TFAWS Cryogenics Paper Session

Thermal Design, Analysis, and Testing of a Conductively-Cooled, High Temperature Superconducting Rotor for a 1.4 MW Electric Machine for Aeronautics Applications

Erik J. Stalcup[1], Justin J. Scheidler[1], Thomas F. Tallerico[1], William Torres[2], Kirsten P. Duffy[3], Tysen T. Mulder[1]

Presented By

Erik Stalcup

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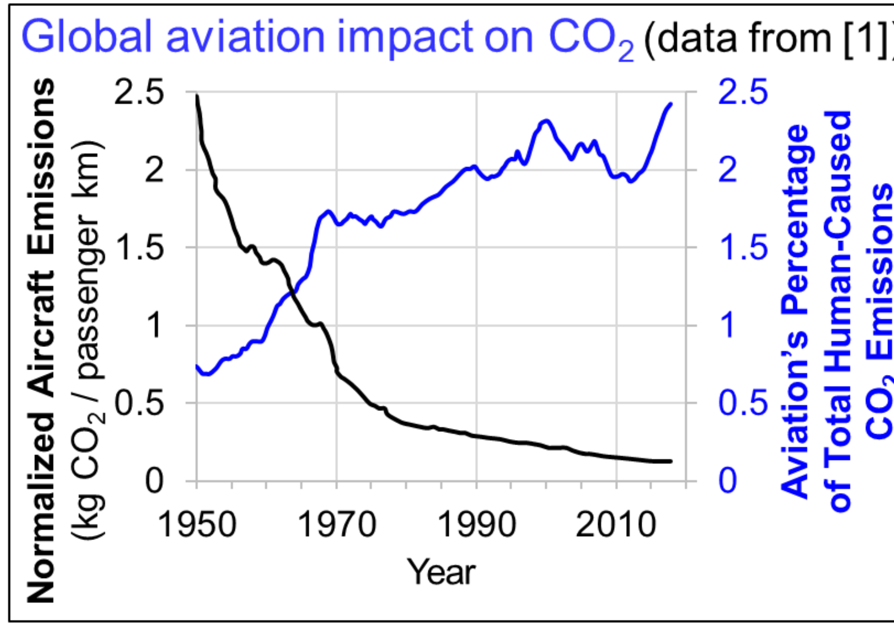
1. NASA Glenn Research Center
2. Wolf Creek Federal Services
3. University of Toledo

Motivation

- Aviation impacts:
  - Climate
    - **CO_2** (dominant), **contrails** (~½ impact of CO_2), **H_2O vapor**, **soot**
  - Environment
    - Air quality – **NOx** (dominant), **sulfur**
    - Noise
- Despite significant progress in efficiency, global CO_2 emissions from aviation growing at increasing rate
- 2 options:
  - Change fuel (e.g., jet A → SAF or H2)
  - Electrify
- NASA's High-Efficiency Megawatt Motor (HEMM) sized as generator for NASA's STARC-ABL concept

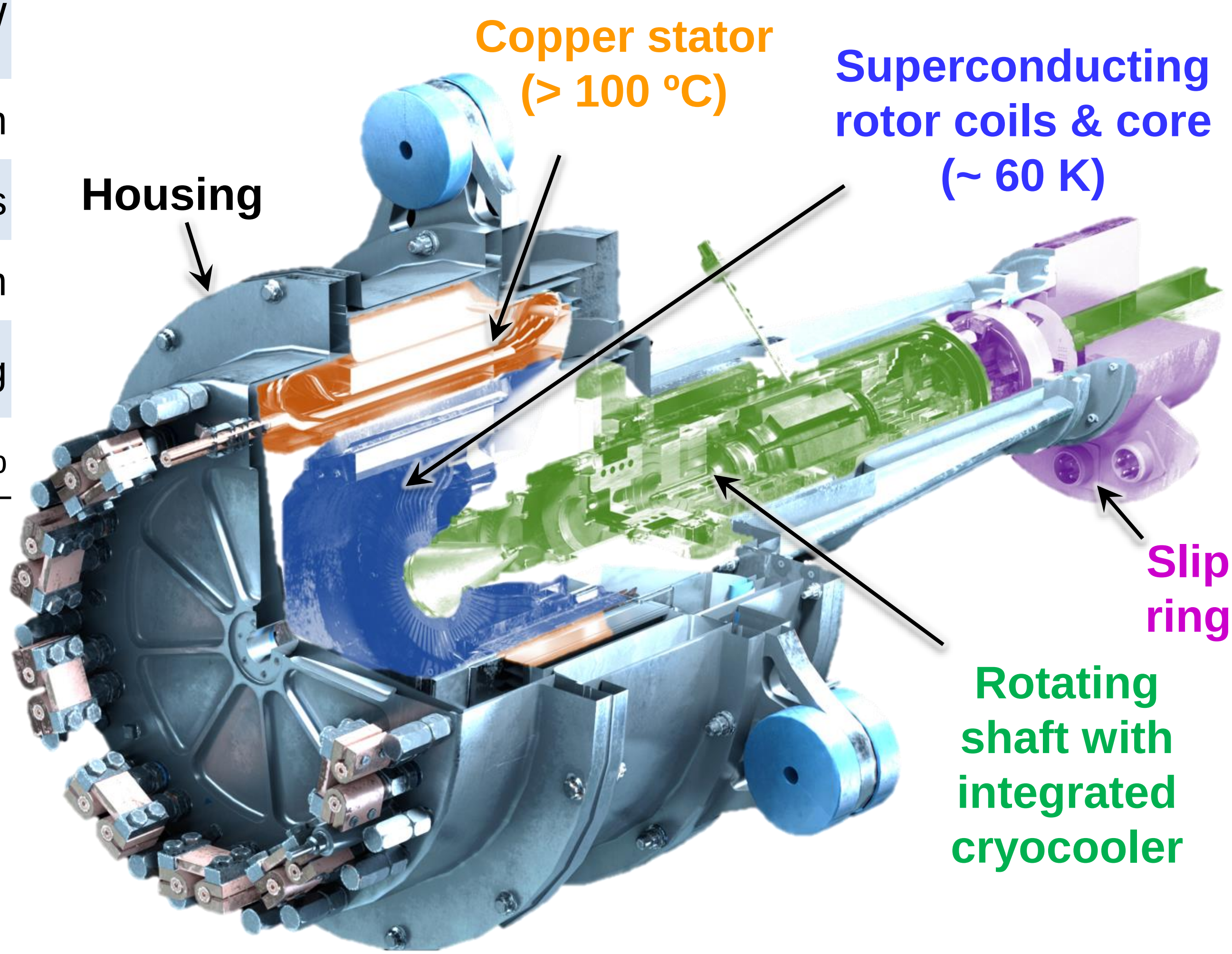


STARC-ABL

1. Lee, D.S. et al., Atmospheric Environment 244, 117834, 2021.

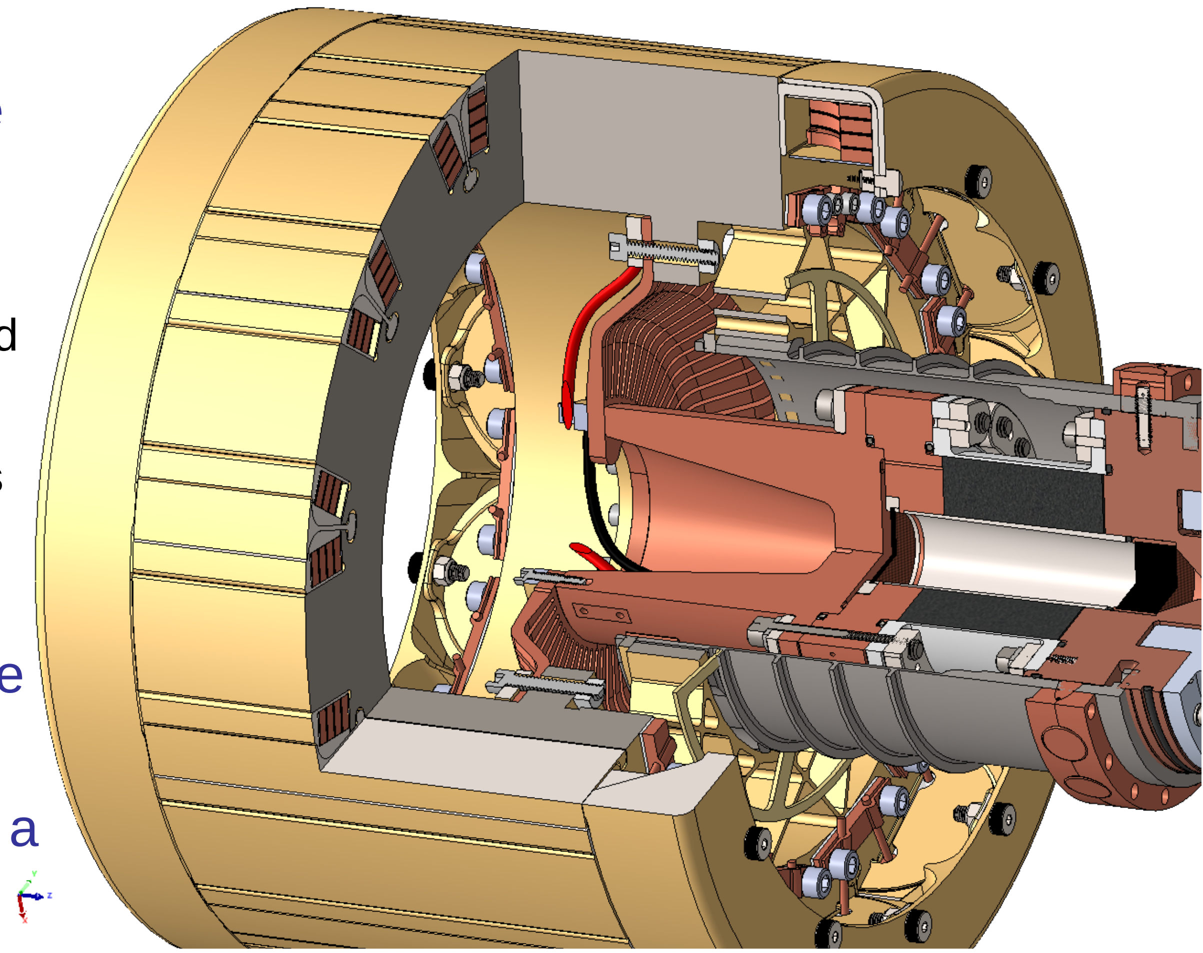
NASA's High-Efficiency Megawatt Motor (HEMM)

Parameter	Value
Rated continuous power	1.42 MW
Nominal speed	6,800 rpm
Tip speed	107 m/s
Rated torque	2 kNm
Electromagnetic specific power goal	16 kW/kg
Efficiency goal	> 98%



HEMM Thermal Design

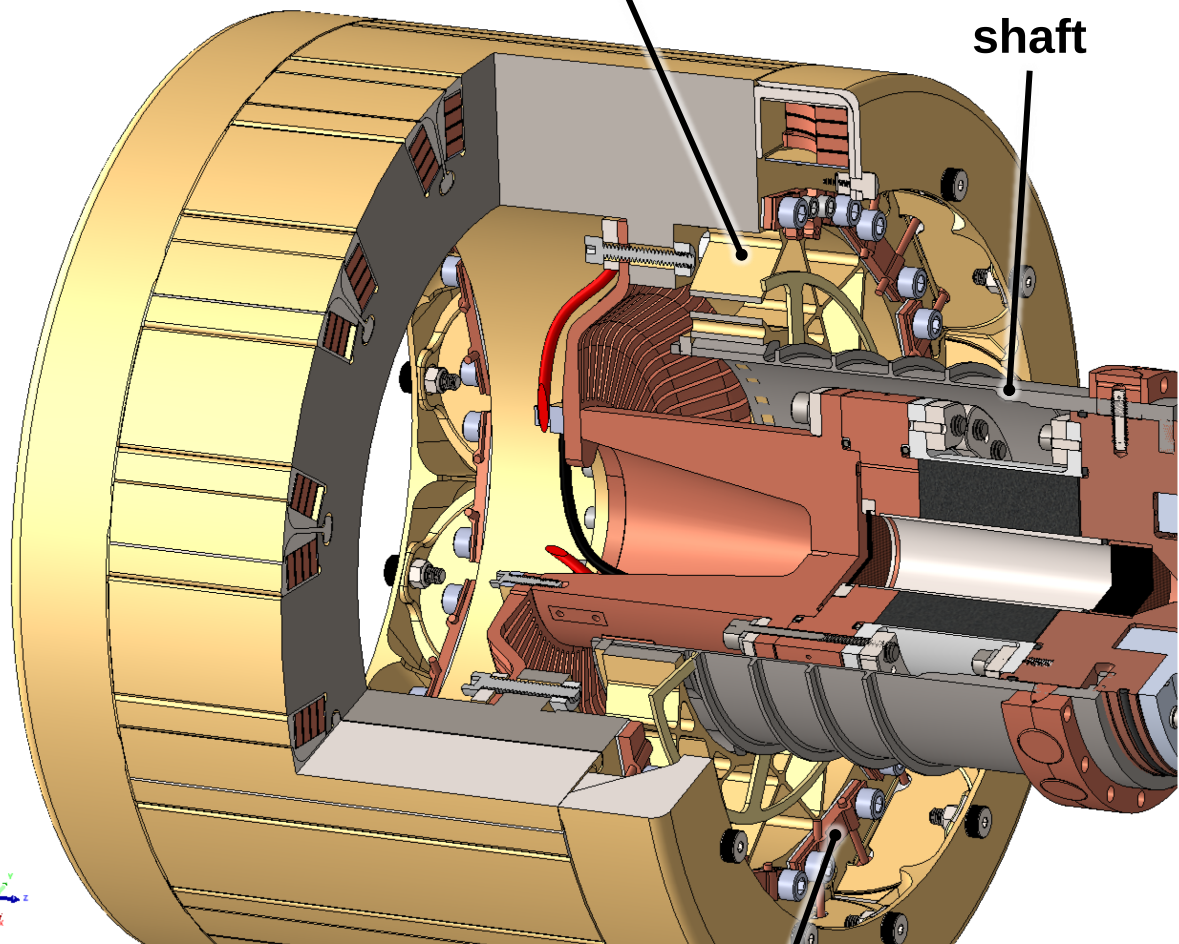
- The thermal design of the HEMM rotor is focused on conductively cooling the superconducting coils.
- Cooling is provided by the integrated pulse tube cryocooler.
- Two requirements:
  - The cryocooler is designed to lift 51 W of heat at a temperature of 50 K
  - The superconducting coils must operate at 62 K or lower
- Therefore, the rotor has been designed to minimize the heat load on the cryocooler and keep the coils at 62 K or lower with a cryocooler cold tip temperature of 50 K.



HEMM Thermal Design

Rotor Heat Sources:

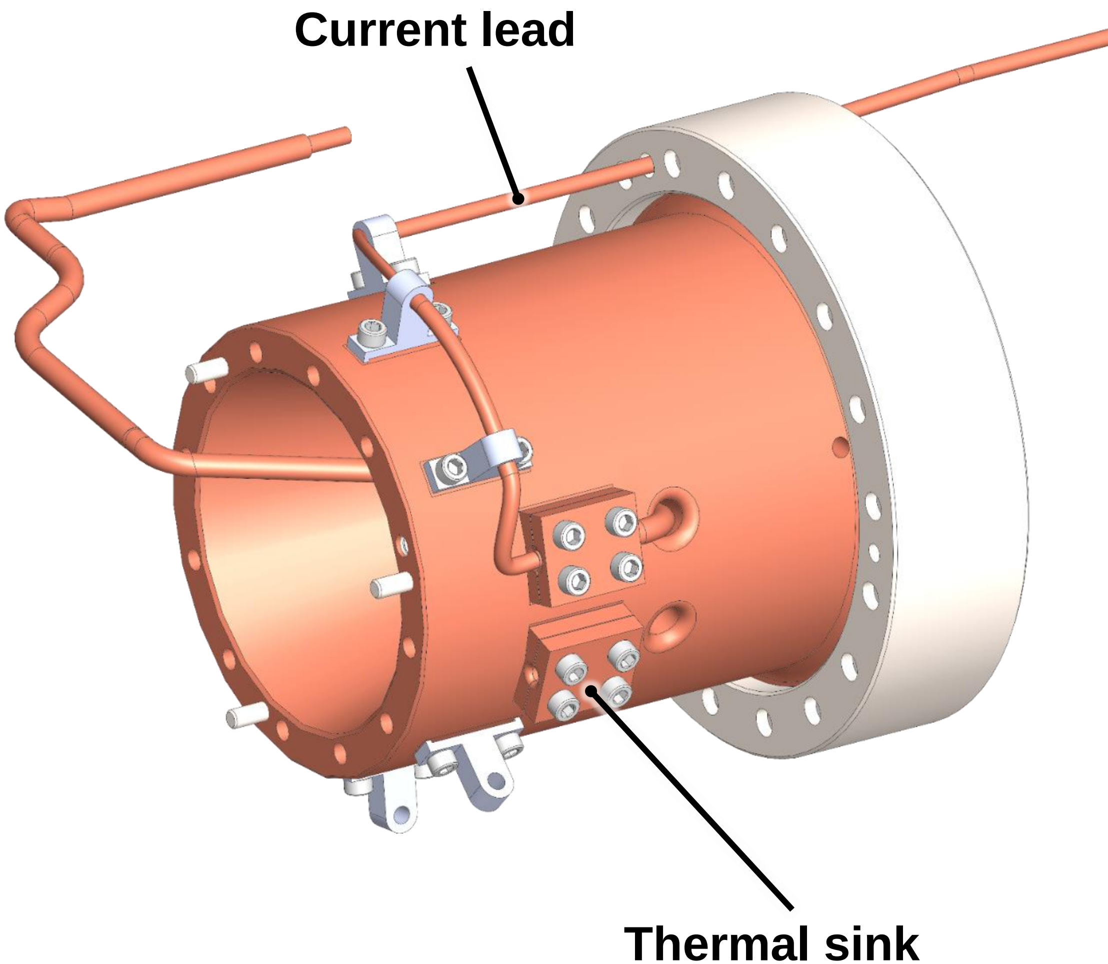
- Shaft Conduction:
  - Heat enters the rotor from the shaft, which is coupled with the heat exchanger at the hot end of the cryocooler
  - Mitigated by thin titanium shaft and webbed structural connection
- Convective Heating and Windage Losses
  - Heat transfers from the warm stator to the rotor through the air and with frictional losses to the air during rotation.
  - Mitigated by operating in a < 10^{-3} torr vacuum enclosure
- Radiative Heating
  - Heat transfer from the warm stator to the rotor through radiation
  - Mitigated by
    - coating the inside of the vacuum enclosure in low-emissivity non-electrically conductive paint (ε = 0.13)
    - polishing and coating all rotor components with physical vapor deposited gold (ε = 0.018)
- Coil-to-Coil Current Leads and Coil Solder Joints
  - I^2R heating will occur in the coil-to-coil leads and at solder joints.



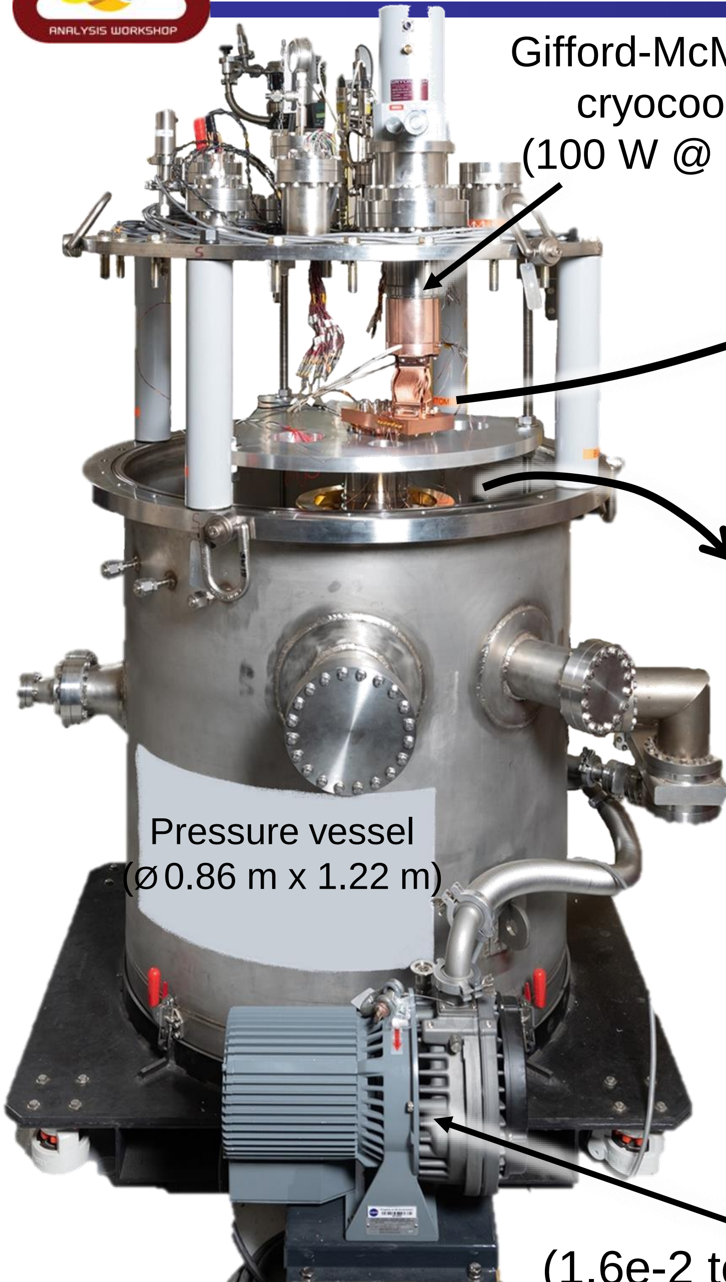
HEMM Thermal Design

Rotor Heat Sources:

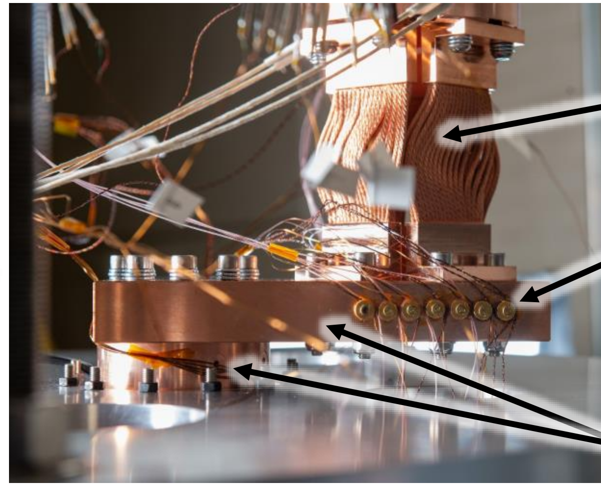
- Current Lead Conduction and I^2R Losses
  - Heat is conducted from feedthroughs at the hot end of the cryocooler
  - Heat is generated via I^2R losses
  - This is mitigated by optimizing the length/diameter of the current lead to minimize the sum of both effects
  - The lead is coupled to the cold tip at the thermal sink in order to reject the heat away from the coils



Experimental Setup – NASA GRC ICE-Box



Gifford-McMahon cryocooler (100 W @ 25 K)



4x thermal straps (4.6 W/K total)

Sensor lead wire heat sink bobbins

Cold tip extensions (solid Cu 101)

Support plate (Al 6061)

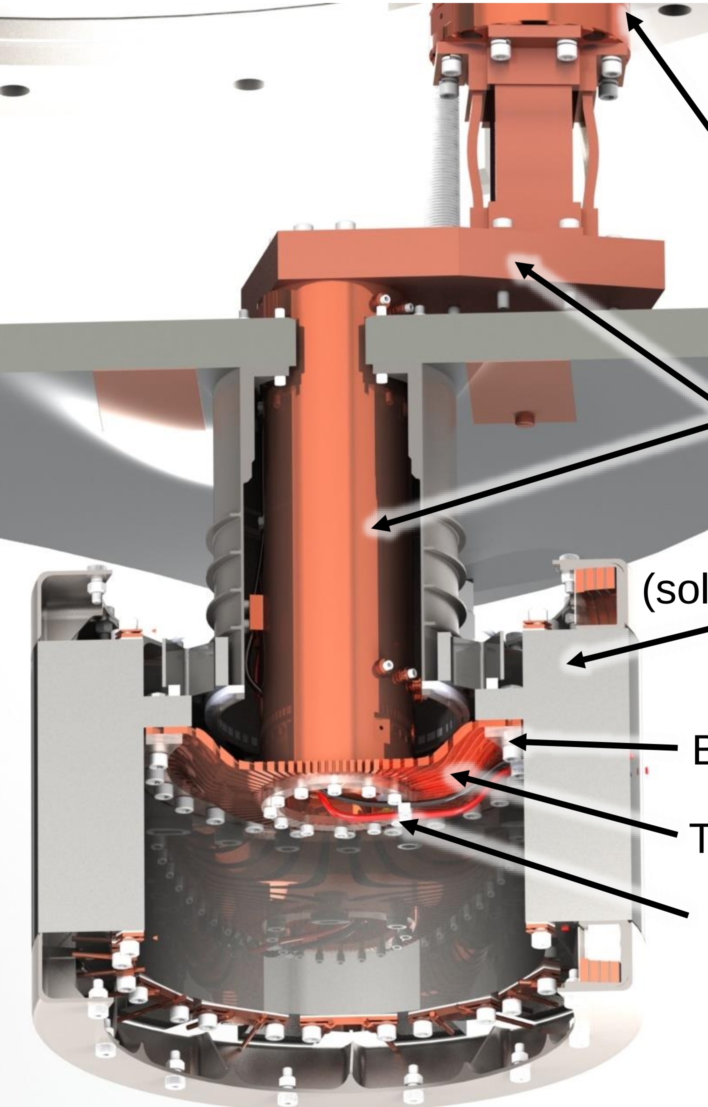
3x support plate heaters

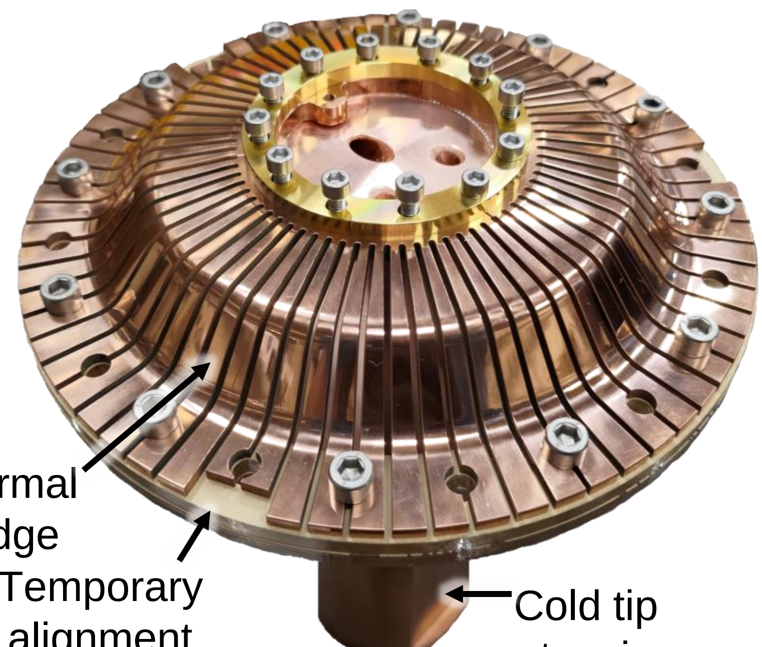
Shaft section (Ti-6Al-4V)

Rotor assembly

Scroll pump (1.6e-2 torr when cryocooler off)

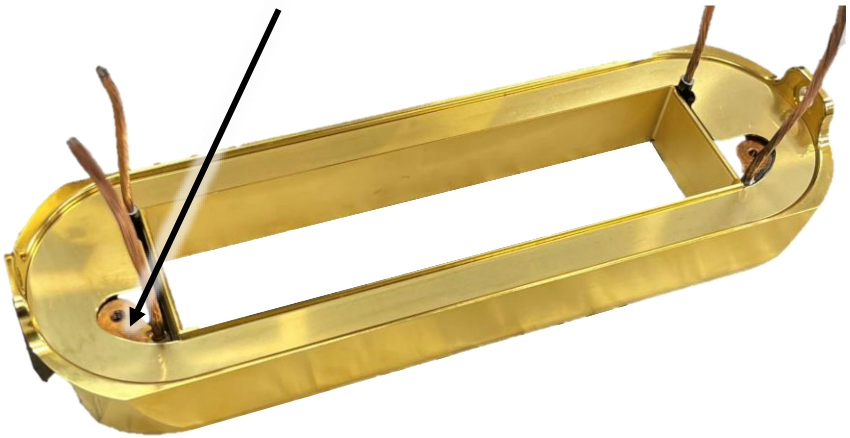
Experimental Setup – Assembly



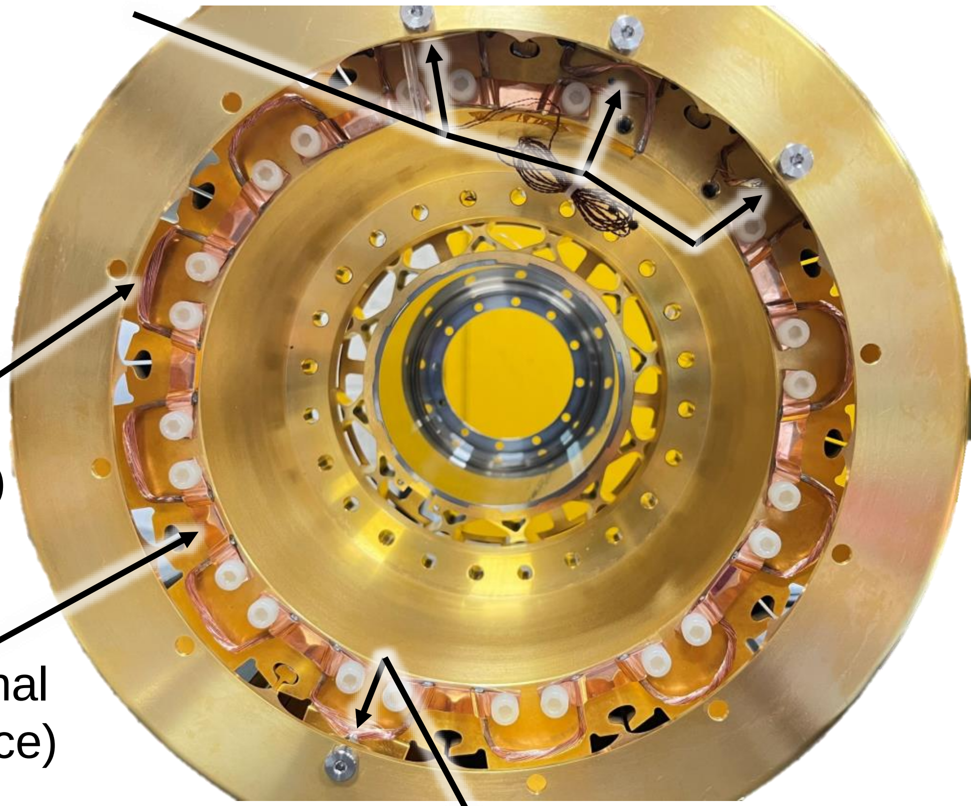


Experimental Setup – Assembly

Current terminal &
threaded mount for RTD (1 of 2)



Superconducting
coils



Copper wire loop
(1 of 9 on each axial face)

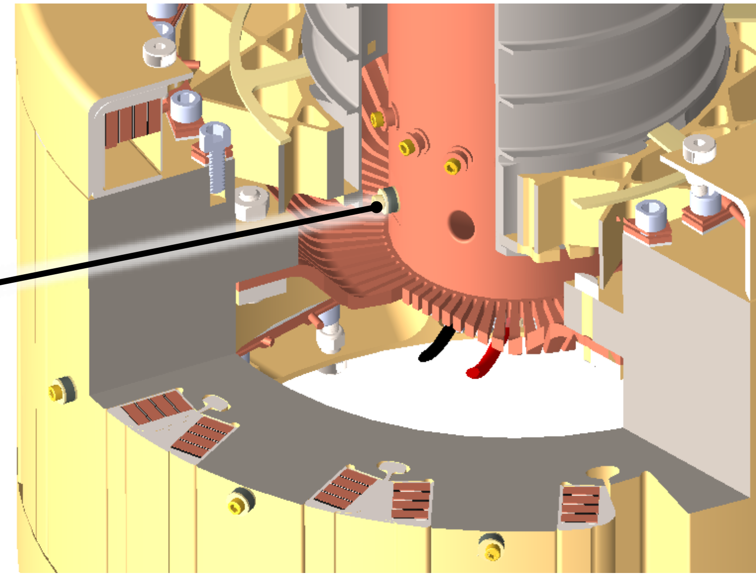
Heat sunk copper terminal
(1 of 11 on each axial face)

Empty coil fixture

Experimental Setup - Instrumentation

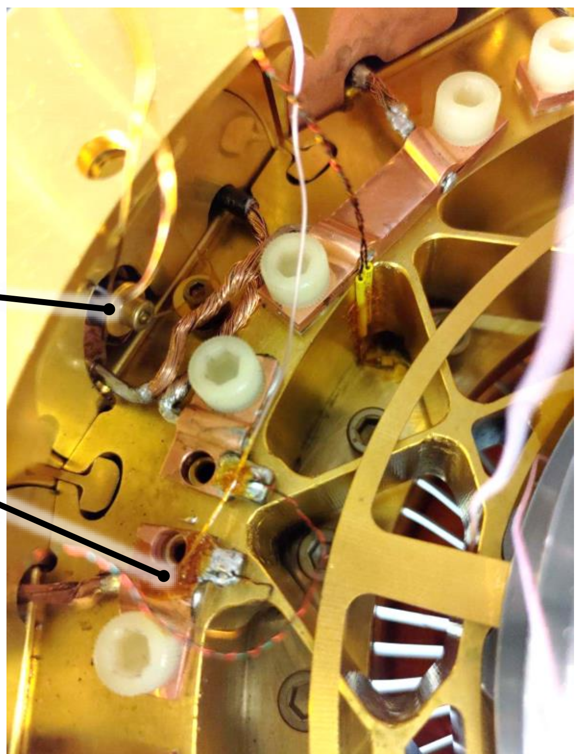
- Vacuum feedthrough channels
  - 15 RTDs
  - 9 Type E thermocouples
  - 4 voltage probes
  - 2 heaters
  - 1 pair high current leads

CU7
on cold tip extension

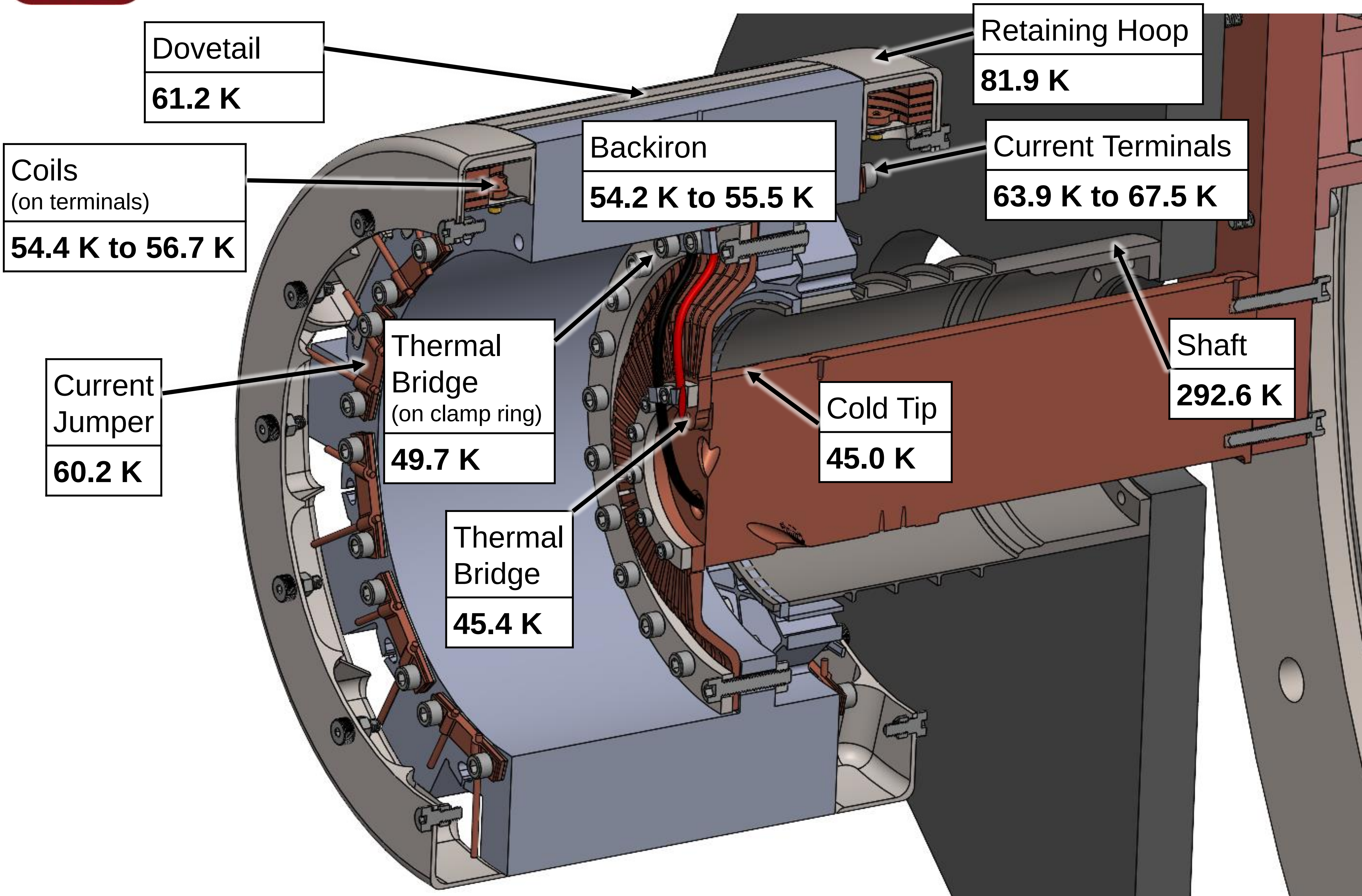


CU6
on coil terminal

TC6
on current lead terminal



Test Results



Test Results

- Steady state: >90% of temperature sensors changing at rate < 0.2 K/hr
- Most tests: cold tip held at 45 K rather than 50 K (HEMM's nominal)
- **Allowable ΔT from cold tip to coils: 12 K**

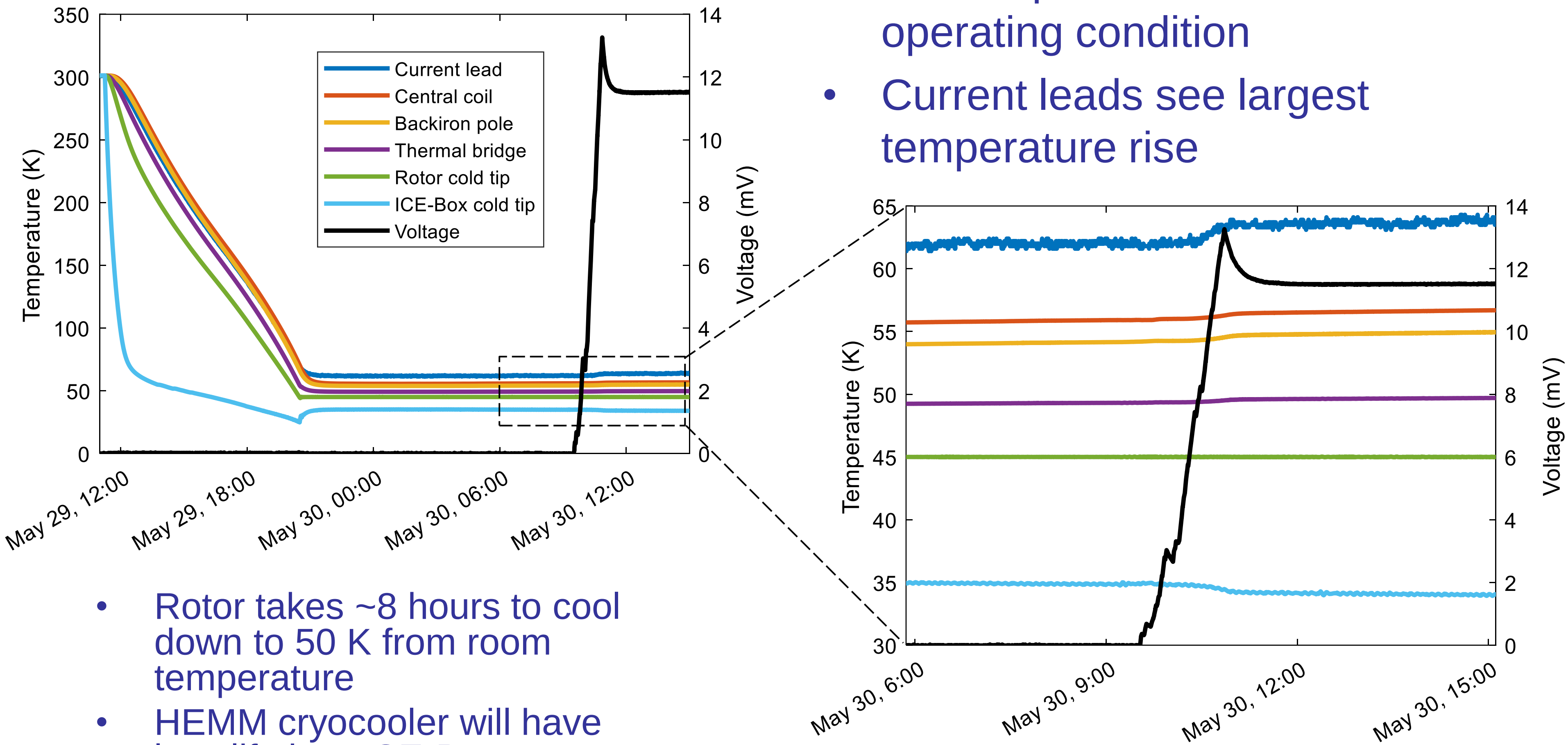
Test Point	Rotor Current (A)	Support Plate Heater Enabled?	HEMM's Cold Tip Temp. (K)	Coil Temp. (K)		ΔT, Cold Tip to Coils (K)	
				Average	Peak	Average	Peak
A	0	Yes	48.2	59.6	60.2	11.3	12.0
B	0	No	26.3	39.1	40.1	12.9	13.8
C	0	No	45.0	55.9	56.6	10.9	11.6
D	0	No	45.0	55.2	55.9	10.2	10.9
E	47.5	No	45.0	55.8	56.7	10.8	11.7
F	0	Yes	45.0	56.6	57.3	11.6	12.3

After improvements (to cleanliness, clamping force, instrumentation)

Measured peak ΔT from cold tip to coils (10.9 to 12.3 K) is acceptable, but with no margin

Transient Response

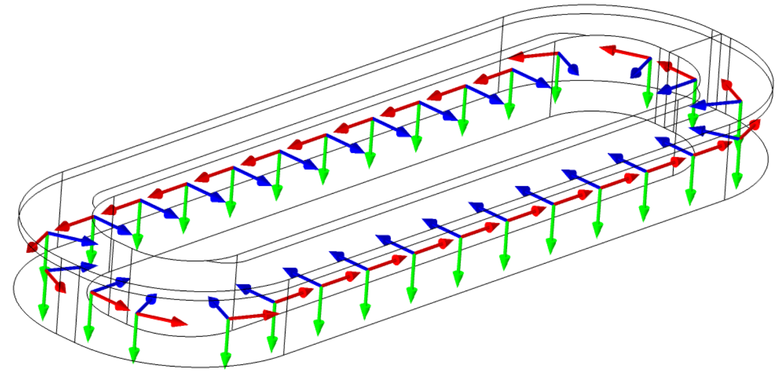
- 1 K to 2 K increase in rotor and coil temperatures at 47.5 A operating condition
- Current leads see largest temperature rise

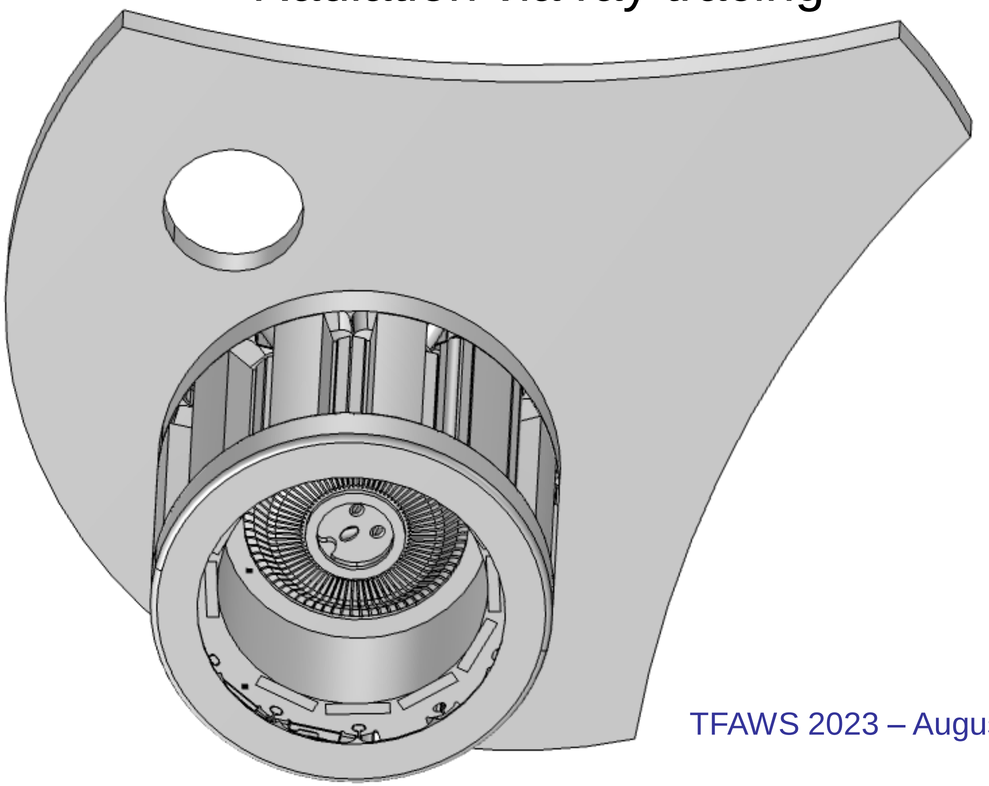


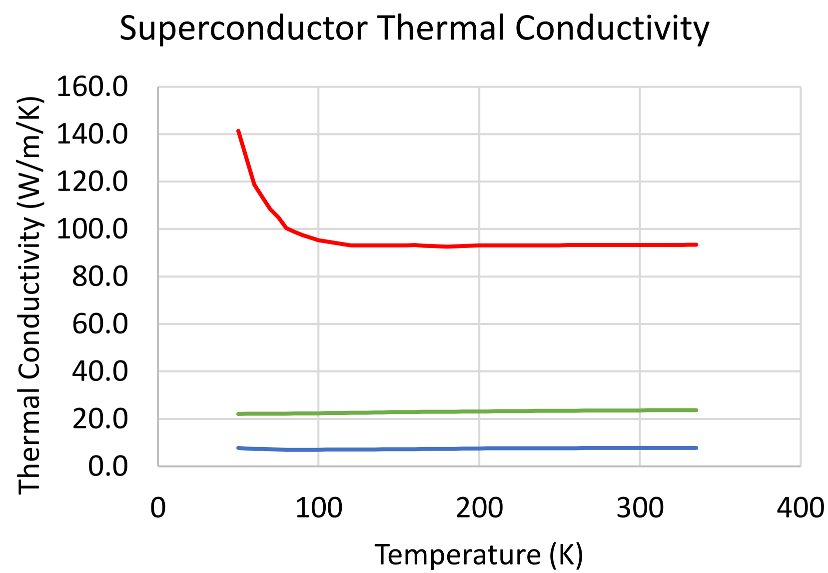
- Rotor takes ~8 hours to cool down to 50 K from room temperature
- HEMM cryocooler will have less lift than ICE-Box cryocooler, but lower thermal mass

Thermal Modeling and Correlation

- Thermal modeling done in COMSOL 5.6
  - Temperature dependent thermal conductivity for all materials
  - Curvilinear coordinates used for coil thermal conductivity
  - Radiation via ray tracing

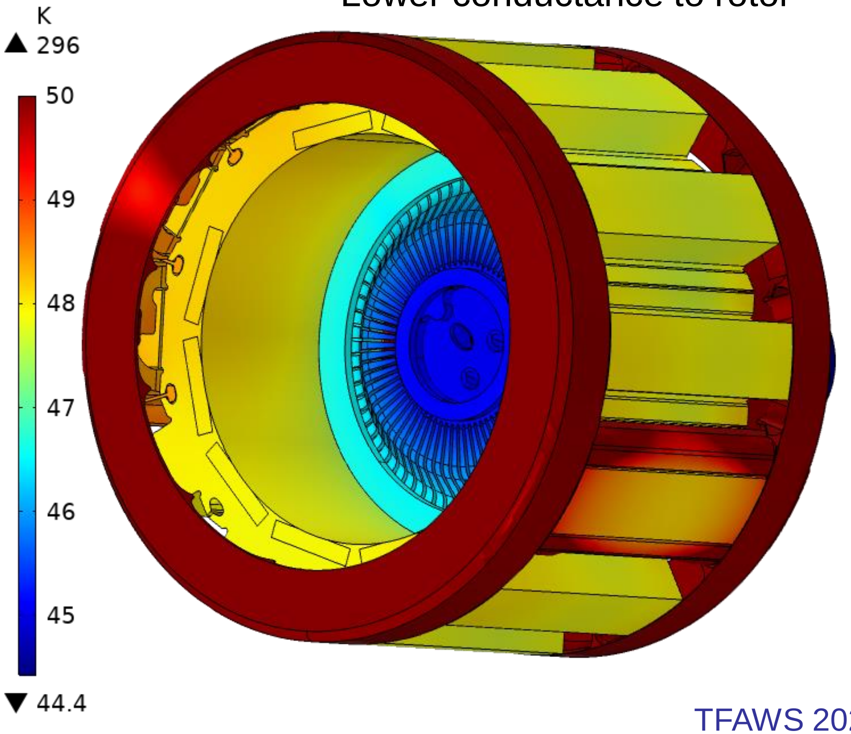






Thermal Modeling and Correlation

- Uncorrelated model underpredicts temperatures
  - Average rotor and coil temperatures are warmer in test. Potential causes:
    - Higher PVD gold emissivity
    - Higher heat leak from shaft
    - Lower conductance at thermal bridge interfaces
  - Current leads are somewhat warmer in test. Potential causes:
    - Poor current lead thermal sinking at cold tip and/or backiron interfaces
    - Higher I^2R heating
  - Hoop is much warmer in test:
    - Lower conductance to rotor



	Measured Temp. (K)	Predicted Temp. (K)	Error (K)
Coils	55.9	48.6	**-7.4**
Backiron	54.9	48.1	**-6.8**
Current Leads	65.7	48.4	**-17.3**
Rotor Cold Tip	45.0	45.0	**0.0**
Hoop	81.9	48.8	**-33.0**

RMS Error = 11.4 K

Thermal Modeling and Correlation

- Model correlation is in progress. Largest impact changes include:
  - Addition of heat at DC terminals from conduction and I^2R losses based on standalone model (~2 watts)
  - Reducing bridge to backiron contact conductance
  - Raising PVD gold emissivity
  - Lowering hoop to rotor contact conductance
- Several changes have the same effect of raising the average rotor temperature. It is difficult to determine which are the cause(s) of the higher temperatures.
  - Re-test with additional temperature sensors. Potentially fix debonded/anomalous sensors.
  - Post-test emissivity measurements

	Measured Temp. (K)	**Predicted Temp. (K)**	**Error (K)**
Coils	55.9	55.4	**-0.5**
Backiron	54.9	55.6	**0.7**
Current Leads	65.7	72.1	**6.4**
Rotor Cold Tip	45.0	45.4	**0.4**
Hoop	81.9	67.4	**-14.5**

RMS Error = 4.5 K

Conclusions

- Stable operation of rotor at rated current and rated temperature demonstrated while conductively cooled with acceptable ΔT
- Model correlation reduced RMS error from **11.4 K** to **4.5 K** and identified opportunities to reduce $\boldsymbol{\Delta T}$
  - Improve current lead thermal sinking
  - Potentially improve thermal bridge contact conductance and/or PVD gold emissivity
- Forward work
  - Continuing model correlation with other test points
  - Post-test emissivity measurements
  - Integrating design changes and model refinements into future HEMM designs

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Contact Info

NASA	**Erik Stalcup**	erik.j.stalcup@nasa.gov
	Justin Scheidler	justin.j.scheidler@nasa.gov
	Thomas Tallerico	thomas.tallerico@nasa.gov
Wolf Creek Federal Services	William Torres	william.torres@nasa.gov
UT	Kirsten Duffy	kirsten.p.duffy@nasa.gov