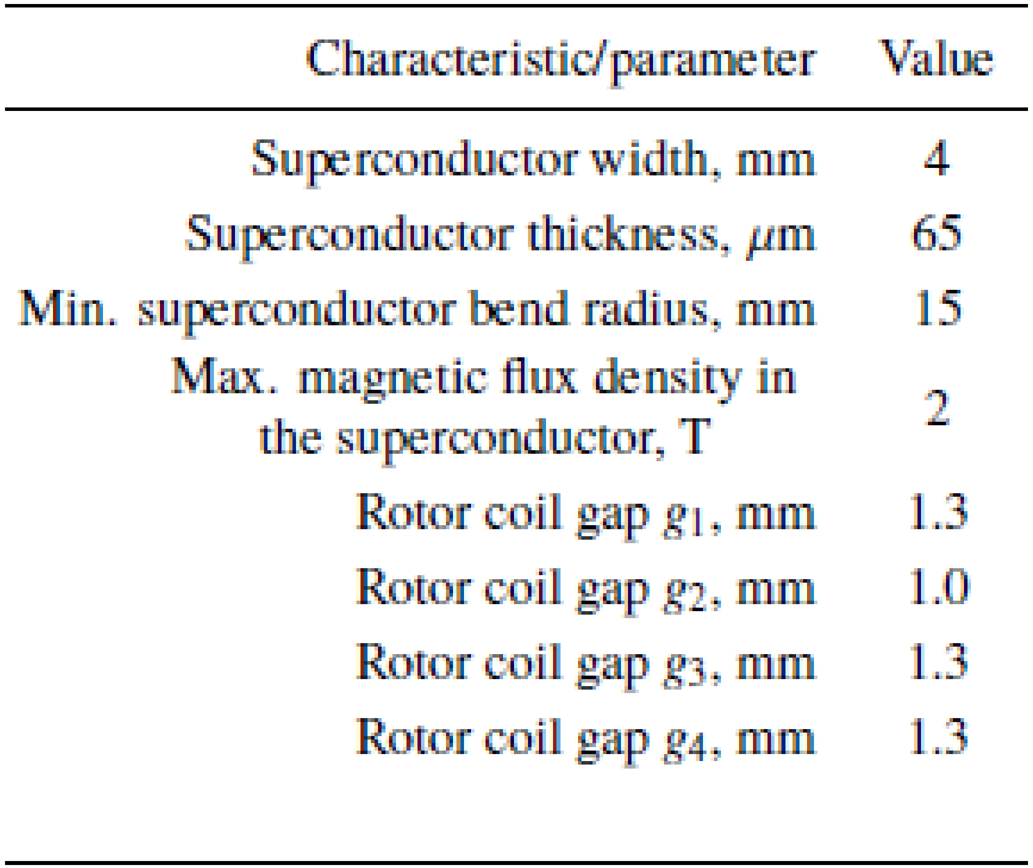
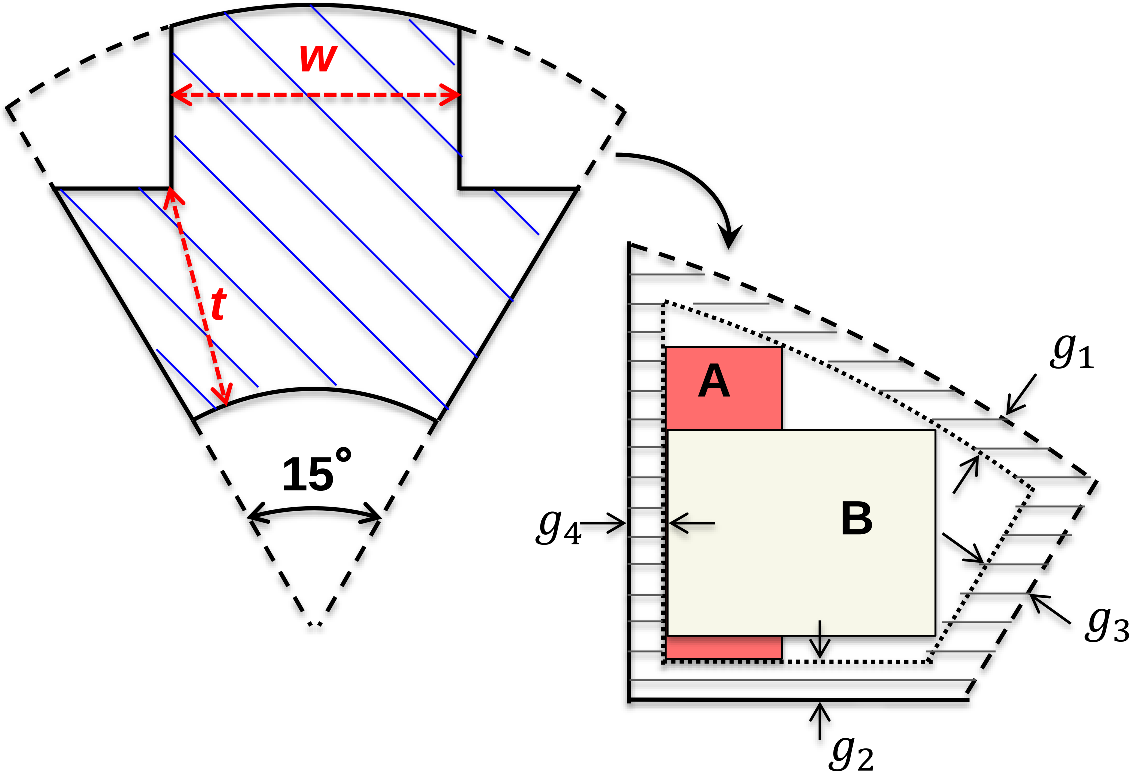
Rotor coil sizing study



Characteristic/parameter	Value
Superconductor width, mm	4
Superconductor thickness, μm	65
Min. superconductor bend radius, mm	15
Max. magnetic flux density in the superconductor, T	2
Rotor coil gap g_1, mm	1.3
Rotor coil gap g_2, mm	1.0
Rotor coil gap g_3, mm	1.3
Rotor coil gap g_4, mm	1.3



▨ Soft magnetic material (back iron)

▤ Region available for containment structure and clearances

Cryogenic yield strength of $Fe_{49}Co_{49}$

- [1] measured yield strength of $Fe_{49}Co_{49}V_2$ (Hiperco 50) at cryo temperatures for different grain sizes
- Yield strength increases by about 90% to 110% going from room temp to 77 K
  - Material is brittle at about 150 K and lower
- Effect of trace elements (Hiperco 50A vs 50 vs 50HS) is small [2]
- Thus, 'failure' strength for Hiperco can be increased by 90%

Material	Temp., K	'Failure' strength, MPa
Hiperco 50A after annealing	293	365
	77	694 (estimate)

1. Jordan, K. & Stoloff, N., Trans. Metal. Soc. AIME 245, p. 2027-2034, 1969.
2. Sourmail, T., Prog. Mater. Sci. 50(7), 2005. (doi: 10.1016/j.pmatsci.2005.04.001)