Methodology for electromagnetic optimization of a partially superconducting 1.4 MW electric machine for electrified aircraft propulsion

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Motivation

- Enable **reduced energy consumption, emissions, and noise of commercial transport aircraft** via electrified aircraft propulsion
- NASA’s High-Efficiency Megawatt Motor (HEMM) sized as generator for NASA’s STARC-ABL concept

Performance impact of HEMM

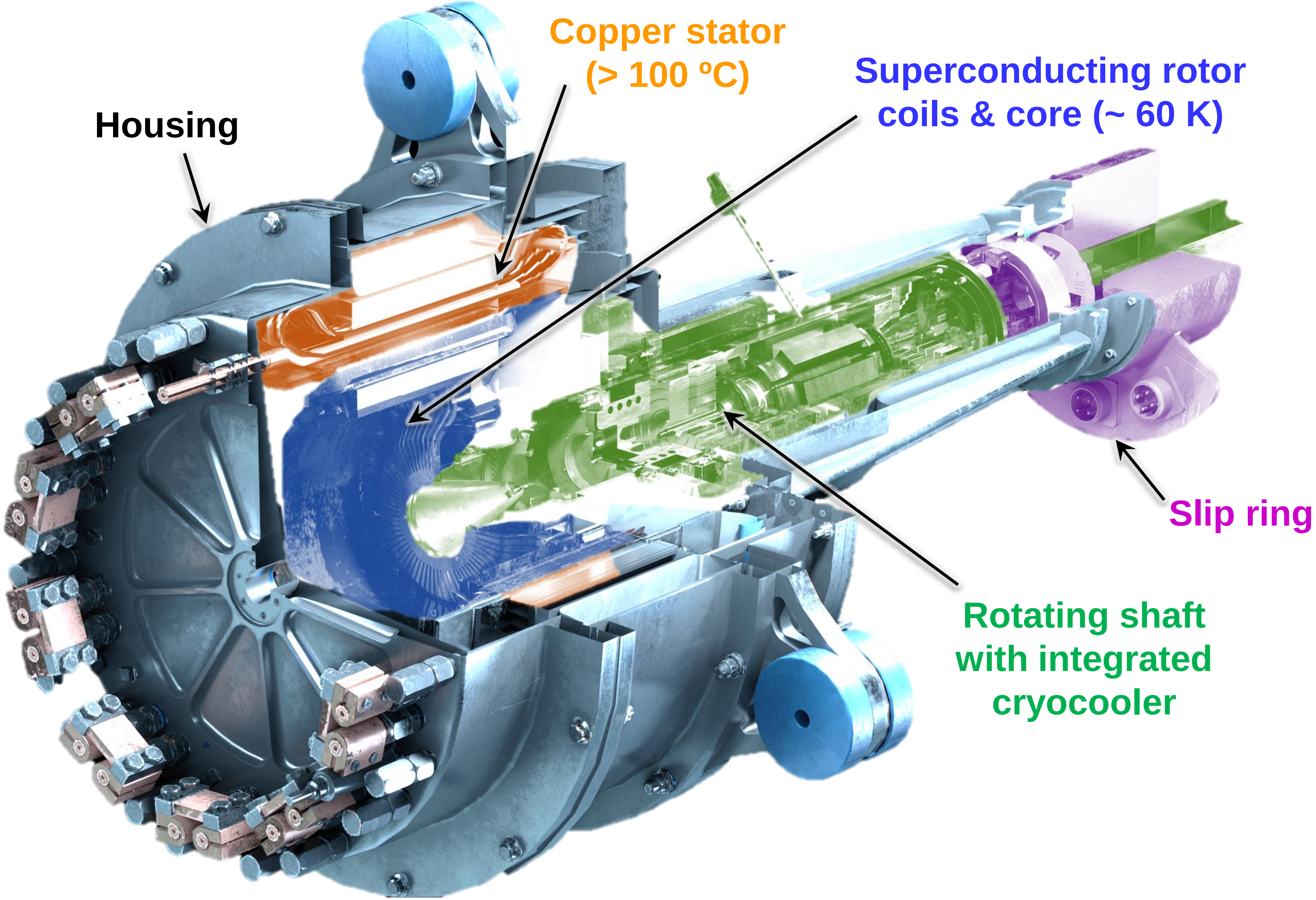
Refined assessment [1] (higher fidelity power system & thermal management)	Fuel burn with HEMM + advanced power electronics	Baseline
	–2.5% to –2.8%	Refined STARC-ABL rev. B2.0

1. Schnulo, S.L. et al., Proc. of EATS, 2020.

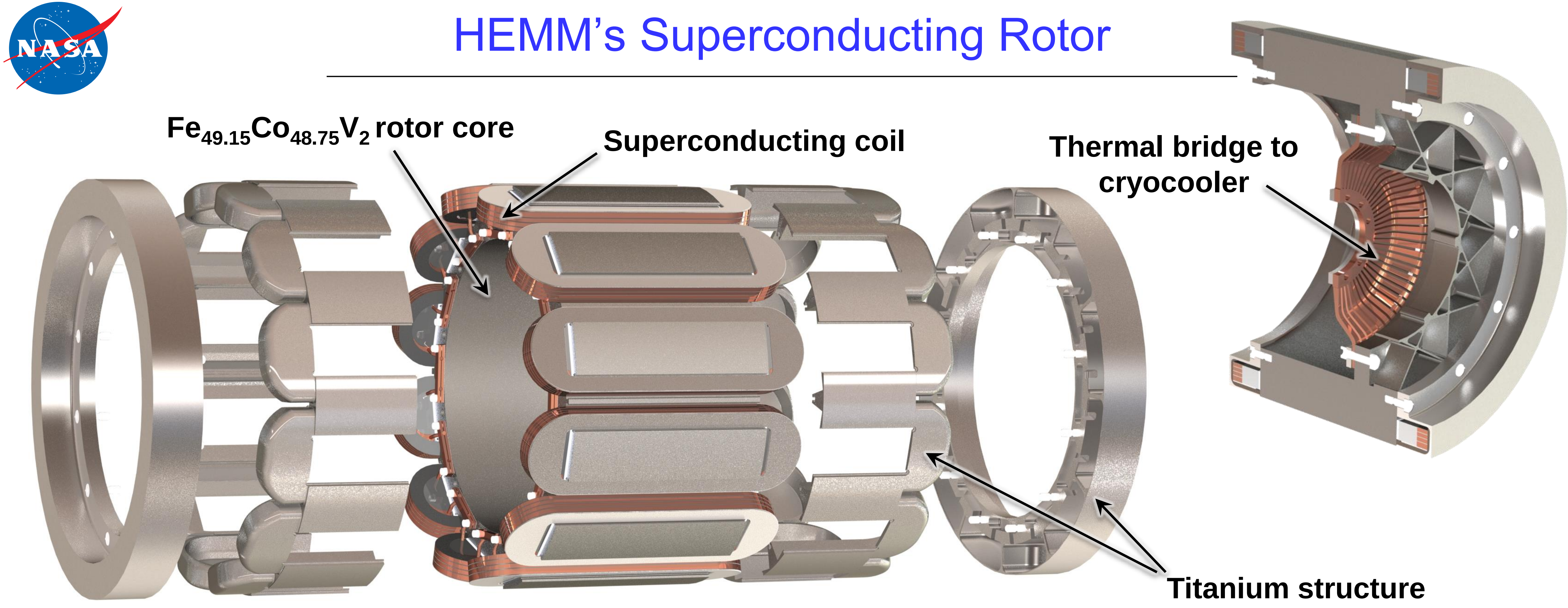
NASA's High-Efficiency Megawatt Motor (HEMM)

Parameter	Value
Rated continuous power	1.42 MW
Nominal speed	6,800 rpm
Tip speed	107 m/s (Mach 0.31)
Rated torque	2 kNm

Goal	Value
Electromagnetic specific power	16 kW/kg
Efficiency	> 98%



HEMM’s Superconducting Rotor



$Fe_{49.15}Co_{48.75}V_2$ rotor core

Superconducting coil

Thermal bridge to cryocooler

Titanium structure

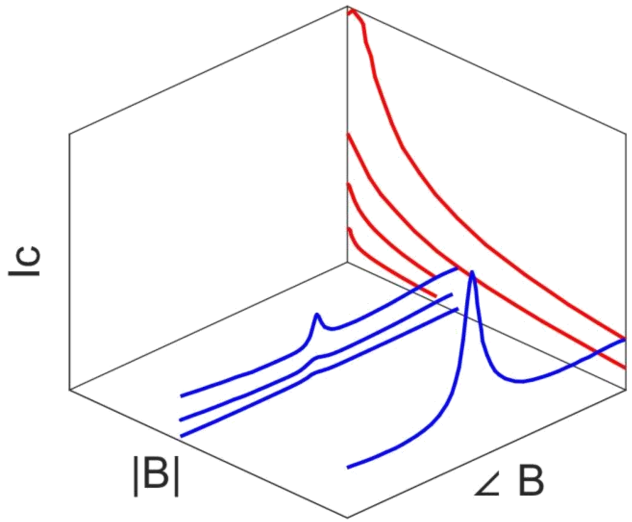
Parameter	Value
# poles (coils)	12
Superconductor	2G HTS

Parameter	Value
Coil configuration	No-insulation quadruple pancake
DC current	≤ 75 A

Critical Current Prediction

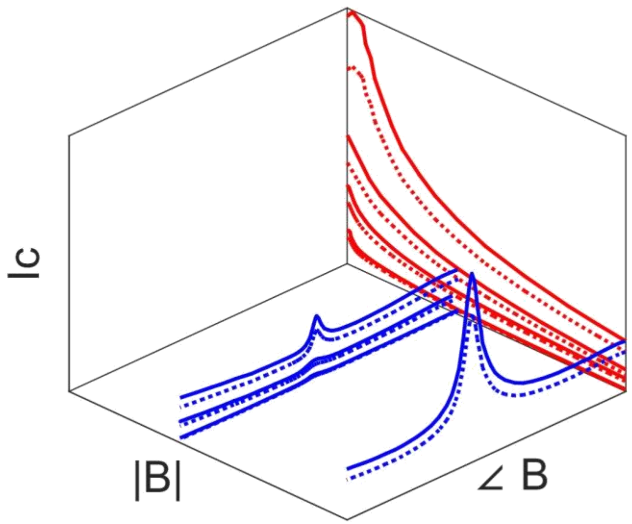
- Limited data at high T, low B
- Observation from larger data set at low T, high B:
  - At a given T, θ-dependent data relative to value at $\theta = 0$ is fairly constant over $|B|$

Manufacturer data



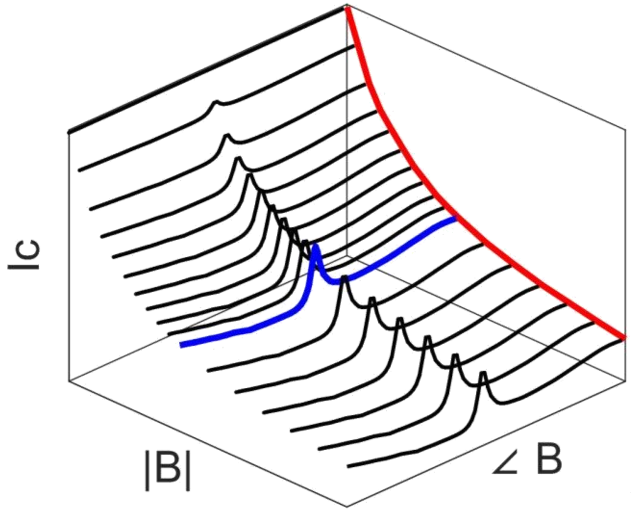
$|B|$-dependent data extrapolated

Data scaled to desired $I_C(77\mathrm{K, s.f.})$



Create $|B|$-dependent curves

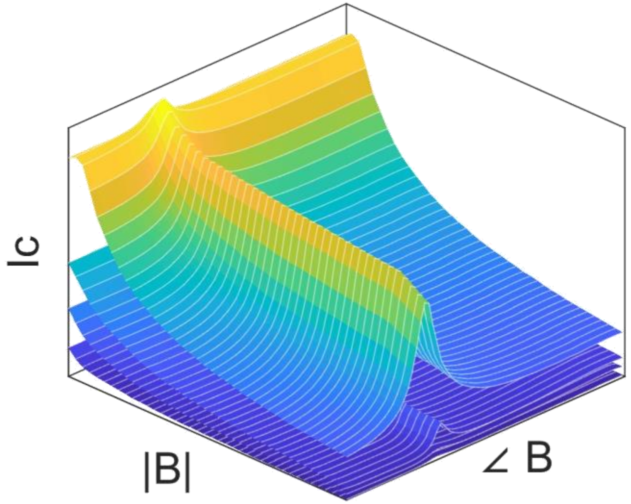
Relative $I_c(\angle B)$ decays to 0 with $|B|$



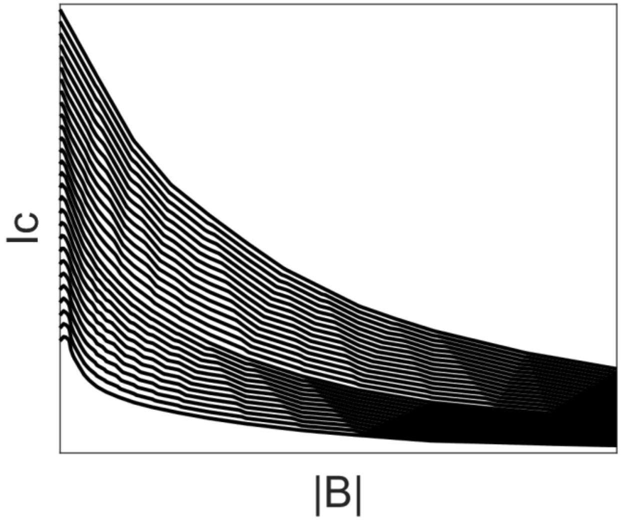
Create linear interpolation functions

Interpolation functions

$I_c = I_c(T, |B|, \angle B)$

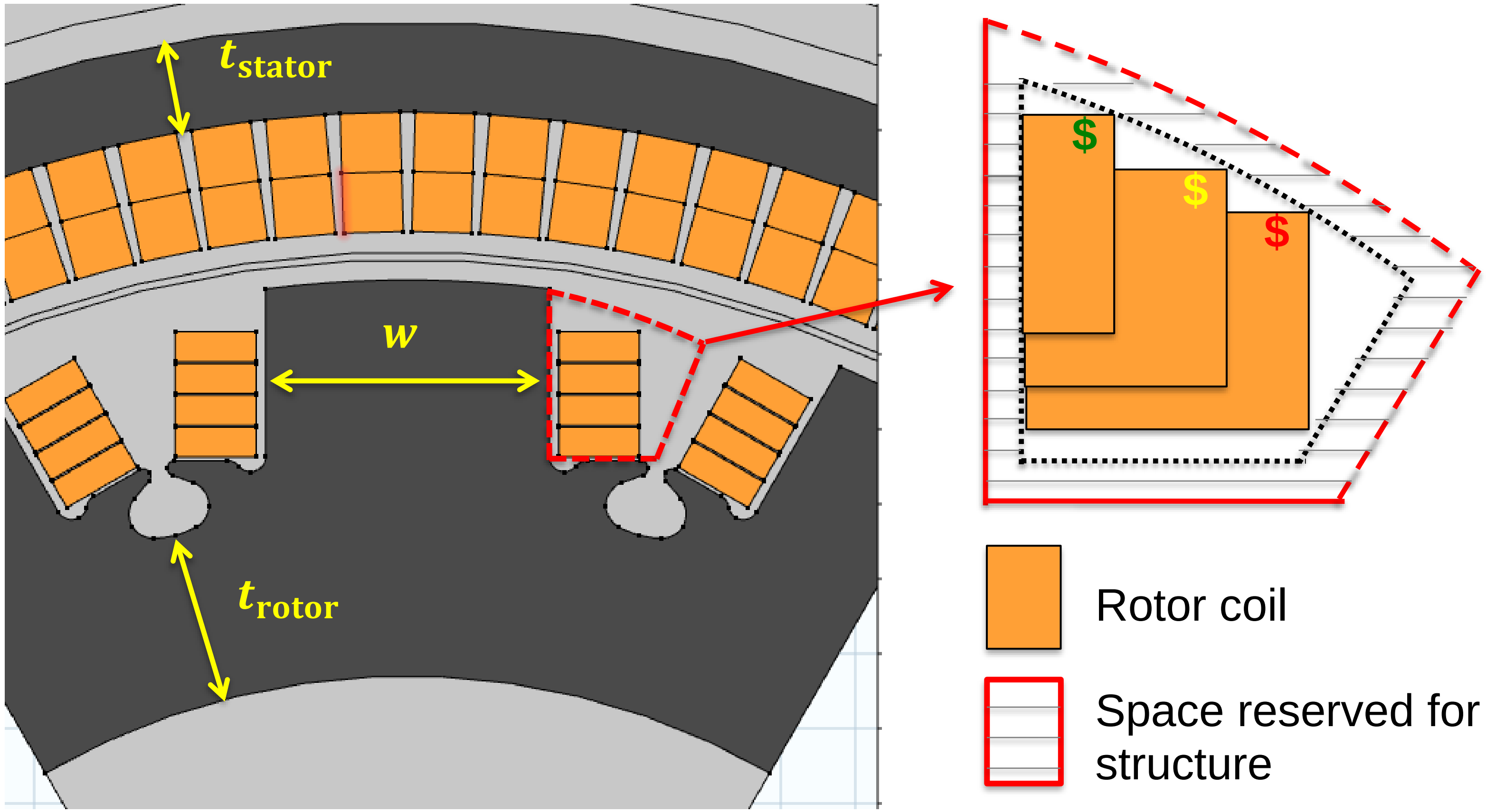


$I_{c,\,\mathrm{min}} = I_c(T, |B|)$



Geometry & Independent Variables

- 4 layer coil
  - Prior analysis: 4 optimal for even # of layers
  - Odd # of layers not considered (current lead on exterior of coil)
- # of turns maximized subject to geometry & cost constraints
- 0.75 mm spacing between pancake coils (for epoxy & separating plate)



Other Assumptions

↑ More optimistic

↓ More conservative

Assumption	Impact	
90° load angle	**Optimistic**	Calculated torque is peak, not operating
$I_{\text{op}} = 67\% \cdot I_c$ (1.5 safety factor)	**Optimistic**	Modest but not large margin
2D model	**Optimistic**	Overpredicts torque
Uniform temperature in superconductor	**Small**	Simulated ΔT = 0.4 K
Nominal thickness of superconductor	**Small**	Fewer or more turns in coil
Sinusoidal stator current	**Small**	Calculating nominal response
Current uniform in rotor coils	**Small**	Slightly inaccurate magnetic loading in coil
Room temperature B-H response for back iron	**Small**	Underpredicts saturation induction
$I_c(77\ K, s.f.) = 150\ \text{A}$	**Conservative**	Rotor current lower
Only 4 mm wide superconductor	**Conservative**	Coils larger & heavier
Superconductor cost = $60/m	**Conservative**	Smaller limit on turns in coil
Rotor coil fill factor = 90%	**Conservative**	Fewer turns in coil

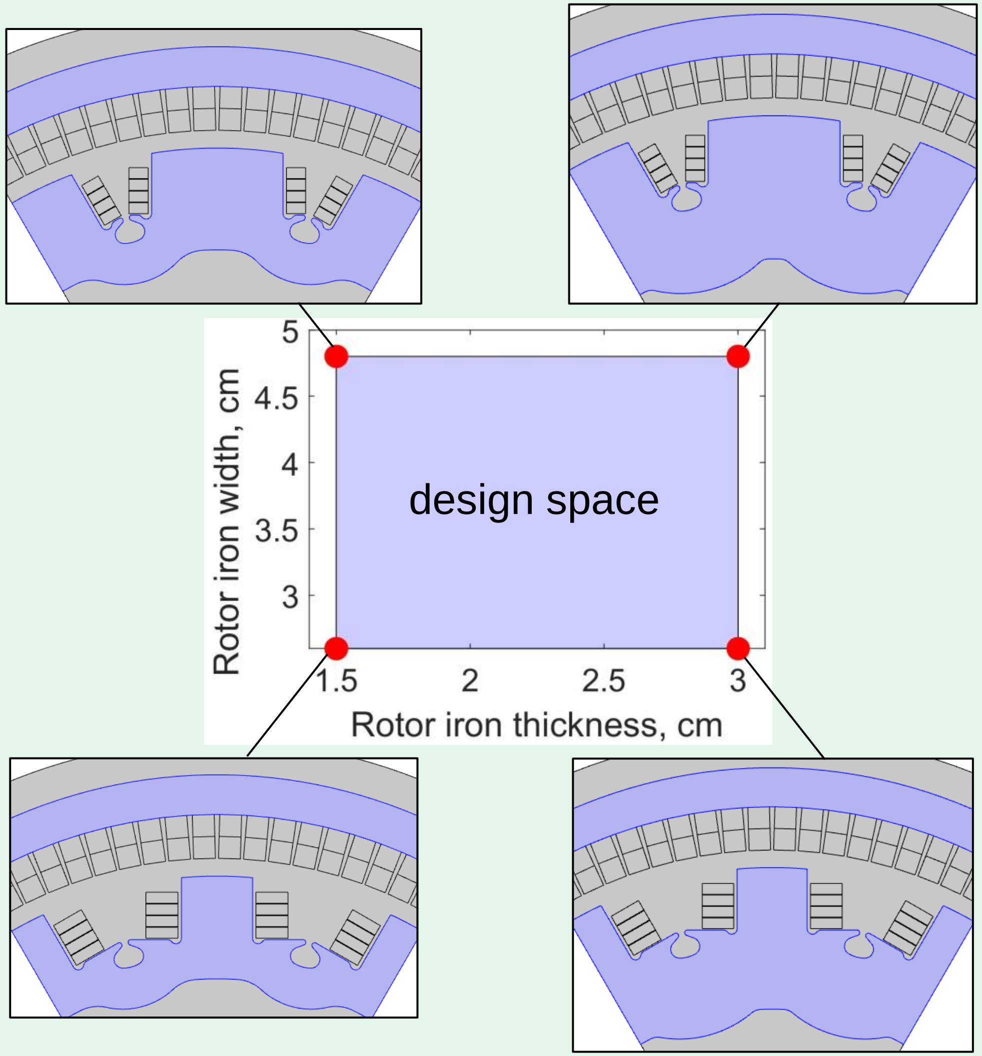
Constraints

Parameter	Constraint	Comment
Rotor diameter	300 mm	
Rotor axial length	≤ 150 mm	Limit for solid billet of rotor core material ($Fe_{49.15}Co_{48.75}V_2$)
Total cost of superconductor	≤ $200k	
Stator teeth	No teeth allowed	Creates unacceptable eddy current loss (cryocooler lift approx. 50 W at 50 K)
Stator coils	2 turns of 8 mm x 8 mm Litz wire (40 AWG Cu)	

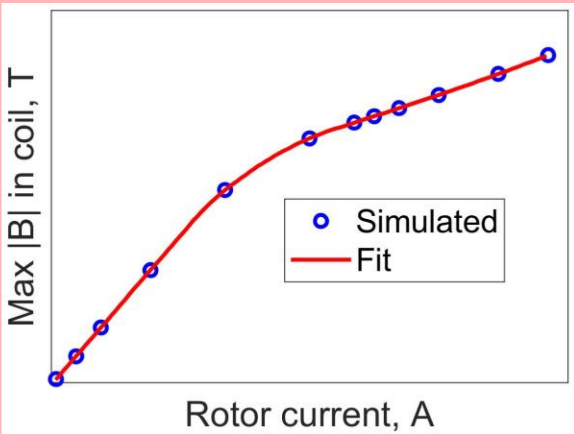
Simulation Steps

Constrained parametric study OR genetic optimization

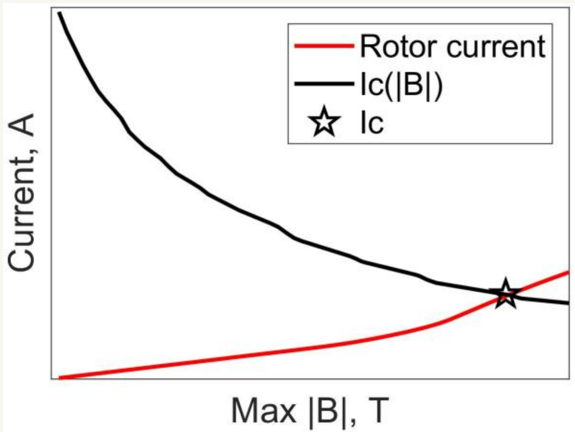
Define geometry



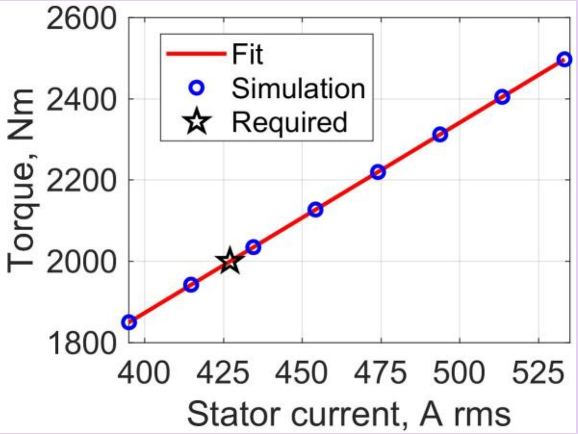
Sweep rotor current



Find max rotor current



Sweep stator current



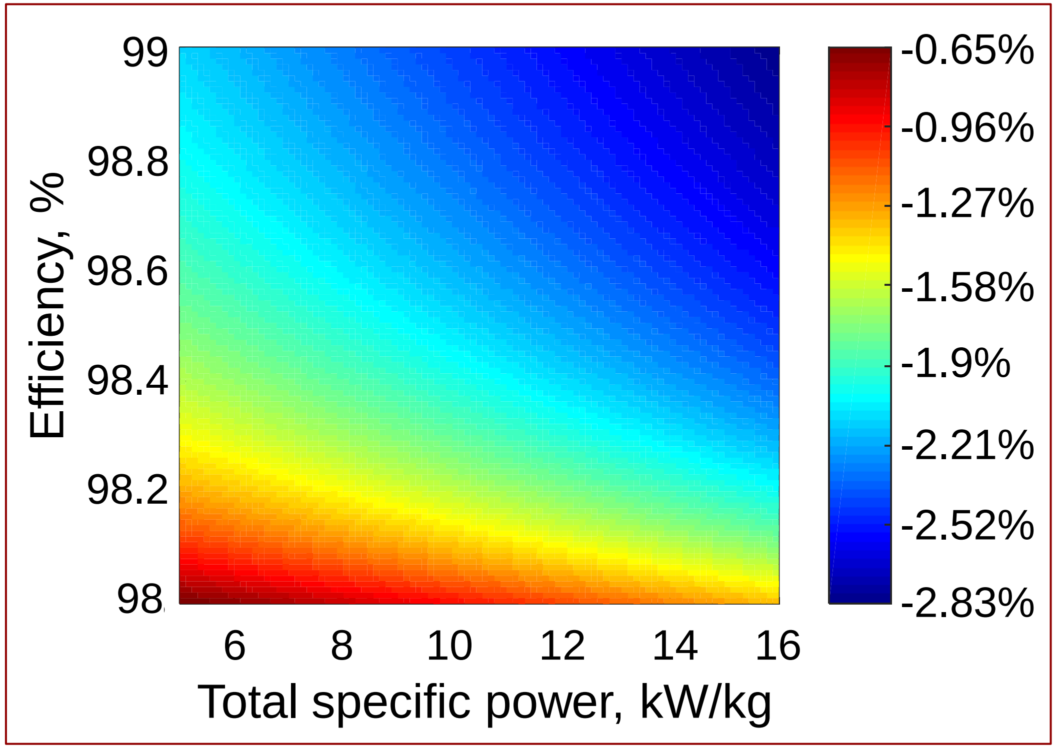
Solve with max I_{rotor} & required I_{stator}

Calculate performance metrics

Performance Metrics & Margins

- ***Specific power:***
  - $\frac{\text{Torque} * \text{Speed}}{\text{Mass}} = \frac{1.424\text{ MW}}{\text{m}_{\text{mech (est.)}} + (m_{\text{back iron}} + m_{\text{coils}})}$
  - Coil mass includes end turns, epoxy, realistic winding path, & measured mass/length of Litz wire
  - Estimated mechanical mass: 65 kg to 100 kg
- ***Efficiency***
  - Electromagnetic, bearings, vacuum seals, cryocooler
- Approximate ***fuel burn change*** of STARC-ABL
  - Based on Breguet range equation & propulsion system parameters from [1-3]
  - Matched calculation to STARC-ABL Rev B2.0 results [4]

Change in fuel burn relative to STARC-ABL rev B2.0



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1. Jansen, R.H. et al., Proc. AIAA Propulsion and Energy Forum, 10-12 July, 2017.
2. Welstead, J.R. and Felder, J.L., Proc. AIAA SciTech, 4-8 January, 2016.
3. Welstead, J.R. et al., One Boeing NASA Electric Aircraft Workshop, Washington, DC, 22 March, 2017.
4. Bowman, C.L. et al., Proc. AIAA/IEEE Electric Aircraft Technologies Symposium, 12-13 July, 2018.

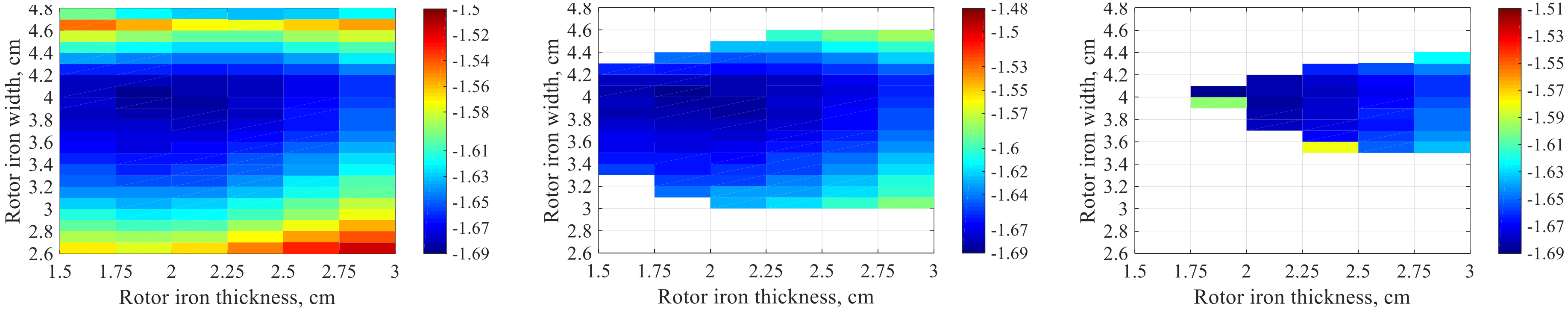
Parametric Study Results

Results

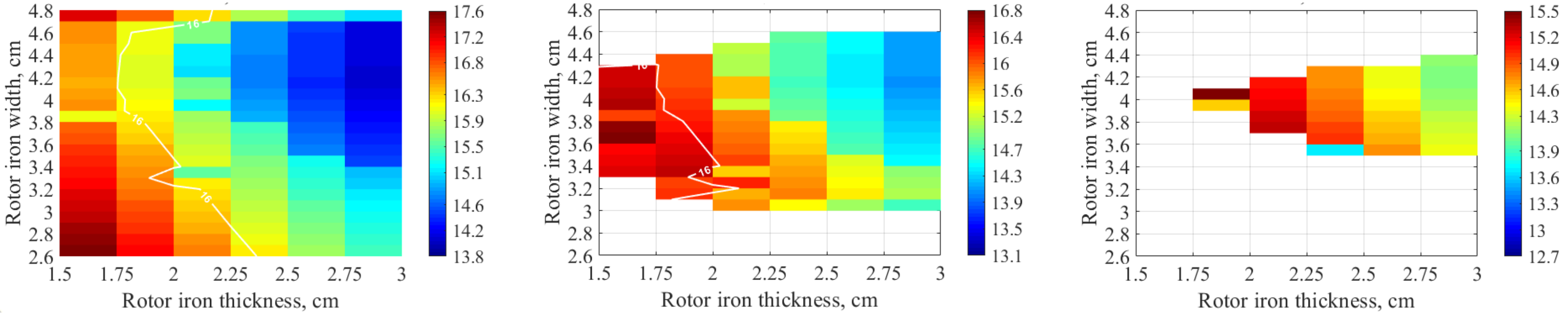
- Each data point is for stator iron thickness that maximizes fuel burn benefit
- ***Need > 425 A RMS stator current to meet specific power goal***

No stator current limit | **450 A RMS max in stator** | **425 A RMS max in stator**

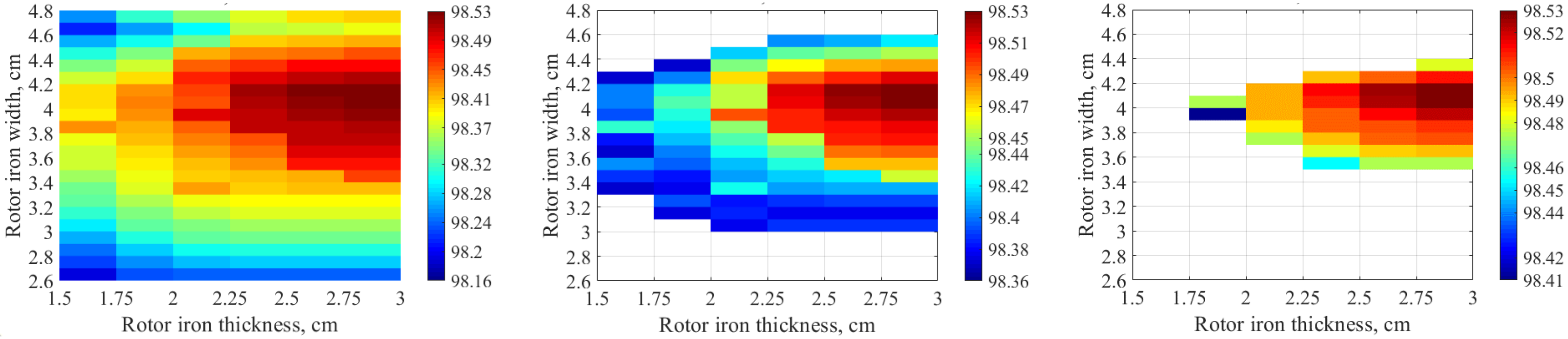
Fuel burn change, % (lower bound) with 20% loss & 10% EM mass margins



EM specific power, kW/kg with 10% margin



Efficiency, % with 20% margin on total loss

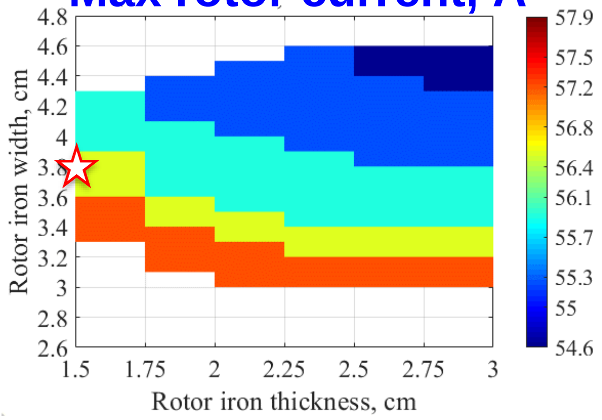


Parametric Study Results

Results

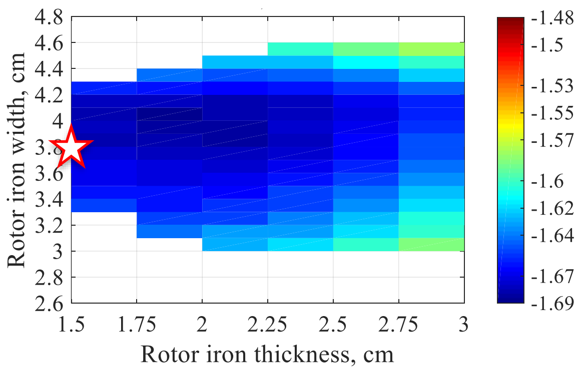
- Results shown for 450 A stator current limit
- Each data point is for stator iron thickness that maximizes fuel burn
- Max rotor current varies little
- Selected a design with near minimal fuel burn, max specific power, and lower current (☆ on plots)

Max rotor current, A

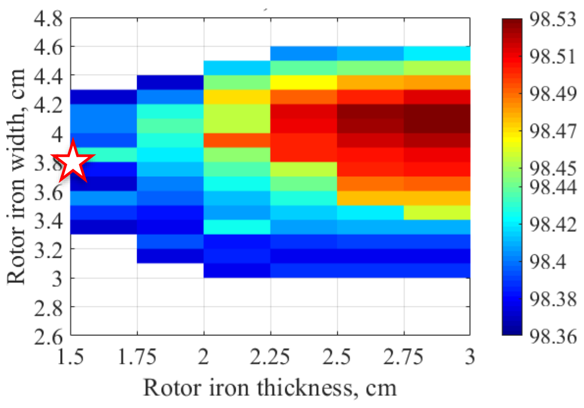


Performance metrics with margins

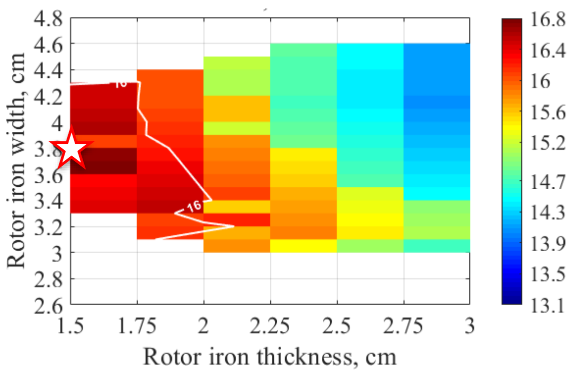
Fuel burn change, %



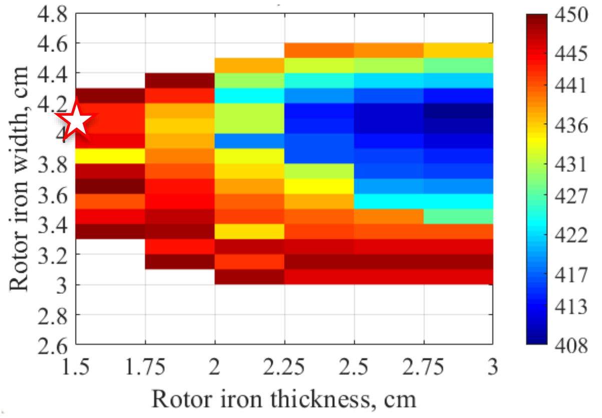
Efficiency, %



EM specific power, kW/kg



Req'd stator current (A RMS)



Design Refinement: Consider Narrower Tape

- **Opportunity:** reduce mass & cost by replacing less excited coil layers with 3 mm wide conductor
  - Rotor coil mass reduction directly reduces dominant load (centrifugal) on structural parts
- **Outcome for HEMM design:** 3 mm tape for all but top coil layer

Approximate mass reduction

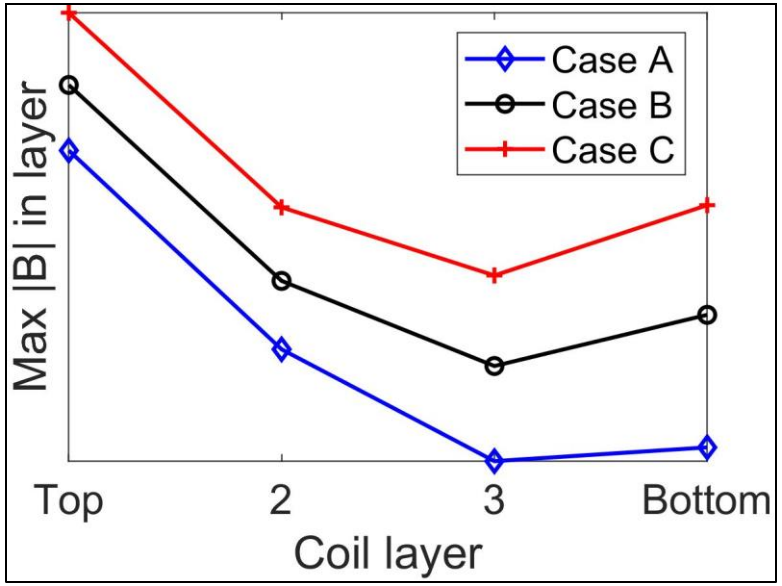
	Replace 2 layers	Replace 3 layers
Total electromagnetic	2.4% (1.94 kg)	3.6% (2.92 kg)
rotor iron	2.5% (0.86 kg)	3.7% (1.30 kg)
rotor coils	11% (1.08 kg)	16% (1.62 kg)

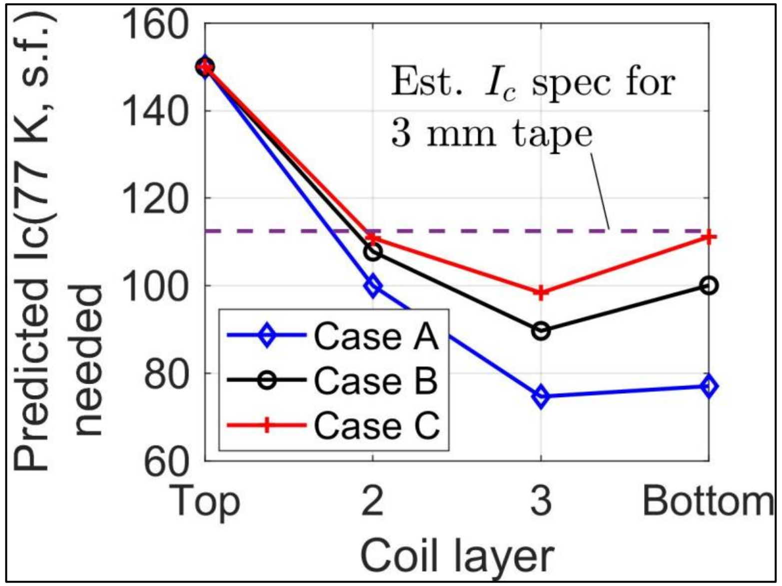
Case A – **Nominal case**

Case B – **Demanding case** (slip ring-limited current [75 A], nominal # turns)

Case C – **Most demanding case** (slip ring-limited current [75 A], max # turns)

Predicted I_c required for each coil layer

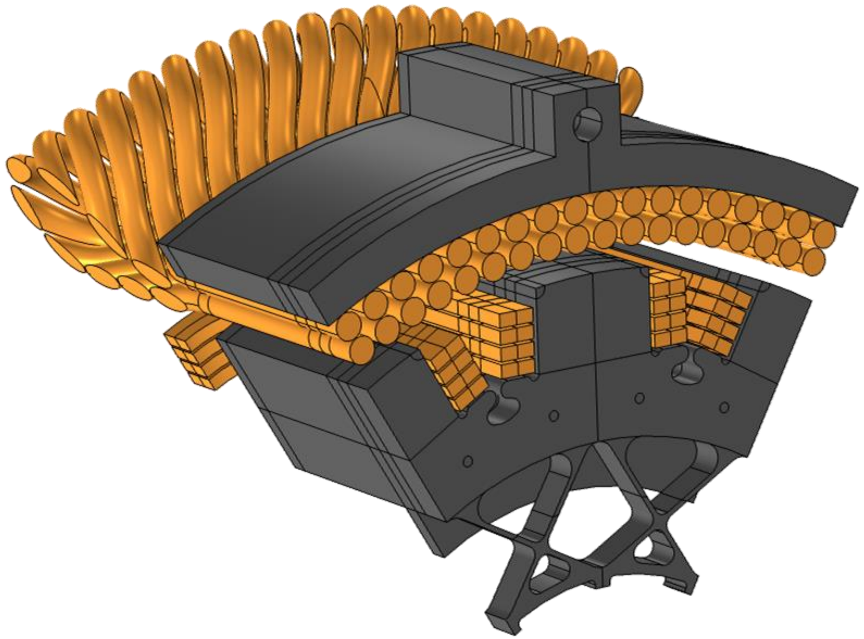




Design Refinement: 3D Electromagnetic Response

Impact on torque

- Thermal bridge & torque transfer webbing add only 0.4% to torque
- **Unanticipated result:** torque from 3D model 7.3% higher than from 2D model

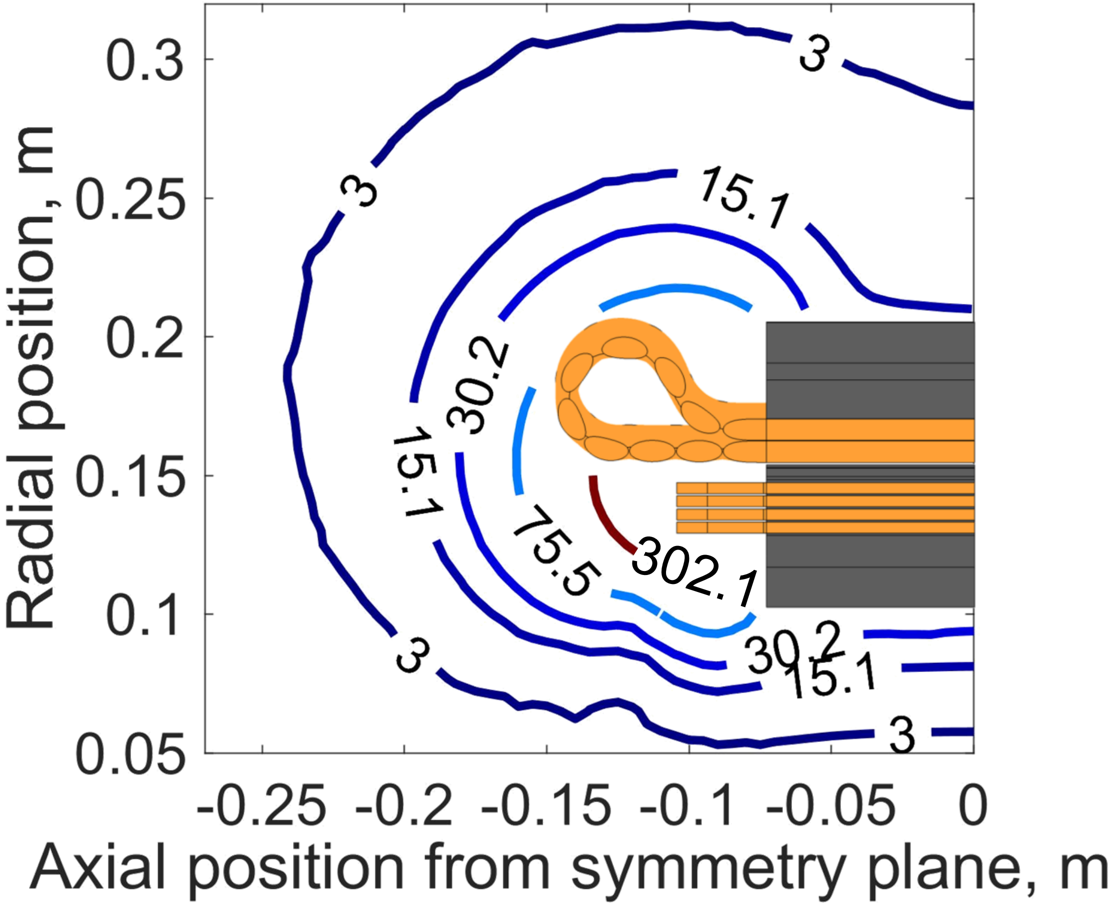


Take benefit to torque		Take benefit to thermal		Take benefit to size, mass
Specific power +7.3%	OR	Stator current –7.1%	OR	Stack length –7.3%
Efficiency +0.10%		Efficiency +0.10%		Mass –6.3%
				Specific power +2.8% to +3.5%

Design Refinement: 3D Electromagnetic Response

Impact on eddy current losses in housing / stationary components

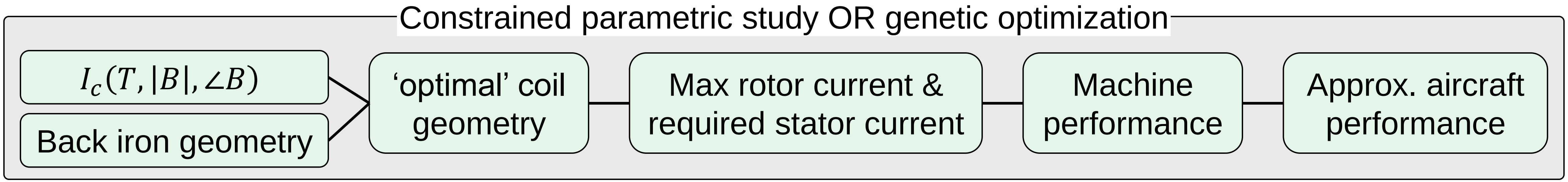
- Electrical fundamental frequency of HEMM: $f_{\mathrm{elec}} = 680\ Hz$



Contour level, T/s	Equivalent amplitude of electrical fundamental $(\sin(2\pi f_{\mathrm{elec}}t))$, T
3	0.001
15.1	0.005
30.2	0.01
75.5	0.025
302.1	0.1

Conclusions

- Developed design methodology to optimize the electromagnetic design of partially superconducting electric machines



Constrained parametric study OR genetic optimization

$I_c(T, |B|, \angle B)$

Back iron geometry

'optimal' coil geometry

Max rotor current & required stator current

Machine performance

Approx. aircraft performance

- Results for HEMM design demonstrate…
  - Ability to achieve performance goals with 10% electromagnetic mass & 20% loss margins
  - Impact of stator current limit
  - Relative importance of efficiency and specific power on fuel burn,
- Selected design refined using detailed analysis
  - Consideration of narrower conductor
  - 3D electromagnetic response – impact on torque & eddy current losses in housing
  - Impact of stator current harmonics from inverter on eddy current losses in rotor [1]

1. Granger, M. et al., "Combined Analysis of NASA's High Efficiency Megawatt Motor and Its Converter", In Proc. of EATS, 2021.

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THANK YOU


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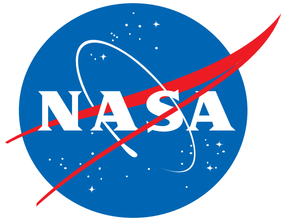
FOR THE BENEFIT OF ALL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Efficiency Prediction

Loss component		Source	Value, kW	Inputs / Assumptions
Electromagnetic	Stator winding (I^2R)	Analytical calculation	Varies	• Copper resistivity from NIST @ coil’s average temperature limit (135 C) • Total length of wire from realistic CAD model with optimal length end turns
	Stator core	Magnetic FEA + numerical calculation (improved generalized Steinmetz equation)	Varies	• Core loss material properties from manufacturer • Rotational speed • Geometry
	Rotor core		Varies	
	Rotor coils		Varies	• Copper resistivity from NIST @ coil’s average temperature (stator: 135 C; rotor: 62 K) • Wire & bundle geometry
	Stator winding proximity	Magnetic FEA + analytical calculation	Varies	
Other	Cryocooler power	HEMM allowable	2	
	Bearings		1	
	Vacuum seals		1	