NASA progress on superconducting electric machines for aircraft

Justin J. Scheidler[1]

Aaron D. Anderson[1] Shishir J. Desai[1] Kirsten P. Duffy[2] Don Fong[1] Jason W. Hartwig[1]
Amy L. Jankovsky[1] Brittany Jonas[1] Peter E. Kascak[1] Paul J. Passe[3] William R. Sixel[1]
Casey J. Theman[1] Frederick W. Van Keuls[3] Andrew A. Woodworth[1]

[1] *NASA Glenn Research Center, Cleveland, USA*

[2] *University of Toledo,Toledo, OH 43606*

[3] *HX5, LLC, Brook Park, USA*

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NASA Interests in Superconducting Technologies

Space

- Photon detectors for telescopes
- Lunar infrastructure for sustained human presence on Moon
  - 'High Power, Long Distance Energy Transmission Across Distributed Surface Assets' ranked 32 out of 187 space technology "shortfalls" [1]

Aeronautics

- Electrified aircraft propulsion systems
  - **Electric machines** [2]
  - DC cables (multi-kA)
  - Fault current limiters

1. https://www.nasa.gov/spacetechpriorities/
2. https://ntrs.nasa.gov/citations/20230010027

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 · maintain U.S. competitiveness · reinvigorate existing aircraft markets & strengthen emerging markets
  - *Example*: for 10 year operation of a specific aircraft, 1% fuel consumption is worth $3M
  - *Example*: ~50% of a twin-aisle aircraft's weight is fuel (at max take-off condition)
- **Societal benefits:** global access to air travel can continue to grow
- **Environmental benefits:** reduced impact on climate · improved air quality
  - Insufficient to only focus on CO_2 emissions and sustainable aviation fuels
- To achieve significant impact, focused on single- and twin-aisle aircraft (~150+ passengers)
  - Aircraft-level studies demonstrate that higher power electrified propulsion systems enable larger reductions in energy consumption (fuel cost) [3-5]

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

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
Approach	• Design a 5 MW machine and cryogenic drive • Build and test at rated conditions and ambient atmosphere a < 5 MW machine and drive • Explore superconducting machines with cryogenic stators (fully superconducting, fully cryogenic, partially superconducting) • Demonstrate key tall poles for high power superconducting (stator cooling, non-contact rotor current supply, low AC loss, cost, flight-like requirements, etc.)

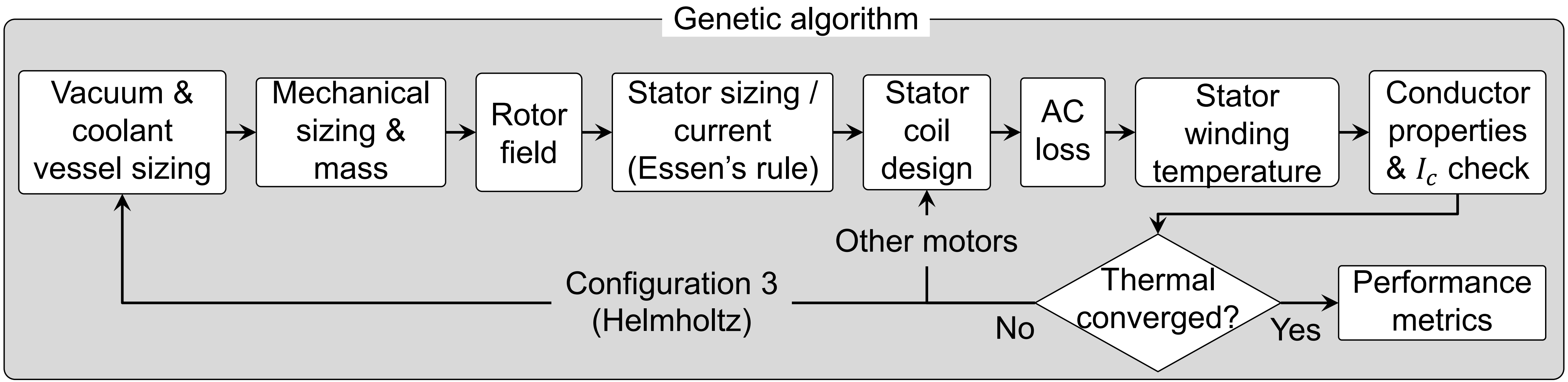
Motor Specifications

Parameter	Requirement	Goal
Continuous power, MW	5	-
Rated speed, rpm	1,500 – 3,000	-
Efficiency at rated speed	≥ 99.5%	≥ 99.9%
Continuous specific power, kW/kg	≥ 20	≥ 40
Rotor field source & temperature	HTS (cryo) or PM (> room temp.)	-
Stator conductor & temperature	Metal (cryo)	Superconducting (cryo)
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 Configuration Study

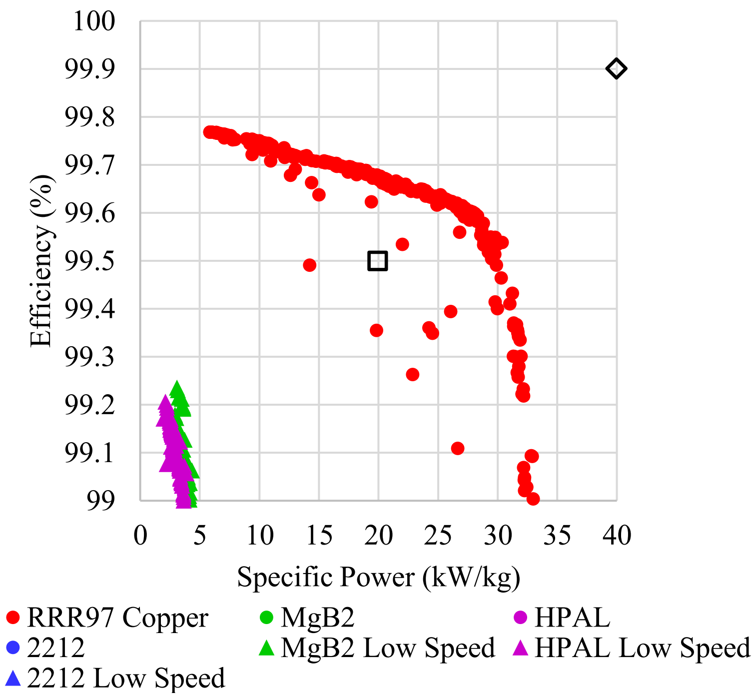
- Lower fidelity motor design codes based on analytical equations developed for 8 different motor configurations
  - Configurations span different magnetic flux directions, number and position of rotors & stators, rotor field source (permanent magnet vs electromagnets), & vacuum vessel approaches
- Included all appreciable losses and approximated the total mass (magnetic + mechanical)
- Evaluated different stator conductors and cryogens
- More details in [6]



6. https://ntrs.nasa.gov/citations/20250003104

Motor Configuration Study

- Permanent magnet motors struggle to meet requirement (99.5% efficiency & 20 kW/kg), except for novel Helmholtz motor that enables stators employing high temperature superconductors
- Fine diameter Litz wire performs surprisingly well, although performance noticeably drops as wire gauge enlarges from 50 to 40 AWG
- Only modest reductions in specific power if GHe used as stator coolant instead of LNe, although improvements to cryofans would be desired for actual application
- Some axial flux configurations only feasible if vacuum and coolant vessels are considerably stiffened



Example Pareto front for one configuration

Motor Configuration Study

Partially cryogenic motors with permanent magnet rotor

Highest performing to date:

Helmholtz motor with HTS stator
(99.78% at 20 kW/kg • 99.5% at 28.5 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 • Reliant on reducing emf for circulating currents (phase voltage constraint)

Fully cryogenic motors with HTS rotor

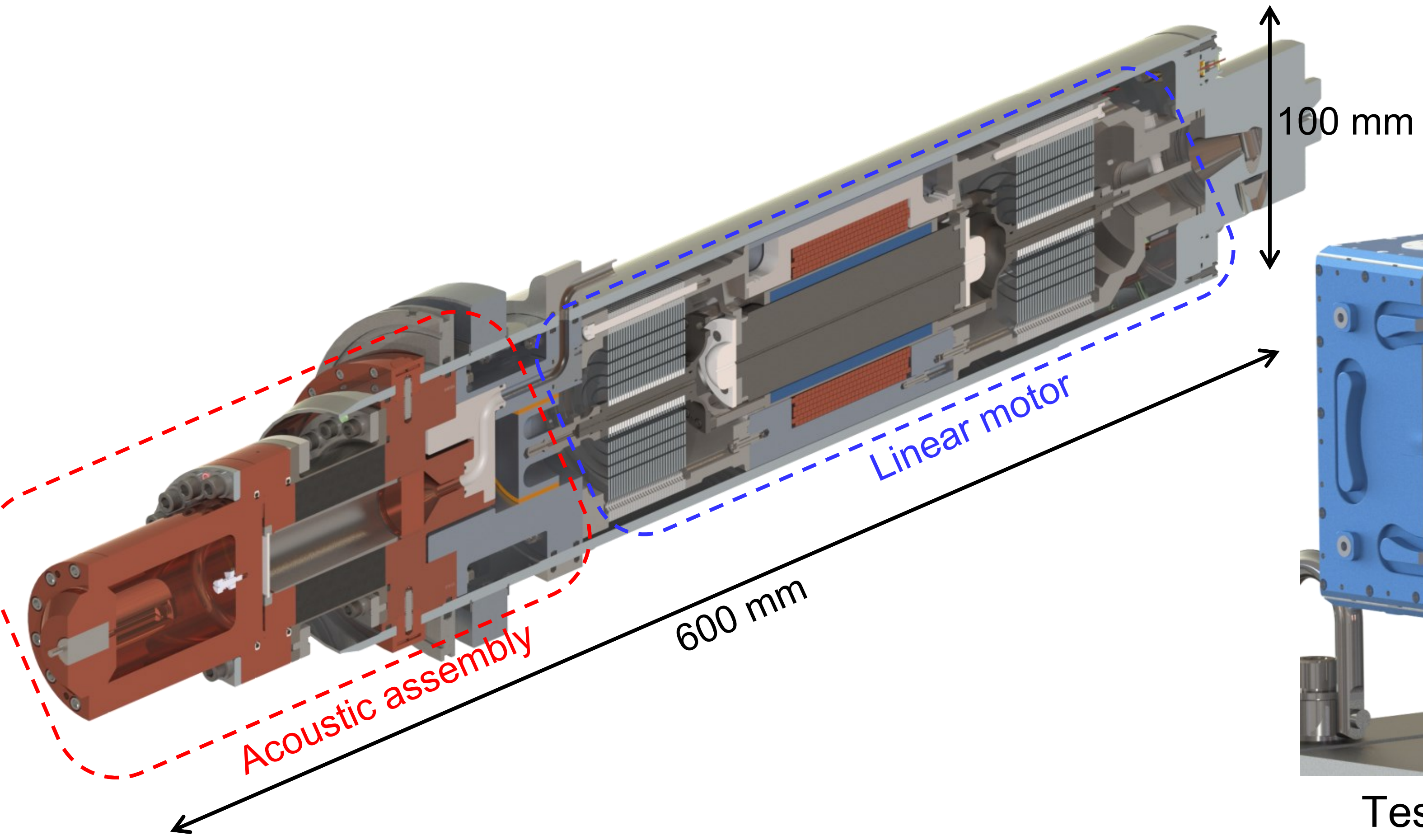
Highest performing to date:

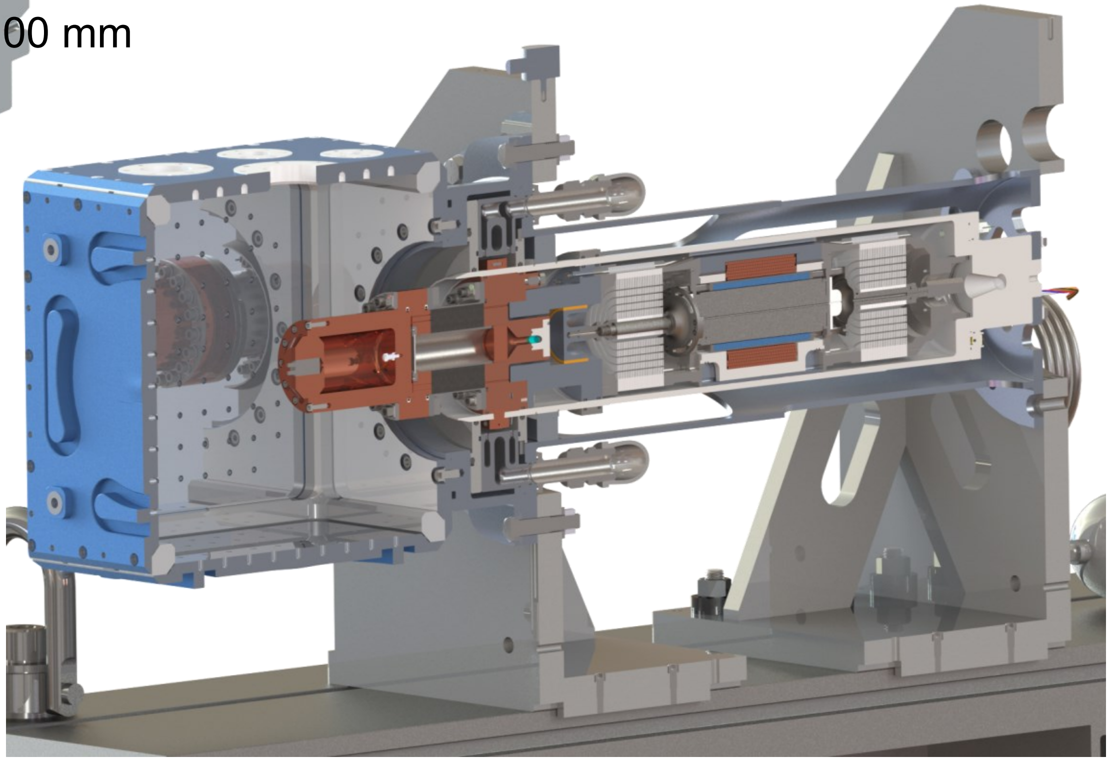
radial flux inner rotor with Cu Litz stator
(99.66% to ~99.75% at 20 kW/kg • 99.5% at 30 to ~40 kW/kg)

Pros	Cons
• 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

Cryocooler Development

- Stirling-type pulse tube cryocooler designed for NASA's 1.4 MW motor [7]
  - Designed to lift 50 W at 50 K with 1.8 kW input power
  - Fits within motor's 100 mm diameter shaft & rotates up to 6,800 rpm





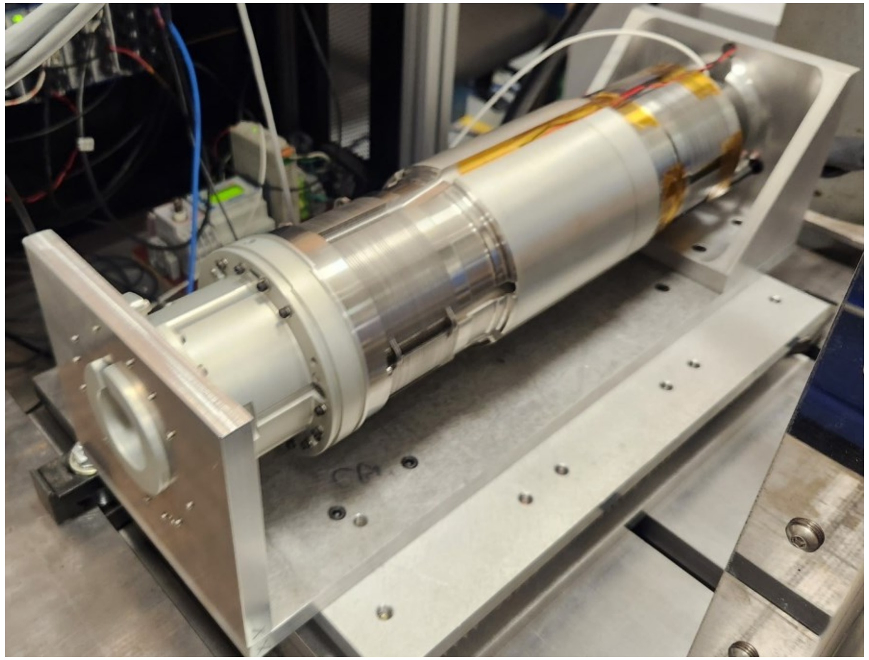
Test rig for stationary (non-rotating) operation

7. https://www.nasa.gov/eap-technology/electric-machines/hemm/

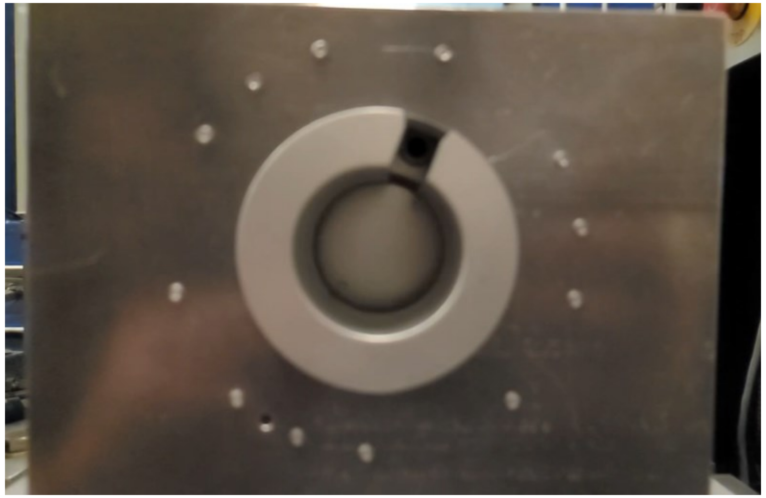
Cryocooler Development

Linear motor

- v1 motor passed 10^7 cycle fatigue test
- v2 motor assembled with piston & compression cylinder and tested to $>10^6$ cycles
  - Successfully operated near resonance at range of frequencies and displacements with no piston-to-cylinder contact
- Used modeling & test results to identify source of unexpectedly low force output



v2 motor assembly

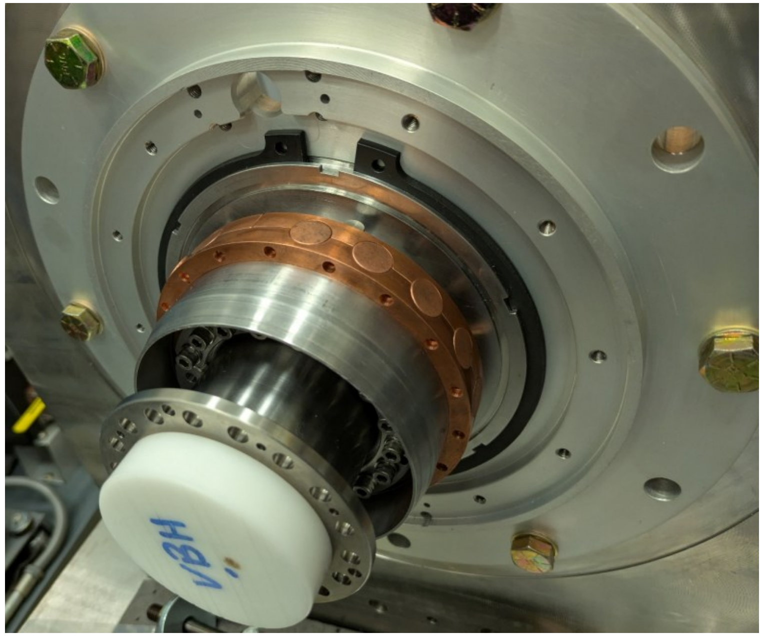


View from end of piston

Cryocooler Development

- Completed engineering drawing package
- All but 1 part received
- Completed fit check of most parts
- Preparing for pressure testing of (a) PAO coolant system and (b) helium system
- Seeking to complete stationary testing of cryocooler by end of September

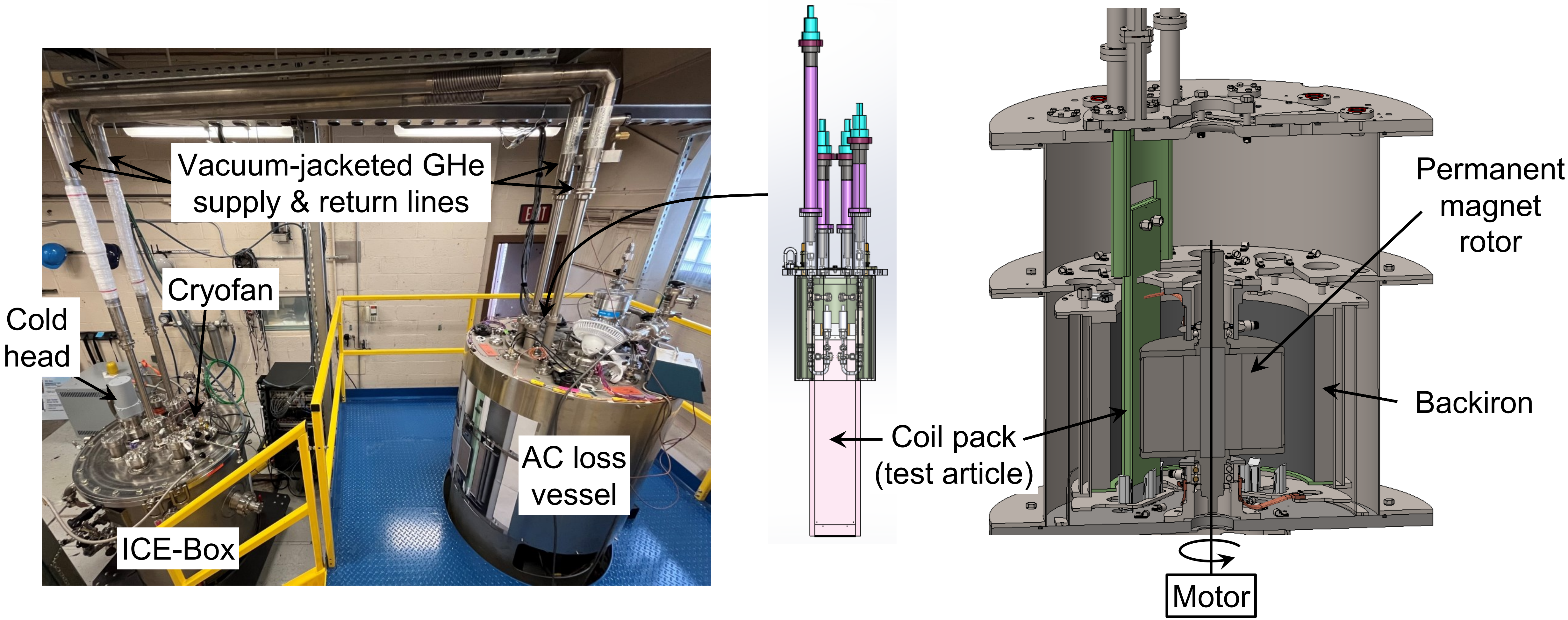
(left) acoustic assembly without internal parts, (right) acoustic assembly + linear motor test fit into the shaft



Successful fit check between shaft, acoustic assembly, and heat sink

Conductor AC Loss Testing

- Developing conductors and electric machines is challenging without data to validate AC loss models
- Very limited AC loss data is available, particularly under magnetic fields relevant to machines
- AC loss rig measures loss via standard calorimetry & null calorimetry

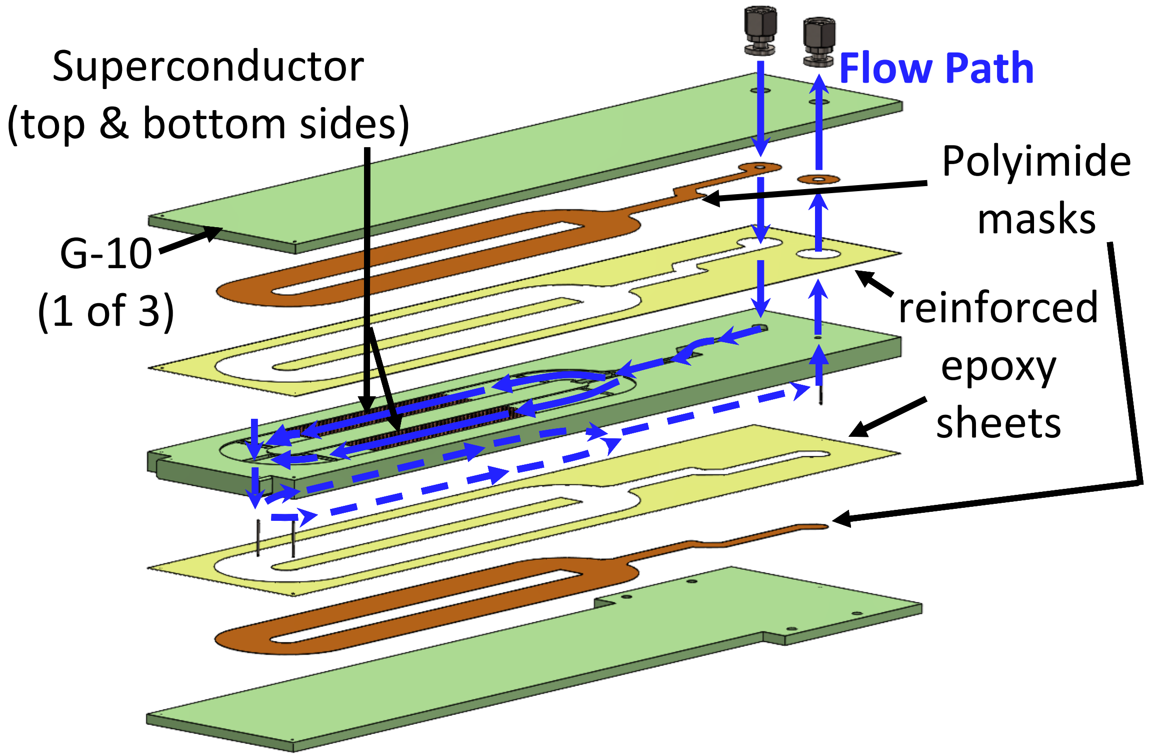


Conductor AC Loss Testing

Test rig's capabilities

Parameter		Capability
Test article temperature, K		~20 to 293
Magnetic excitation	Frequency, Hz	0 to 400
	Magnitude, T	~0.45
Cooling system	Coolant	GHe
	Working Pressure, bar	up to 5.2
Target AC loss, W		~5 to 50
Expected tare loss, W		< 2

Current test article



Current status:

- Fully operational with approval for unattended operation
- Cool down from ambient takes ~12 hours
  - Each test at a given temperature expected to take 1-2 days
- Currently finishing checkout testing

Future Work

- Down select motor configuration for detailed design and eventual manufacture
- Initiate mechanical design and higher fidelity electromagnetic and thermal analyses
  - Complete higher fidelity analysis of AC loss in HTS stator of Helmholtz motor
- Conduct more comprehensive study on construction of stator conductor then down select stator conductor

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Contact Info

justin.j.scheidler@nasa.gov

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Glenn Research Center
Lewis Field
RESEARCH AND TECHNOLOGY
NASA
Glenn
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