Motor configuration selection for a new technical challenge to develop a 5 MW cryogenic motor and drive

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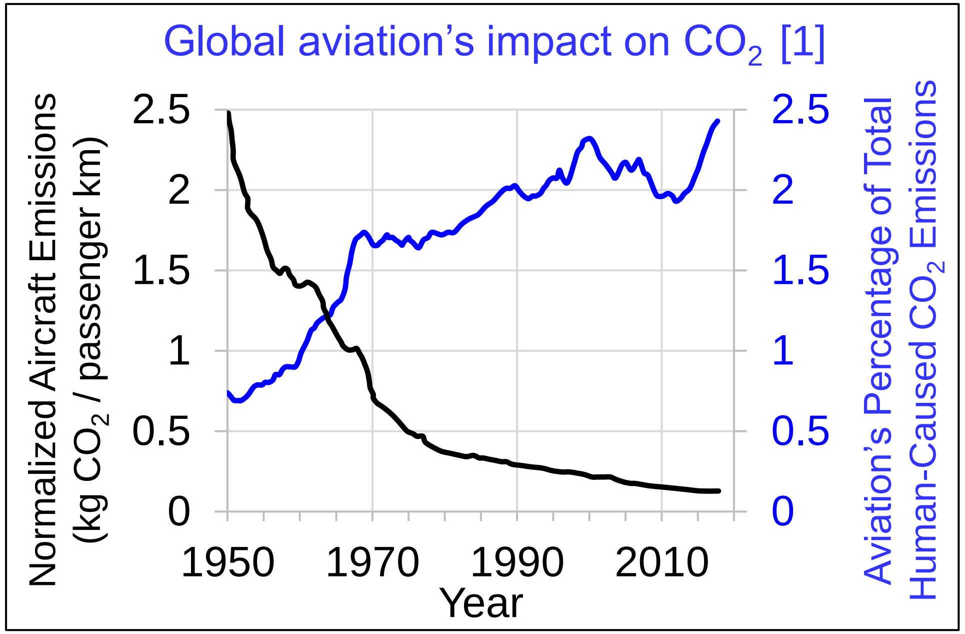
Agenda

- Motivation
- Technical challenge & motor specifications
- Description of motor configurations
- Motor design codes
- Motor trade study results
  - Permanent magnet rotors
  - Superconducting rotors
- Conclusions

Motivation

- *Status quo won't cut it* – global CO_2 emissions from aviation growing at increasing rate
- US Aviation Climate Action Plan (2021) [2] set goal for net-zero carbon emissions by 2050
- *CO_2 only accounts for 34% of total radiative forcing* [1]
- SAF (sustainable aviation fuels) alone cannot address environmental impact, and it has cost & significant scalability concerns



- Achieving significant impact necessitates focus on large transport aircraft
- Aircraft-level studies demonstrate that higher power electrified propulsion systems enable larger reductions in energy consumption (fuel cost) [3-5]

1. https://doi.org/10.1016/j.atmosenv.2020.117834
2. https://www.faa.gov/sustainability/aviation-climate-action-plan
3. https://ntrs.nasa.gov/api/citations/20210016661/downloads/TM-20210016661.pdf
4. https://doi.org/10.2514/6.2024-1326
5. https://ntrs.nasa.gov/api/citations/20240001480/downloads/NASA-TM-20240001480.pdf

Brief Overview of the Technical Challenge

Develop a 5 MW superconducting motor system and demonstrate at subscale to enable new higher performance airplane architectures (TRL 3)

Design (2024 – 2028), build & test (2028 – 2030)

Objectives	• Develop 5 MW Superconducting Machine Technologies (TRL-3) • Determine high power EAP aircraft and powertrain architectures

Motor Specifications

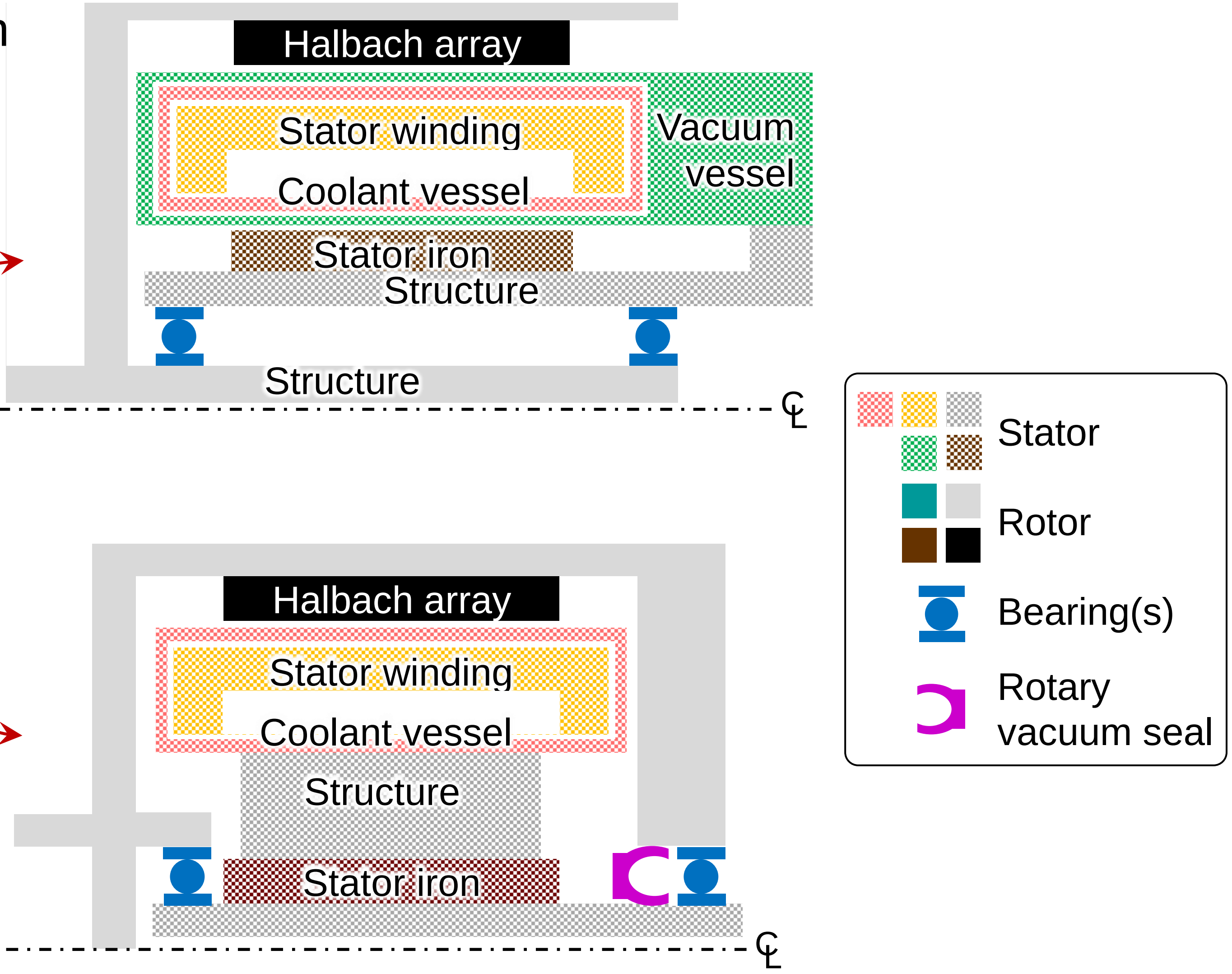
Parameter	Requirement	Goal
Continuous power, MW	5	-
Rated speed, rpm	≥ 2,000	3,000
Rotor field source & temperature	HTS (cryo) or PM (> room temp.)	-
Stator conductor & temperature	Metal (cryo)	Superconducting (cryo)
Efficiency at rated speed	≥ 99.5%	≥ 99.9%
Continuous specific power, kW/kg	≥ 20	≥ 40
Equivalent tip speed at outer radius, m/s	≤ 100	-
DC bus voltage (relative to neutral), V	≥ ±270	≤ ±1,000
Rated voltage of insulation, V	≥ 1,000	2,000
Local heat sink	Not fuel	-
Local heat sink temperature, K	> 20	-
Time from off to operational, min	-	≤ 30
Thermal cycle life	-	≥ 10,000
Random vibration, Grms	-	TBD
Mechanical shock, G	-	6

- Motor to direct drive multi-MW fans / propellers
- Considering fully cryogenic (HTS rotor) & partially cryogenic (permanent magnet rotor)
- TRL advancement prioritized over performance
- Upper limit of ±1,000 V to limit material development & electronics packaging issues
- Desire to be fuel agnostic, but not allowing fuel to be local heat sink

Motor Configurations

- Distributed winding in all but 1 configuration

#	Motor type (rotor field source)	Flux direction	Construction	
1	Partial cryo (permanent magnet)	Radial	Outer rotor	Stator is vacuum vessel
2				Rotor is vacuum vessel
3			Helmholtz	
4		Axial	Rotor – stator – rotor	
5		Radial + axial	Tri-rotor, no iron	
6	Fully cryo (supercond.)	Radial	Inner rotor	
7		Axial	Stator – rotor – Stator	
8			Rotor – stator – rotor	



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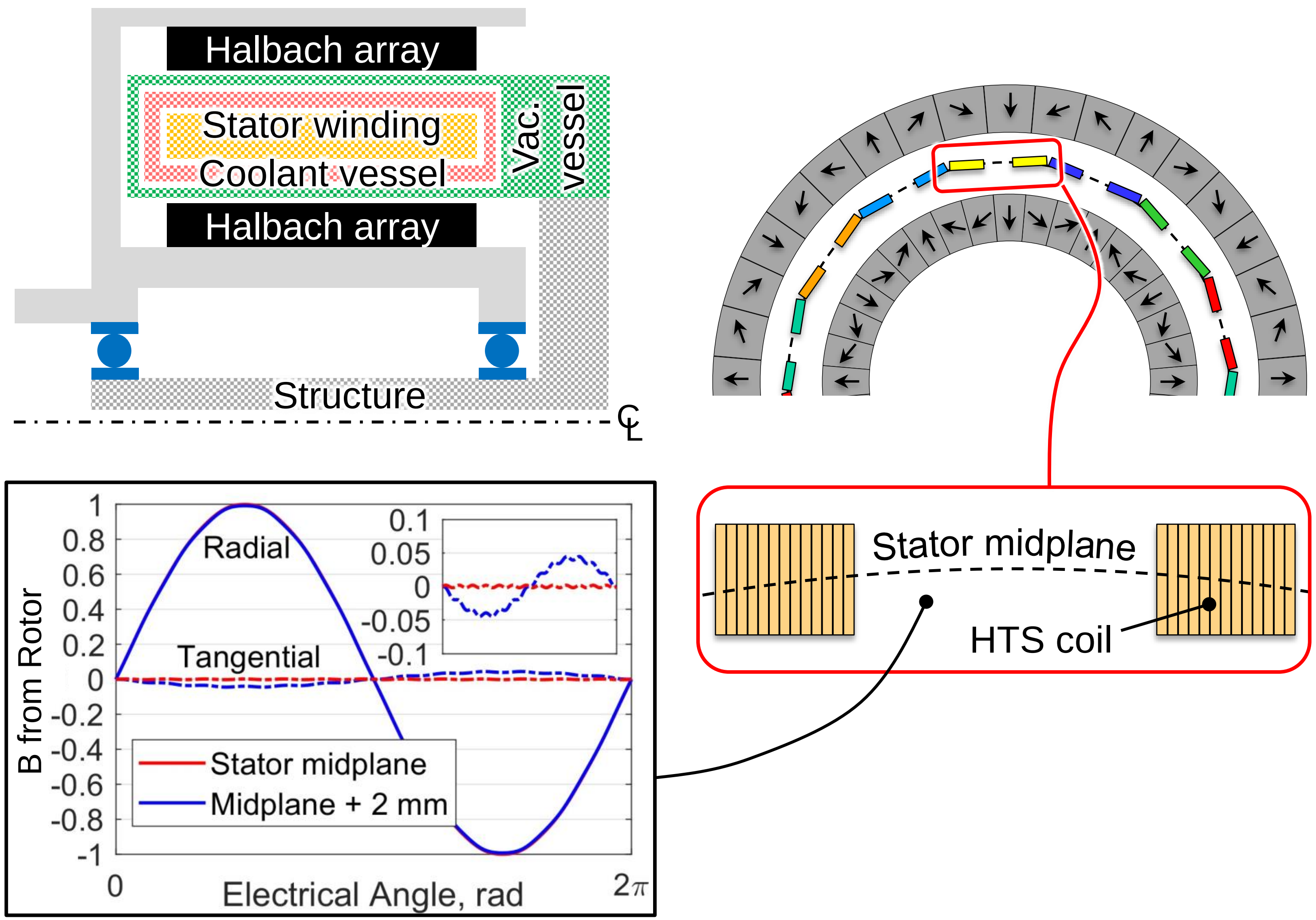
Radial flux Helmholtz machine with permanent magnet rotors
(*patent pending*)



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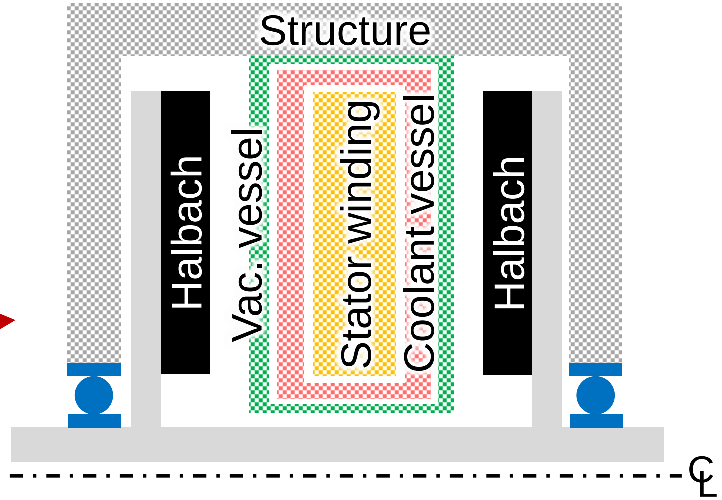

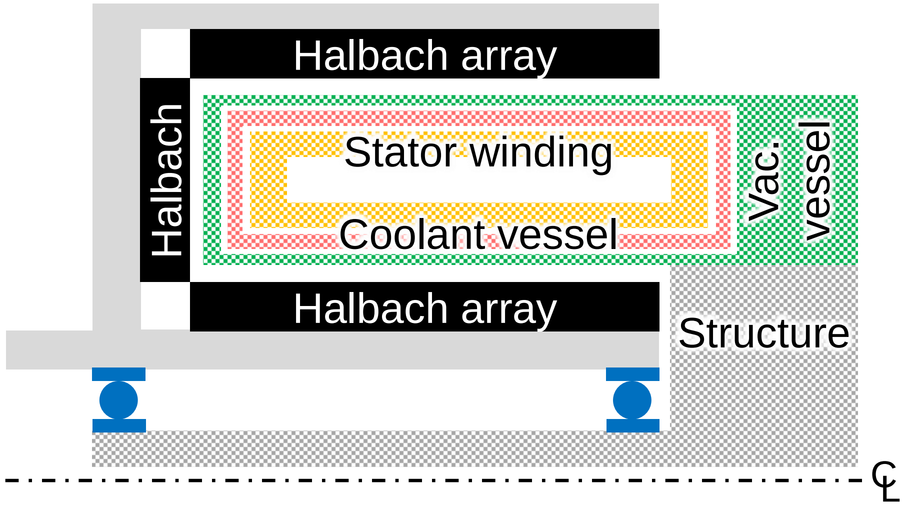

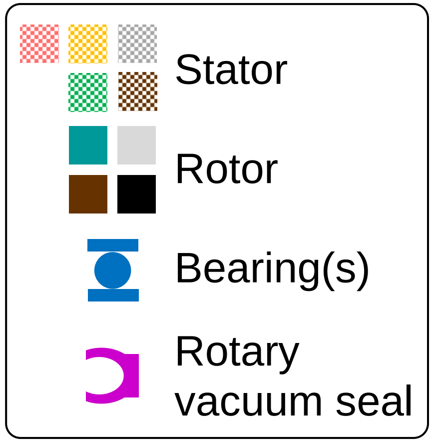

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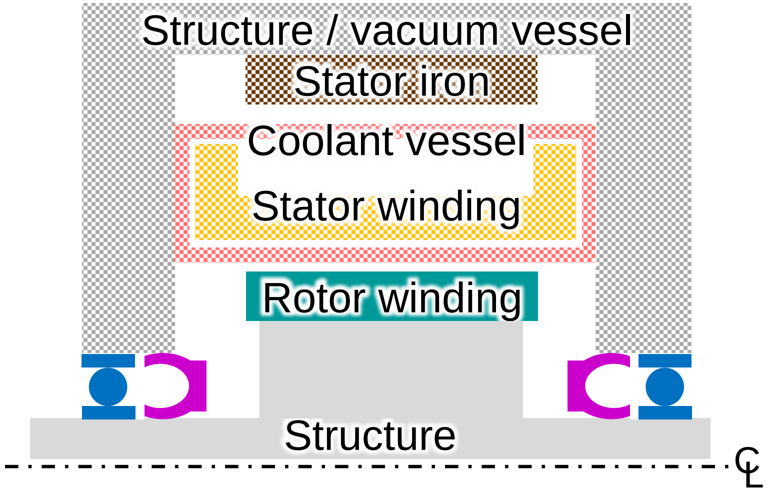
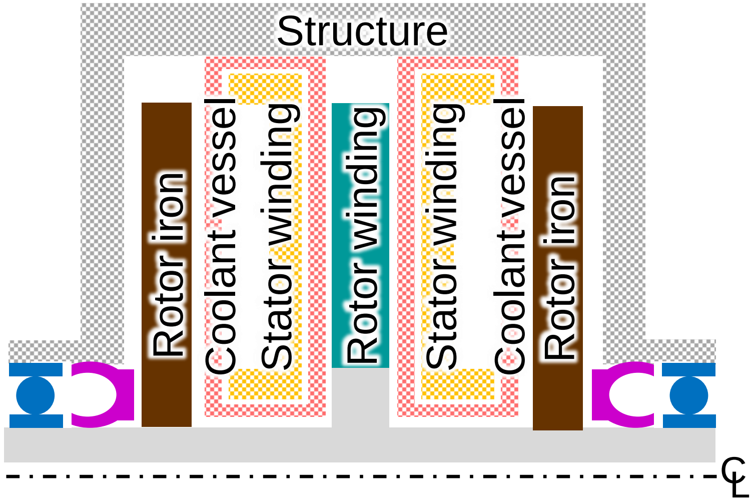
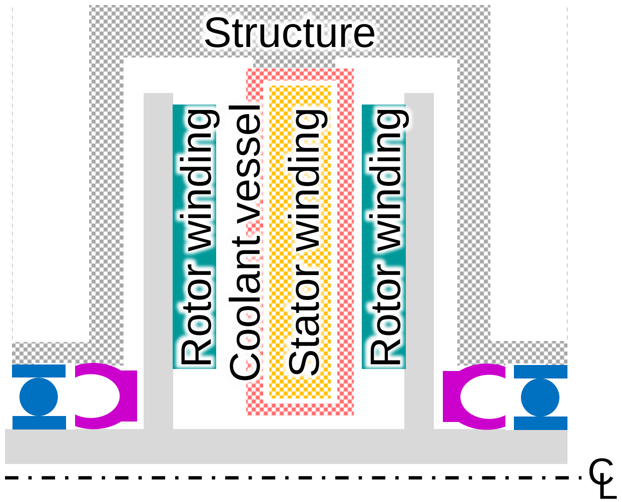
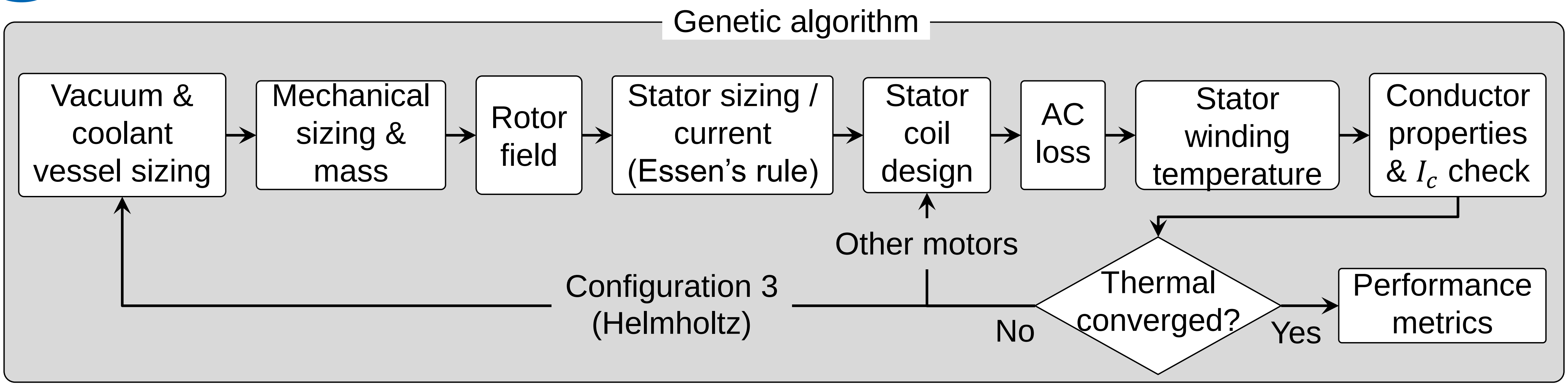






Motor Design Codes



- Analytical equations to calculate rotor & stator magnetic fields over a half period, heat transfer, & AC loss
- Winding surface directly cooled: on one active face (tri-rotor & axial flux) or inner & outer diameters (radial flux)
- 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
- For superconducting rotors:
  - Rotating cryocooler used with Carnot efficiency from [6] & mass based on commercial Stirling coolers [7]
  - Heat load = radiation + 10 W

6. D. Ladner, "Performance and Mass vs. Operating Temperature for Pulse Tube and Stirling Cryocoolers," in International Cryocooler Conference, 2008.
7. https://www.sunpowerinc.com/products/stirling-cryocoolers/cryotel-cryocoolers.

Motor Design Codes

Losses considered	Masses considered
• *In Litz wires*: AC resistive & proximity eddy current losses • *In superconductors*: hysteresis, eddy current, coupling, (also transport in HTS) • Bearing • Windage (Helmholtz motor only) • Pumping fluid through motor • Cryocooler (fully cryo motors) • Iron (where required) • 1.5 kW for rotary vacuum seals (where required)	• Electromagnetic • Shafts & bearings • Vacuum vessels, fluid containment, fluid, & rotors • Cryocooler & thermal connection to it • 10 kg for miscellaneous components

Motor Design Codes

- 10% margin on torque
- Assumed 1 inverter for Helmholtz motor, but 1 inverter per pole pair for others
- **Results shown for 3,000 rpm, ±1,000 V DC bus, & 100 m/s equivalent tip speed**
  - Coolant: mostly subcooled LNe but also GHe

Parameter		Conductor		
		HPAL	MgB_2	Bi-2212
Diameter	Filament	10 μm		
	Wire	Optimized		
	Core	100 μm		
Thickness	Wire sheath	50 μm		
	Chemical barrier	10 μm		5 μm
	Wire insulation	30 μm		
Resistivity of wire sheath & matrix		36.5 μΩ-cm		1.5 μΩ-cm
Twist pitch		30x wire diameter		

Parameter		Value
Motor	Phases	9 (distributed) or 3-9 (concentrated)
Structural	Rotor materials	316 SS (coil former), 17-4 SS (shaft), titanium (other)
	Stator materials	G-10 (in field), titanium (other)
Magnetic	Back iron	$Fe_{49.5}Co_{48.5}V_{1.9}$
	Rotor conductor (fully cryo only)	REBCO, 90% fill
	Magnets (partial cryo only)	NdFeB, Br = 1.3 T, 90% fill
	Physical air gap	1 mm (radial, partial cryo) variable (other)

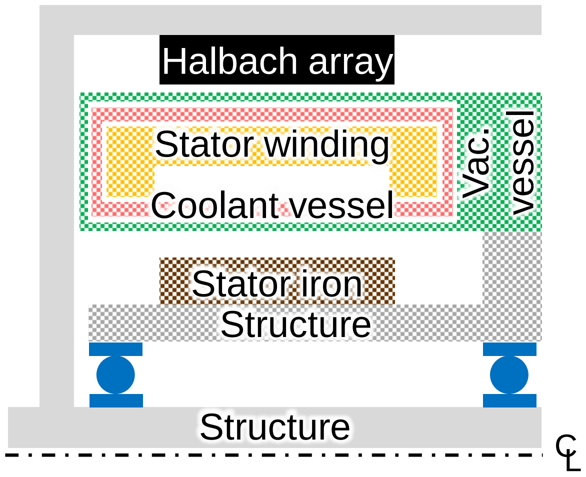
Results – Permanent Magnet Rotors

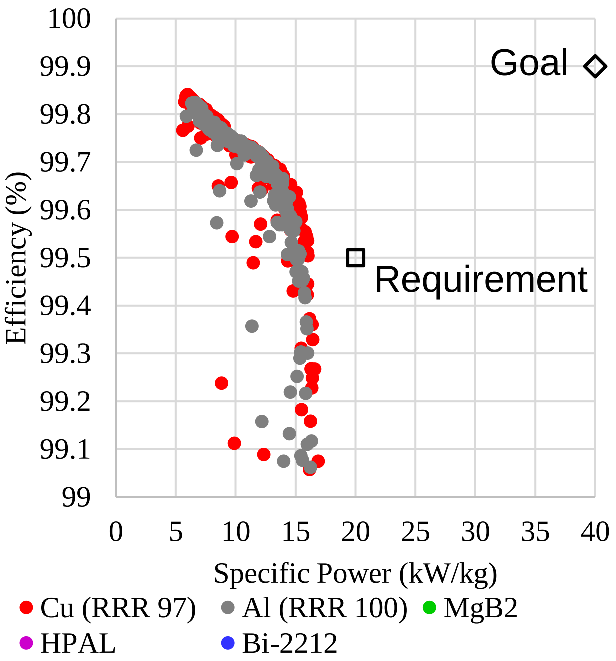
- Subcooled LNe (25 K at inlet)
- Bi-2212 did not close, HPAL & MgB_2 closed outside range shown for stator vacuum case
- Eliminating vacuum vessel from air gap provides ~7 kW/kg benefit but at expense of rotary vacuum seal

Subcooled LNe

25 K inlet, 6-40 m³/hr, 1 bar

Config. 1

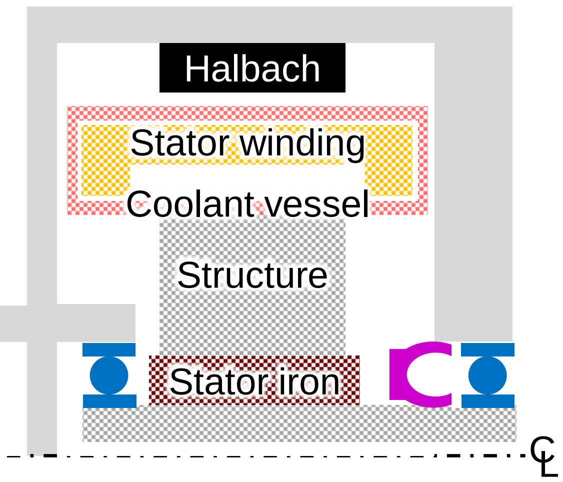


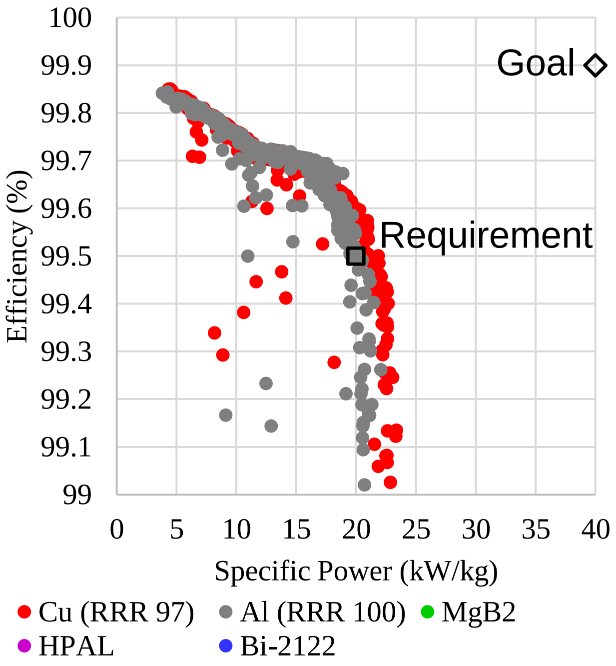


Subcooled LNe

25 K inlet, 6-40 m³/hr, 1 bar

Config. 2





Results – Permanent Magnet Rotors

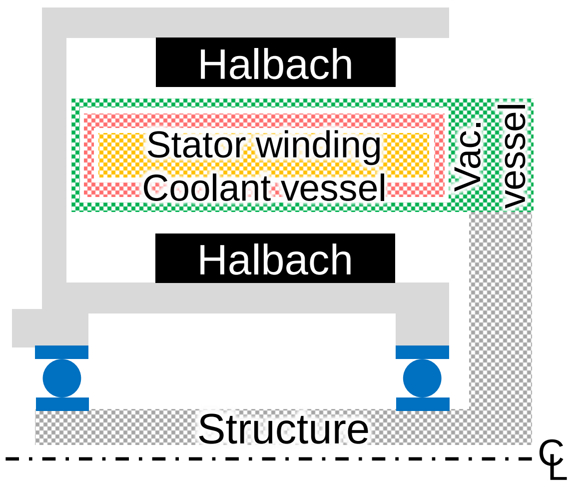
- Helmholtz configuration (#3) enables HTS stator that exceeds Cu Litz performance by 10-15 kW/kg
  - Primary limitation: AC loss due to self field, particularly coupling currents between the 15-35 tapes in hand that are needed to avoid exceeding voltage limit
- Tri-rotor (#5) can attain very high efficiency but requires considerable improvement to thermal management to meet specific power requirement

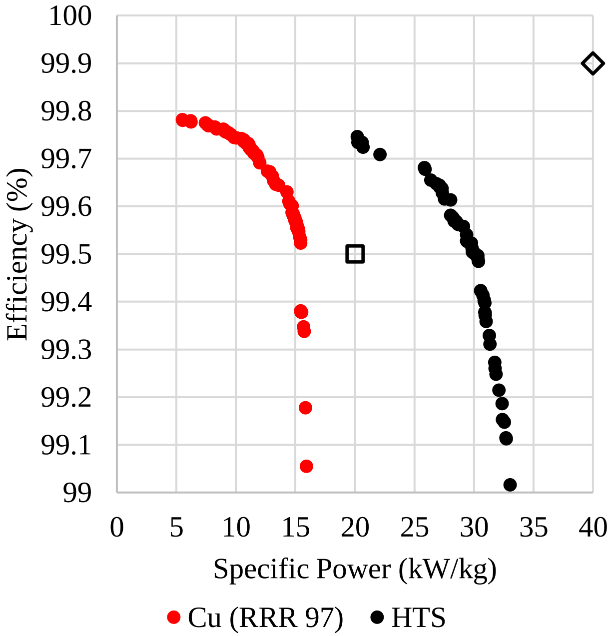
GHe

<u>HTS</u>: 43-55 K inlet, 365-600 m^3/hr, 15-25 bar

<u>Cu Litz</u>: 25 K inlet, 90-600 m^3/hr, 2-3 bar

Config. 3

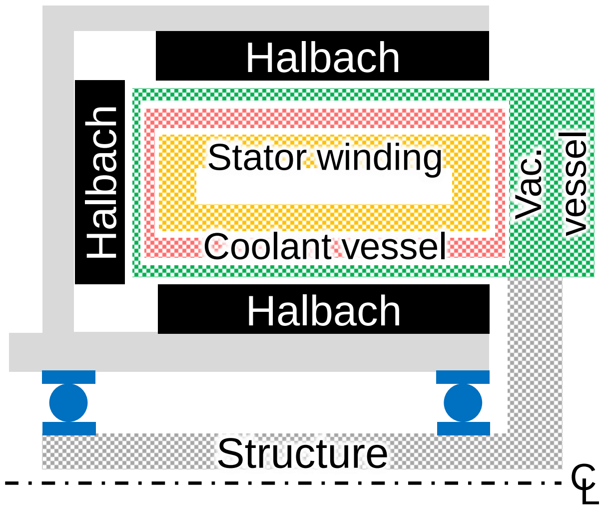


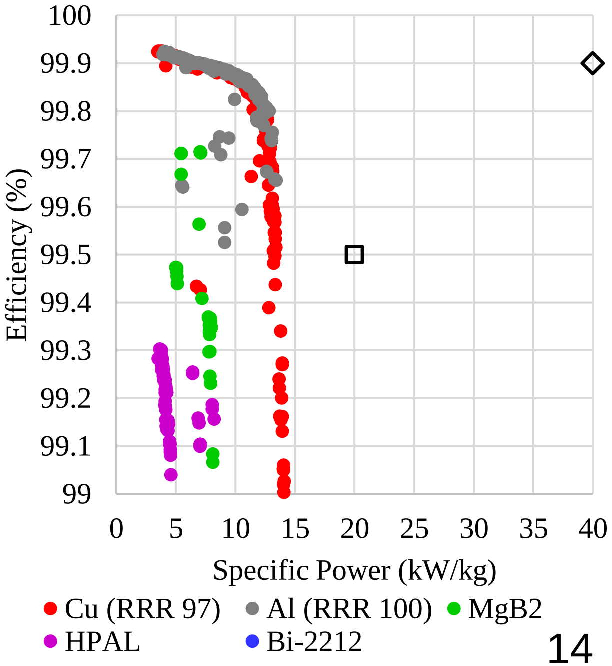


Subcooled LNe

25 K inlet, 5-31 m^3/hr, 1 bar

Config. 5





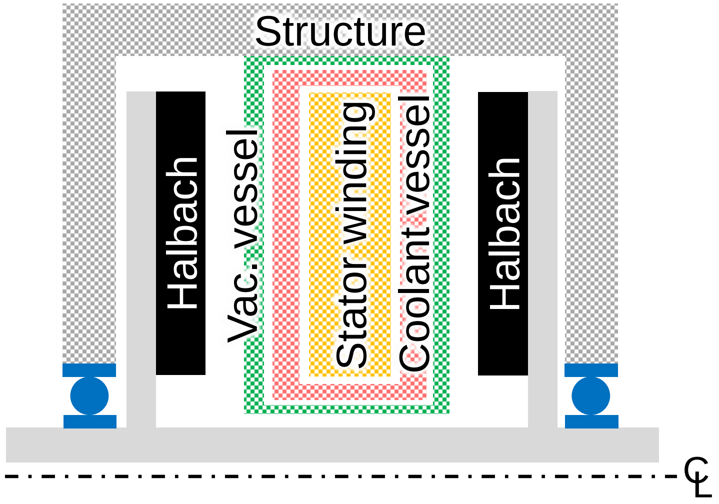
Results – Permanent Magnet Rotors

- Disc-shaped G-10 vacuum & coolant vessels too thick → magnetic field in stator too low

Subcooled LNe

25 K inlet, 1 bar

Config. 4



Did not close

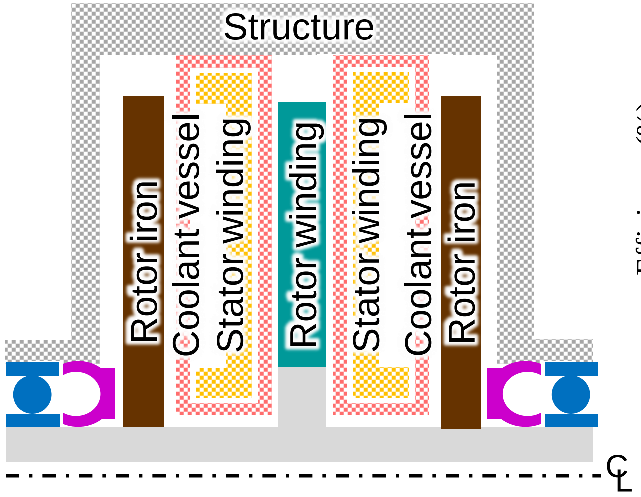
Results – Superconducting Rotors

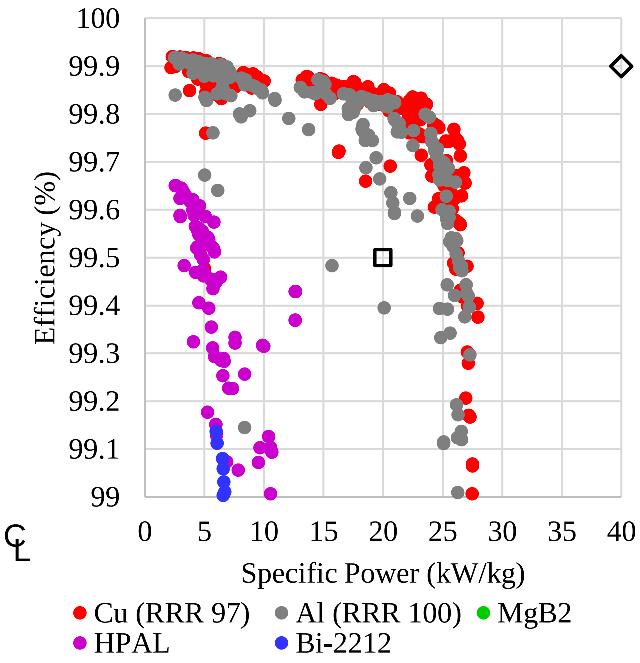
- Rotor-stator-rotor (#8) performs much worse due to (a) thicker stator winding [larger impact of one-sided cooling] & (b) larger rotor heat load & mass

Subcooled LNe

25 K inlet, 1 bar

Config. 7

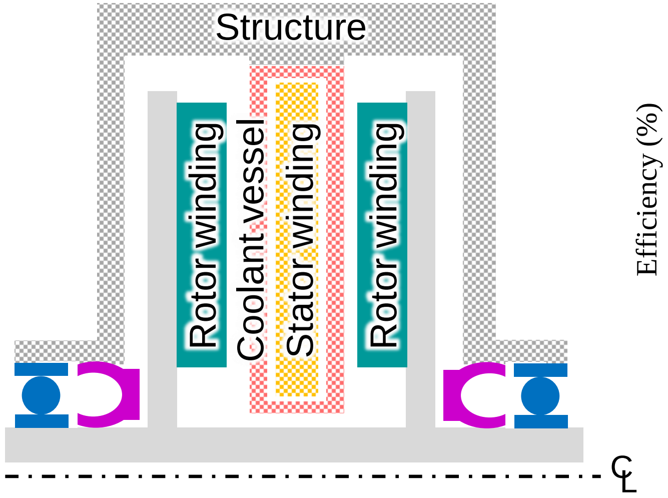


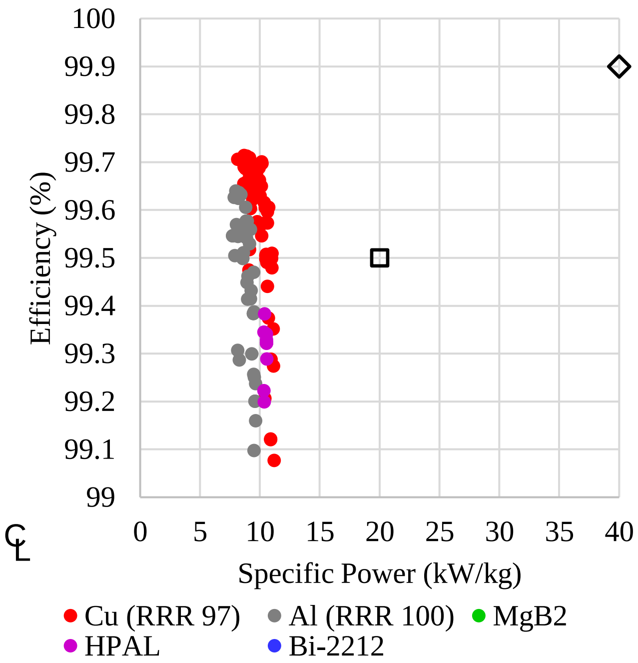


Subcooled LNe

25 K inlet, 1 bar

Config. 8

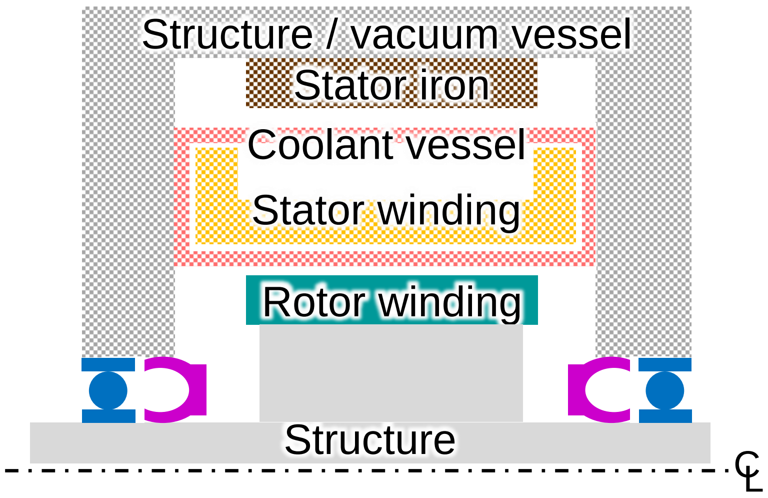




Results – Superconducting Rotors

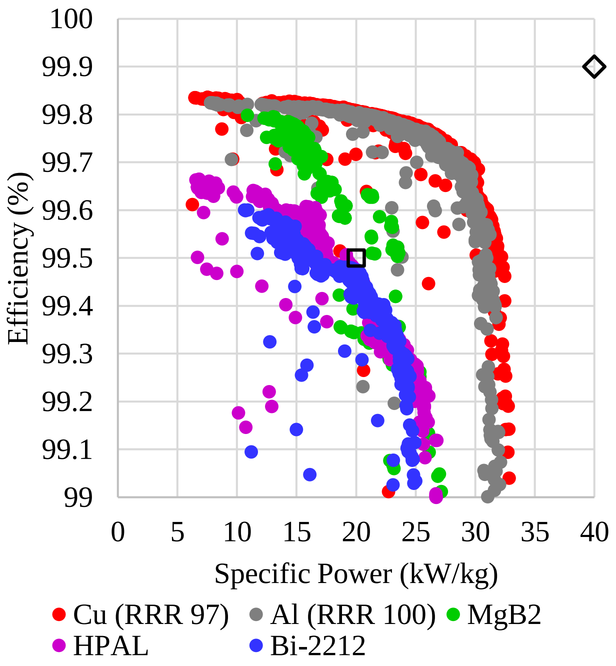
- Best combination of specific power & efficiency
- Only modest (~0.07%) drop in efficiency if Litz wire gauge reduced from 50 AWG to 40 AWG
- Only modest (~2.5 kW/kg) drop in specific power if GHe used instead of LNe

Config. 6

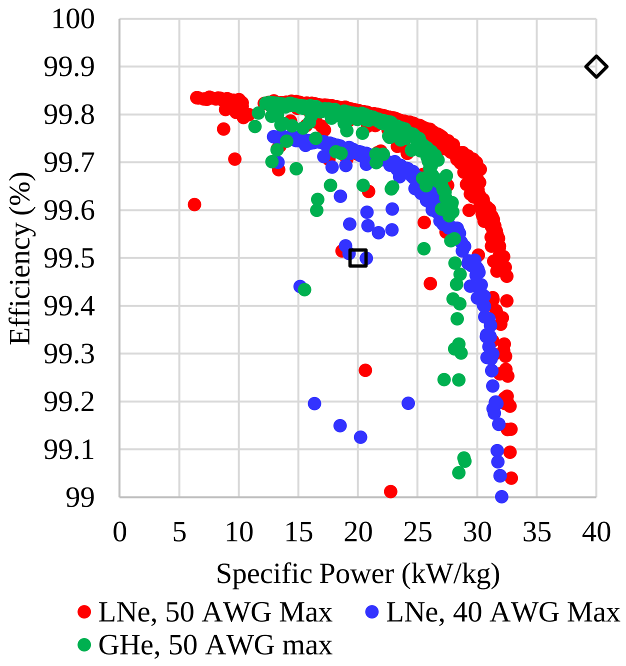


Subcooled LNe

25 K inlet, 5-32 m^3/hr, 1 bar



Sensitivity to coolant & stator wire gauge for Cu (RRR 97) Litz



Conclusions

- Most permanent magnet motors cannot meet requirement of 99.5% at 20 kW/kg due to low magnetic field & subsequent thermal challenge of cooling more heavily-excited stator winding
  - New Helmholtz motor can overcome this & enable HTS stators
- Performance of axial flux motors can be improved if vacuum & coolant vessels can be stiffened
- Litz wire benefits from very fine strand diameters (Ø80 to Ø25 μm) & high slot fill factor (~50%)
  - Refined comparison of conductors will be completed after motor configuration down selected
- Results suggest only modest reductions…
  - in specific power occur if GHe used instead of LNe
  - in efficiency occur if Litz wire gauge reduced from 50 AWG to 40 AWG
- Points of uncertainty
  - AC loss in thick stacks of HTS
  - Rotary vacuum seals: power loss, constraints on leak rate & life

Conclusions

Partially cryogenic motors with permanent magnet rotor

Highest performing:

Helmholtz motor with HTS stator
(99.75% at 20 kW/kg • 99.5% at 30.4 kW/kg)

Pros	Cons
• Simple rotor cooling • No rotary vacuum seals • Lighter / more efficient inverter (likely tolerates higher current distortion)	• Structural support of outer rotor & stator more difficult • More reliant on higher voltage

Fully cryogenic motors with HTS rotor

Highest performing:

radial flux inner rotor with Cu Litz stator
(99.81% at 20 kW/kg • 99.5% at 32.2 kW/kg)

Pros	Cons
• Highest performing • Relatively easy rotor structure & rotordynamics • Lower cryogenic heat load	• Requires 2 rotary vacuum seals (heat & reliability concern) • Cryogenic rotor (cooling & heat load concerns) • Requires current supply with very low distortion

Acknowledgements

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THANK YOU

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Overview of the Technical Challenge

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- Design (2024 – 2028), build & test (2028 – 2030)

Objectives	• Develop 5 MW Superconducting Machine Technologies (TRL-3) • Determine high power EAP aircraft and powertrain architectures
Approach	• Explore fully superconducting and fully cryogenic machines to increase percentage electrification and meet weight targets at the airplane level • Design a 5 MW machine and drive • Demonstrate key tall poles for high power superconducting (stator cooling, non-contact rotor current supply, low AC loss, cost, flight-like requirements, etc.) • Support component-level work with system studies at all levels (power quality, thermal management, airplane performance) • Focus on solutions that support SAF and Hydrogen

Stator Windings for Axial Flux Motors

Configuration 7 →

Fig. 3 "Distributed" stator topology. Windings have no skew in the active region of the machine and correspondingly complex end turn geometry.

Configuration 8 →

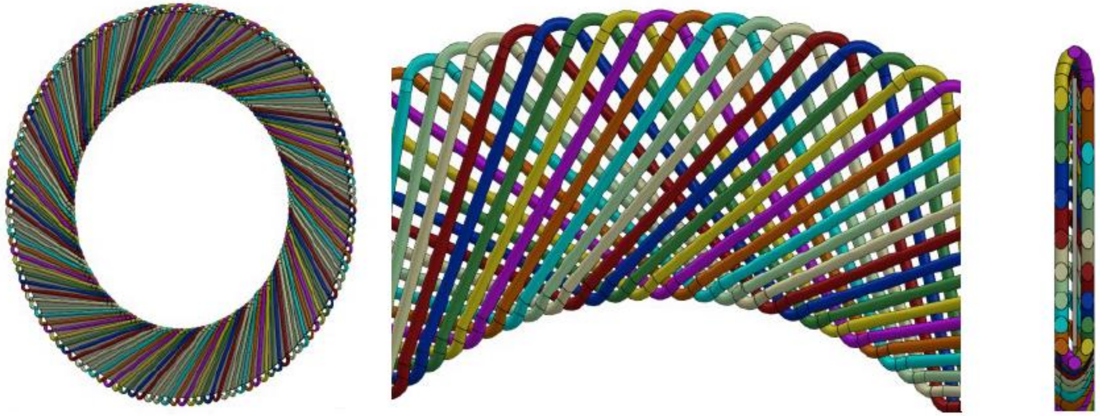

Fig. 4 "Zig-Zag" stator topology. Windings are skewed by approximately one pole arc in the active region of the machine in order to minimize end winding complexity and mass at the cost of reduced torque production due to the winding skew.