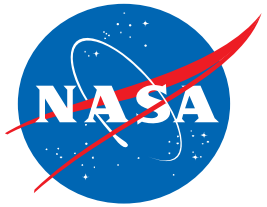
Helmholtz motor: a novel electric machine that enables high temperature superconducting armatures

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Motivation

Enable more fuel-efficient air transportation and advanced engine cycles
via electrified propulsion systems

- **Economic benefits:** reduced fuel consumption ▪ decreased energy costs & increased cost stability ▪ abundant domestic supply ▪ U.S. export advantage ▪ shared fuel infrastructure across transportation sectors
- **Societal benefits:** global access to air travel can continue to grow
- **Environmental benefits:** reduced emissions ▪ pathway to fully renewable production
- High-power electrification focused on single- and twin-aisle aircraft (~150+ passengers)

Advanced electric machines are needed to achieve the promise of electrified aircraft propulsion
HTS use in armatures can enable high performance at temperatures > 40 K

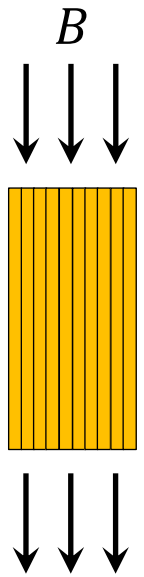
HTS = high temperature superconducting tapes

Working Principle

- The Helmholtz machine (*patent pending*) optimizes the magnetic excitation on the HTS armature winding to minimize AC loss

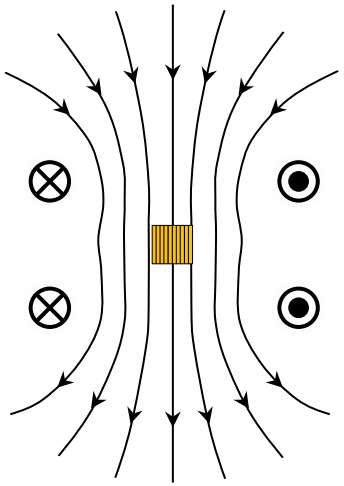
Goal

Align external magnetic field applied to the armature with the plane of REBCO film

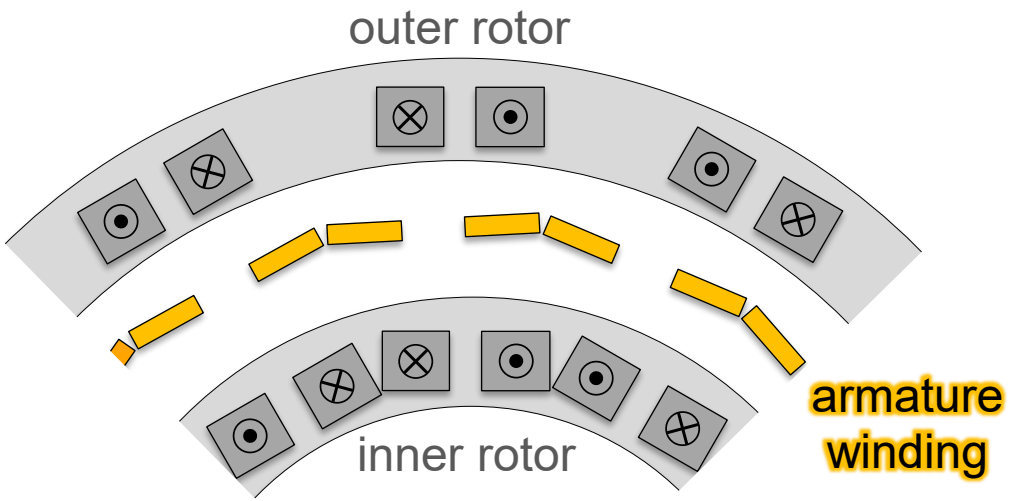


Approach

Use a collection of Helmholtz coils



single Helmholtz coil



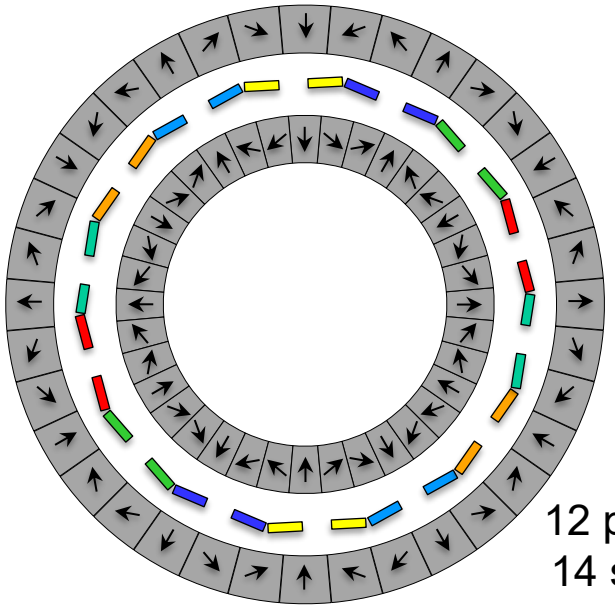
Construction

- Variants: radial flux or axial flux · permanent magnet rotors or electromagnet rotors
  - Likely only concentrated HTS armature winding

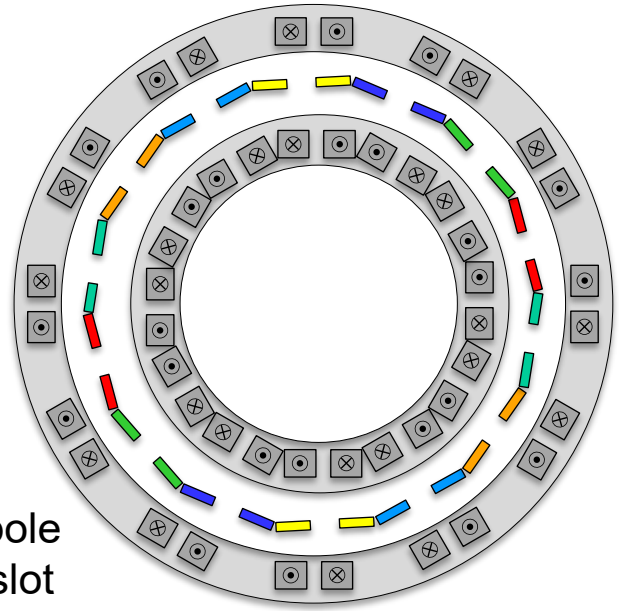
Cross sections of example radial flux Helmholtz machine

Radial-circumferential section

permanent magnet rotors

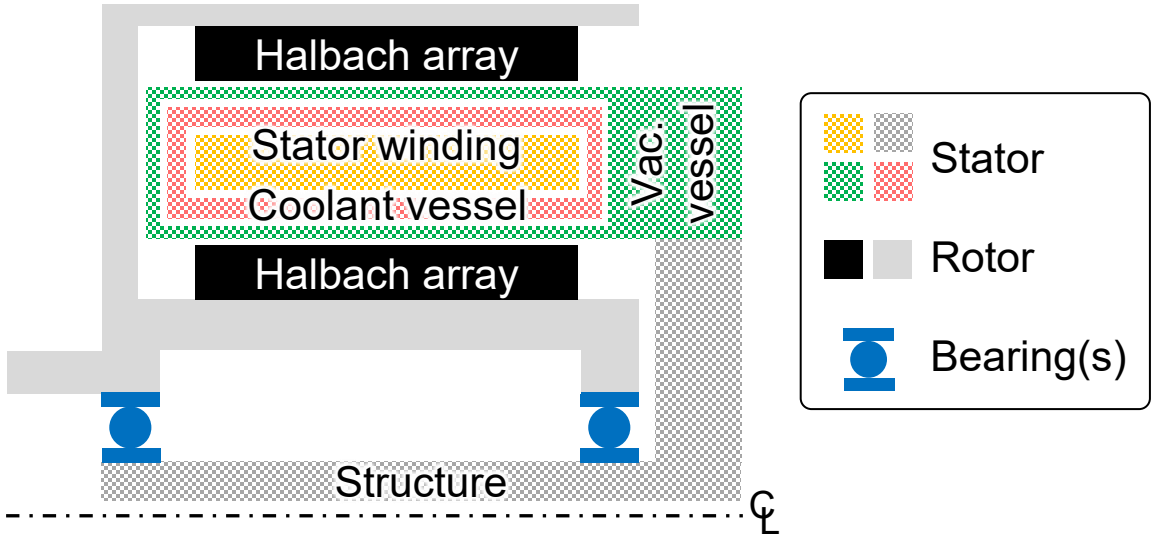


electromagnet rotors



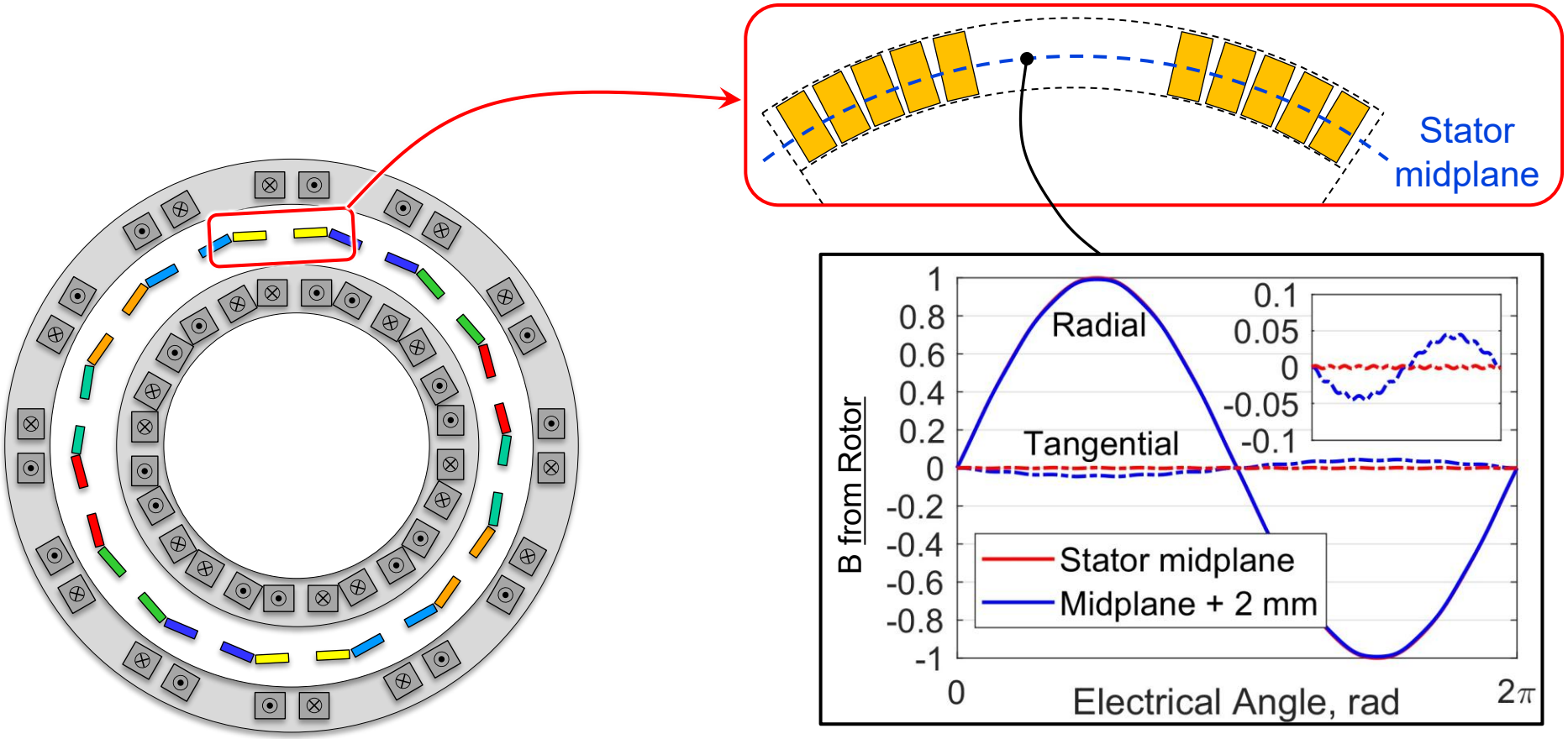
12 pole
14 slot

Axial-radial section



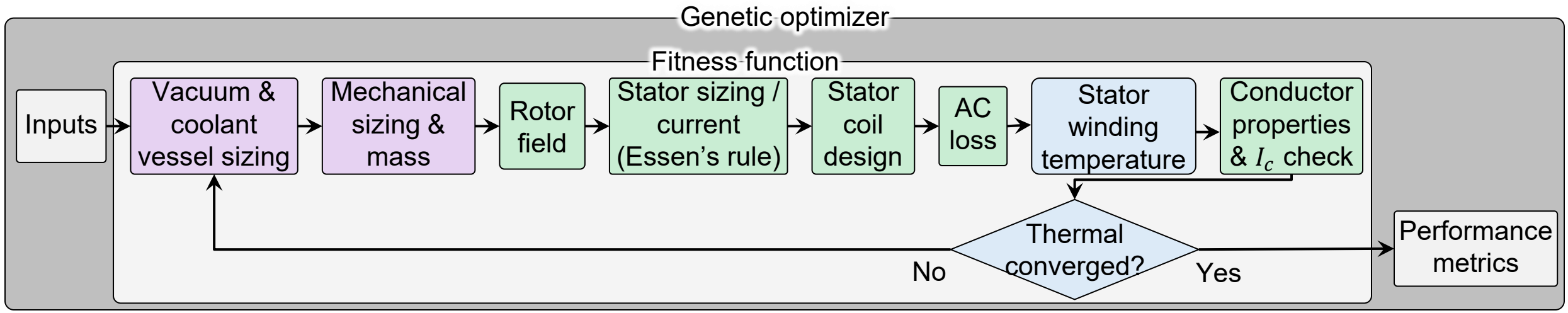
Magnetic Field

- *Rotor-produced* magnetic field in stator winding is very small if HTS does not extend too far from the stator midplane



Note: stator midplane does not need to coincide with geometric middle of the gap between rotors

Motor Design Code



- Analytical equations to calculate rotor & stator magnetic fields over a half period, heat transfer, & AC loss
- Vacuum & coolant vessels sized based on buckling (external pressure) or hoop stress (internal pressure)

- Shafts & bearings sized to direct drive propeller subjected to aircraft maneuvers with ≥90% bearing reliability

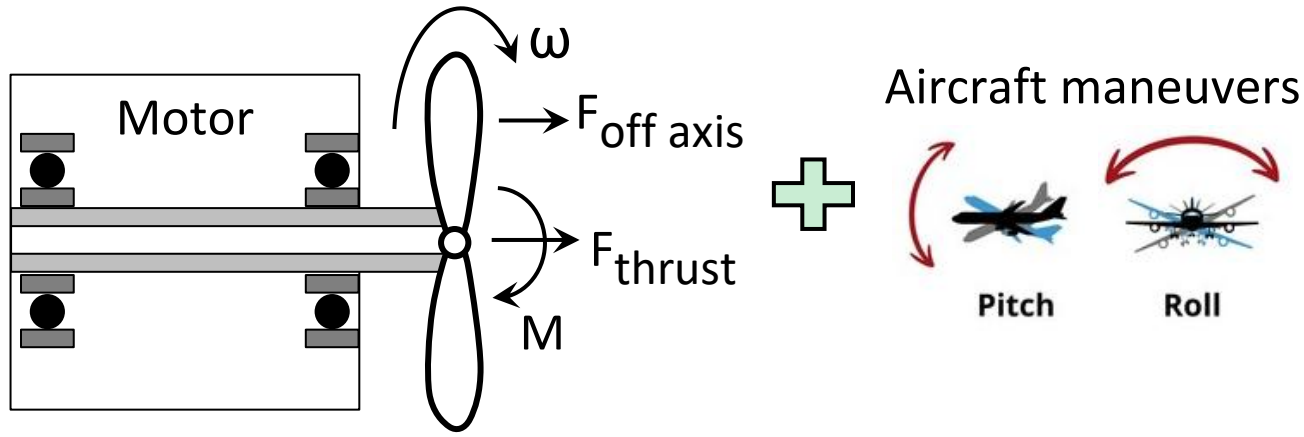
Overview of Mechanical Analysis

Mechanical analysis

Dimension	2D
Geometry	Simple cylinders & discs
Structural materials	G-10 (vessels in field), 17-4 stainless (shaft), Ti-6Al-4V (other)
Temporal fidelity	Static
Loads	Air & coolant pressures, torque, centrifugal, prop loads (see below)
Bearing reliability & life	90% to reach 5,000 hour life
Temperature-dependent properties?	No

- Vacuum & fluid containment vessels sized for buckling (external pressure) or hoop stress (internal pressure)
  - Inner & outer walls of both vessels in air gaps
- Manufacturability considered: lower limit of 1.5 mm on section thickness
- Total mass estimated, including:
  - Electromagnetic
  - Shafts & bearings
  - Vacuum vessels, fluid containment, fluid, & rotors
  - 10 kg for miscellaneous components

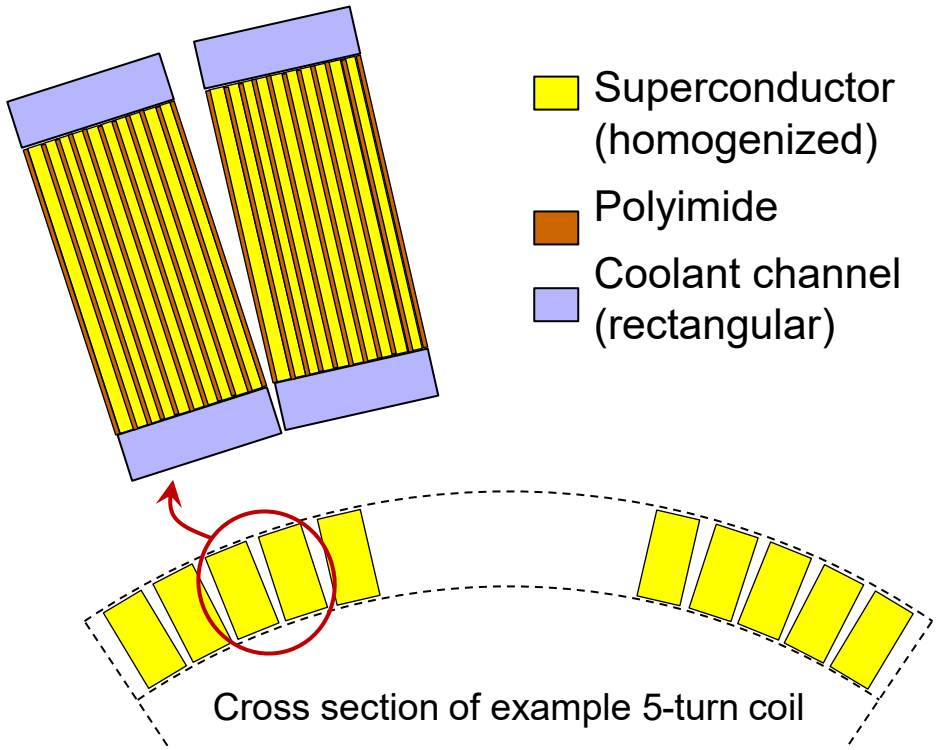
Loading for bearing & shaft sizing



Overview of Thermal Analysis

Thermal analysis

Dimension	2D
Geometry	See right
Temporal fidelity	Time averaged
Spatial fidelity	Loss per SC tape
Coolant temperature	At inlet
Temperature-dependent properties?	Yes



- Flooded cooling of stator: winding surface directly cooled on inner & outer diameters
- HTS tapes electrically insulated from each other

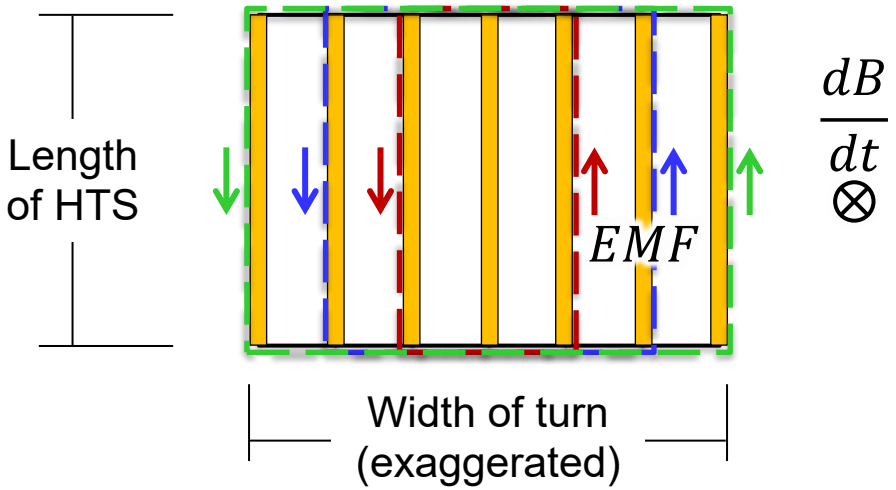
Overview of Electromagnetic Analysis

Electromagnetic analysis

Dimension	2D
Temporal fidelity	Pseudo time-stepping
Magnetic field sources	All (rotor produced & self field from full stator winding)
Mechanical air gap size	1 mm (outer gap), 1.5 mm (inner gap)
Superconductor model	Full fidelity (temperature-, field-, and field angle-dependence)
Superconductor current safety factor	≥ 1.5
Material properties of permanent magnets	Temperature-dependent
Winding type	3- to 9-phase (concentrated)

- Appreciable currents can circulate *within* a turn (between HTS tapes in hand) because turn cannot be twisted within stator slot (electromotive force can be relatively high)
  - Calculated self inductance and mutual inductance of each circulating current loop within a phase

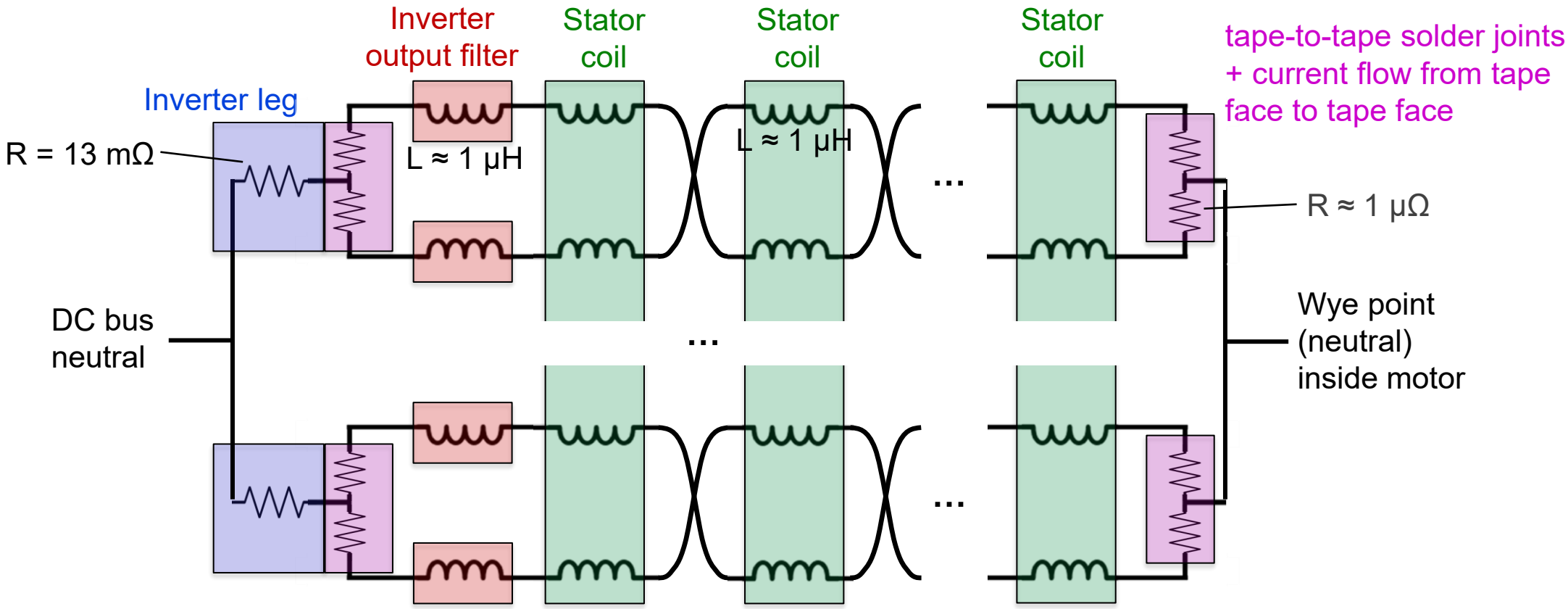
Circulating current loops considered for example turn composed of 7 HTS tapes



EMF = electromotive force

Motor-Inverter Electrical Circuit

- Modular inverter with output filter is assumed
  - Number of HTS tapes connected to each inverter leg can vary (2 shown in example below)
- Stator turn twisted 180 degrees between series-connected coils to reduce electromotive force driving circulating currents



Loss Quantification

Thermomechanical losses

- *Bearing, windage, & fluid pumping* (through motor) *losses*

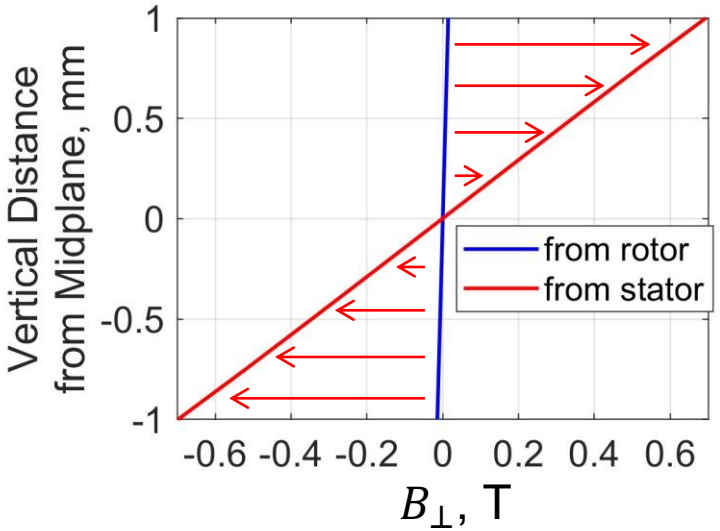
Electromagnetic losses

$B_{//}$ and $B_{\perp}$ calculated relative to *each* tape in stator coil (including harmonics of rotor-produced field)

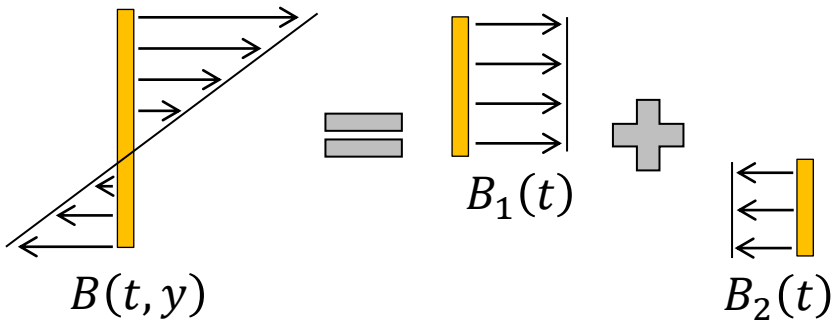
- *Eddy current loss* due to each B component in each of substrate, silver overlayer and stabilizer [1]
- *Ohmic loss* due to circulating currents in resistive parts of tape and circuit
- *Combined transport and $B_{//}$ field loss* [1]
- *Hysteresis loss* of tape stack due to $B_{\perp}$, including saturation of stacking effect experimentally determined in [2]

Perpendicular field in a single HTS tape

Example actual



Simplification of B_{total} used



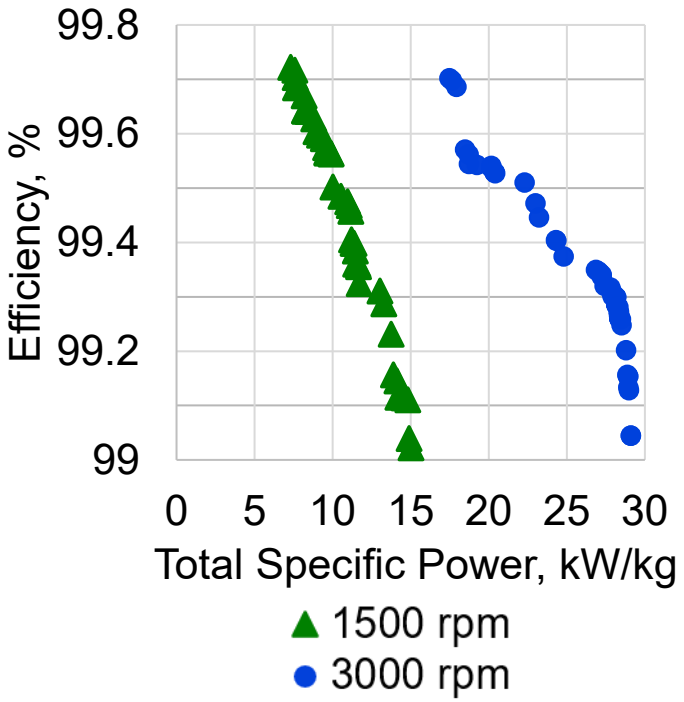
[1] M.D. Sumption et al., *Handbook of Superconductivity*, vol. 3, Chapter G2.7, 2021.
[2] M.D. Sumption et al., Cryogenics, 144, 103963, 2024.

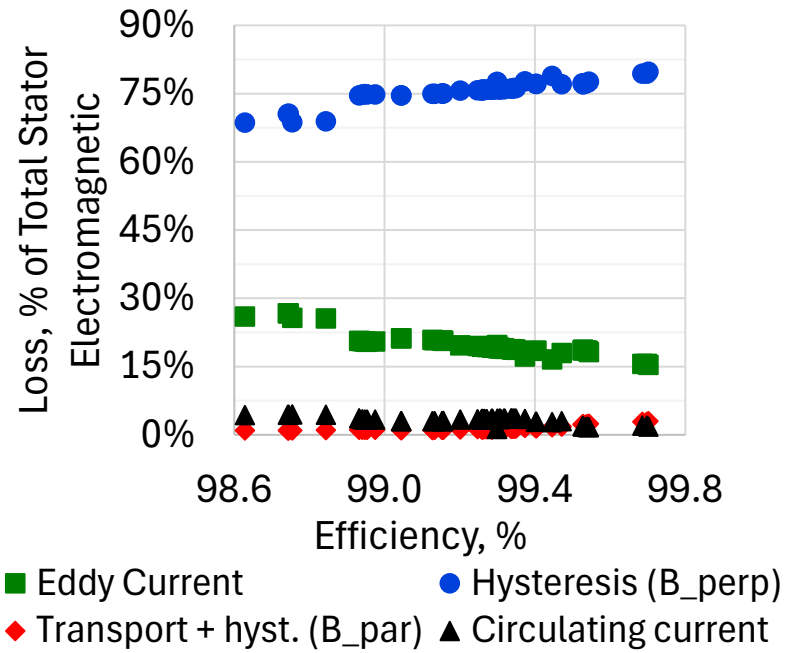
Optimization Results – Radial Flux, Permanent Magnet Rotors

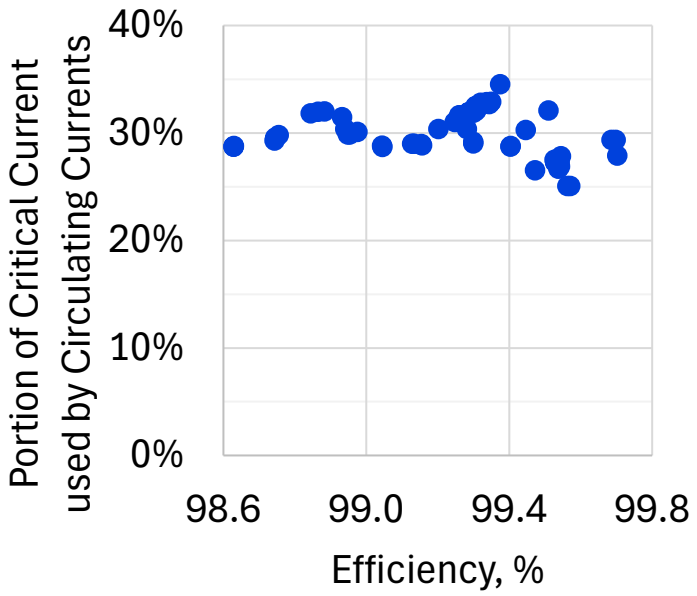
Key Conditions

5 MW at 3,000 rpm or 1,500 rpm ▪ GHe coolant at ≥ 35 K ▪ 637 mm outer diameter

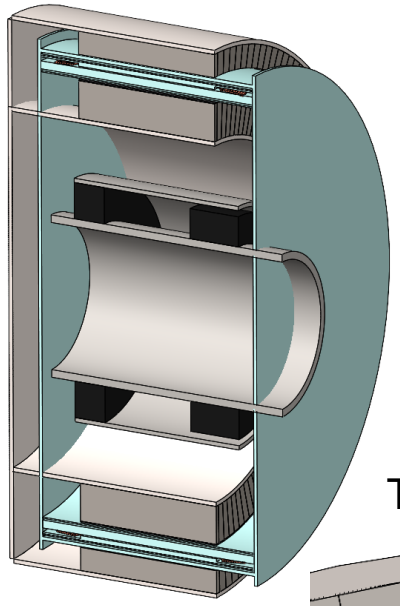
- Coolant inlet temperature optimized to 35 to 45 K (peak HTS temperature of 42 to 55 K)
- All optimal designs with ≥ 98.5% efficiency use 2 mm wide HTS
- Circulating currents produce little loss but have significant impact on allowable transport current
- Up to ±1 kV DC bus allowed but peak phase voltage optimized to 300 to 500 V – need to investigate



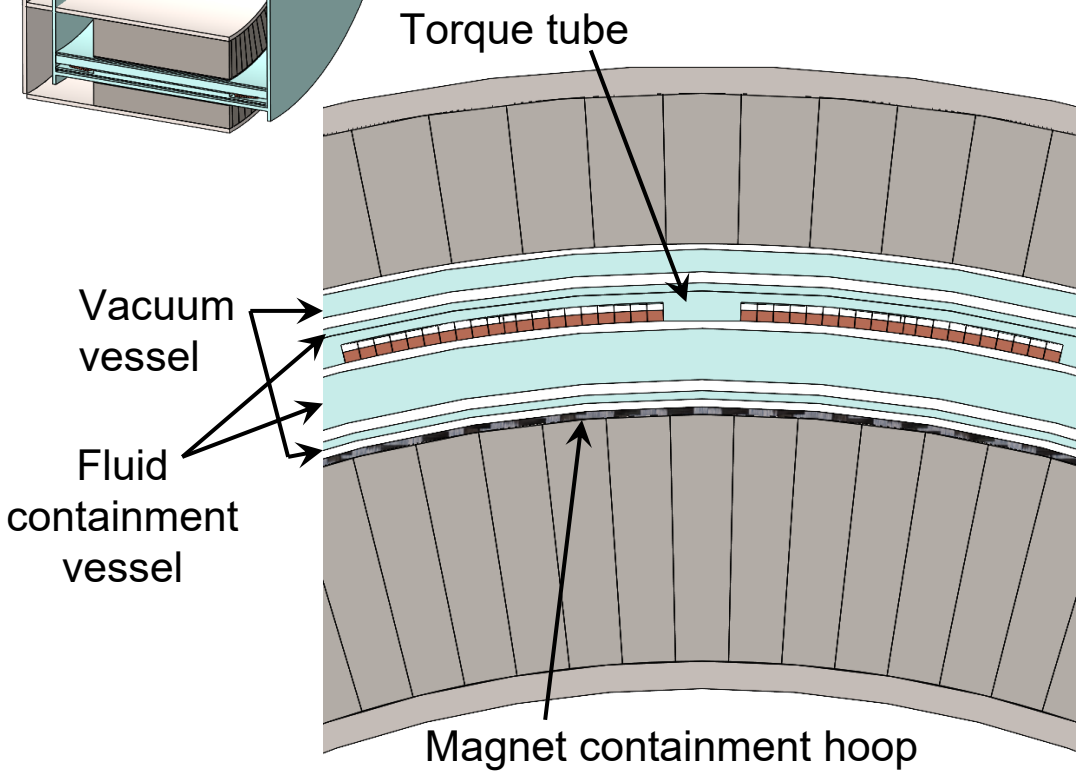




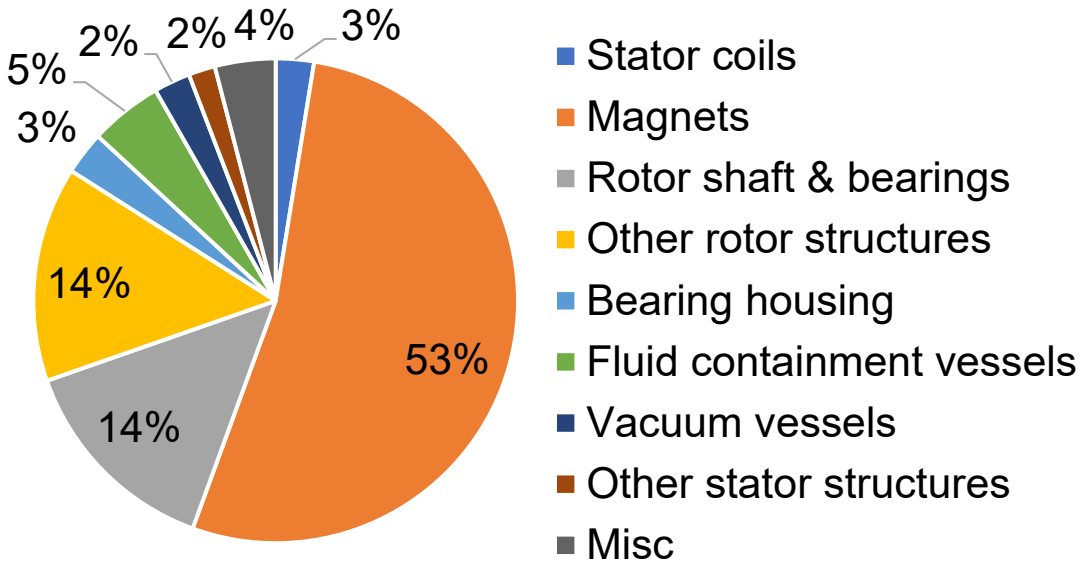
Example Design



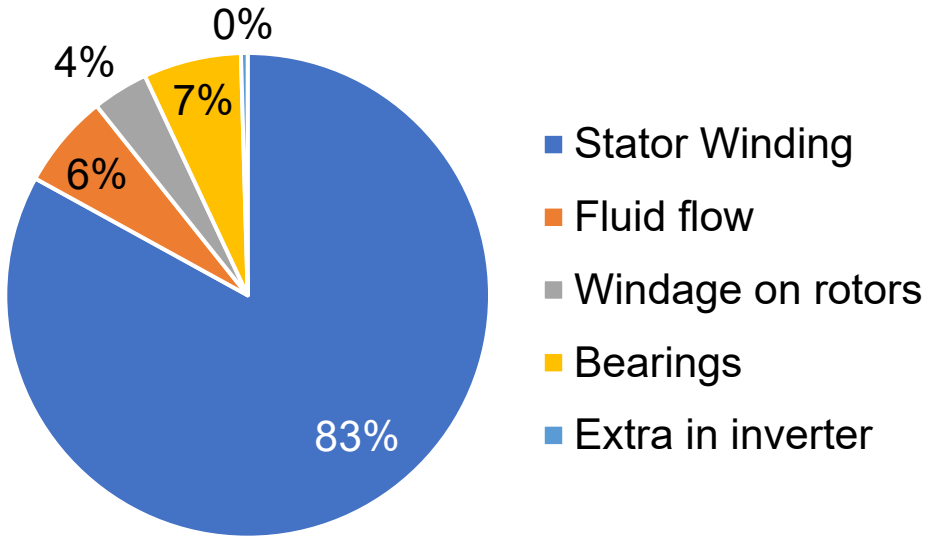
Parameter	Predicted
Continuous power, MW	5
Rated speed, rpm	3,000
Efficiency at rated speed	99.54%
Continuous specific power, kW/kg	20.2
DC bus voltage, V	± 471



Mass breakdown



Power loss breakdown



Conclusions

- Novel electric machine invented that enables use of HTS tape in armature
- Performance evaluated using a moderate fidelity, analytical code that quantifies total efficiency and specific power based on mechanical, thermal, and electromagnetic analyses
- Highly efficient and lightweight radial flux designs are possible using permanent magnet rotors
  - Higher performance and/or warmer operation achievable if circulating currents can be further reduced
  - Key uncertainty: AC losses in tape stacks excited by a non-uniform, bipolar field

Key Benefits	Key Challenges
Acceptable AC loss with HTS tape	Cantilevered stator & 2nd rotor (*radial flux variant*)
High performance with warm rotors	Vacuum vessel in air gap
Relaxed inverter output distortion limit	Assembly of large magnets
Heat transfer within winding can be independent of insulation & epoxy	Packaging of stator feedthroughs

- Future work: AC loss measurements & refined predictions · optimization of axial flux designs

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