Stationary testing of a pulse tube cryocooler designed to rotate at 6800 RPM with the superconducting rotor of an electric machine

William R. Sixel[a], Paul J. Passe[b], Aaron D. Anderson[a], Don Fong[a], Casey J. Theman[a], Justin J. Scheidler[a]

[a]NASA Glenn Research Center, Cleveland, OH, 44135, USA
[b]HX5, LLC, Brook Park, OH, 44142, USA

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INTRODUCTION

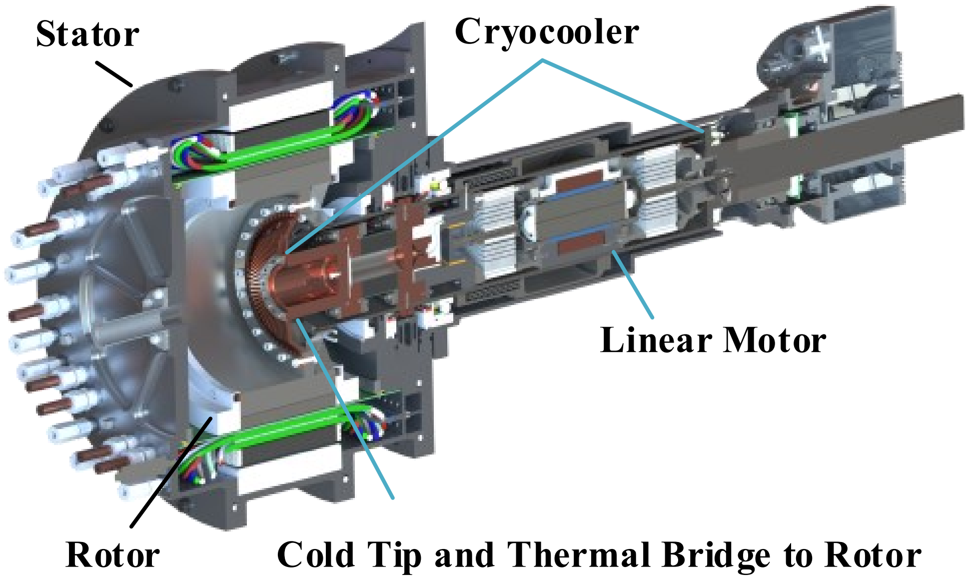
- Electrified propulsion systems are being developed for future aircraft to provide economic, societal, and environmental benefits.
- Superconductors are of high interest for power distribution, circuit breakers, and electric machines to enable very high efficiency and high specific power, but they must be cooled to < 80 K.
- Partially-superconducting wound field machines are of particular interest as the rotor field is only DC.
  - Superconductors have near zero loss under DC excitations but can still incur significant AC losses, and this is an on-going area of research at NASA GRC and elsewhere.
- The HEMM is such a machine that helps provide 2-3% reduction in fuel burn in the STARC-ABL concept [1].

STARC-ABL

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

HIGH EFFICIENCY MEGAWATT MOTOR (HEMM)

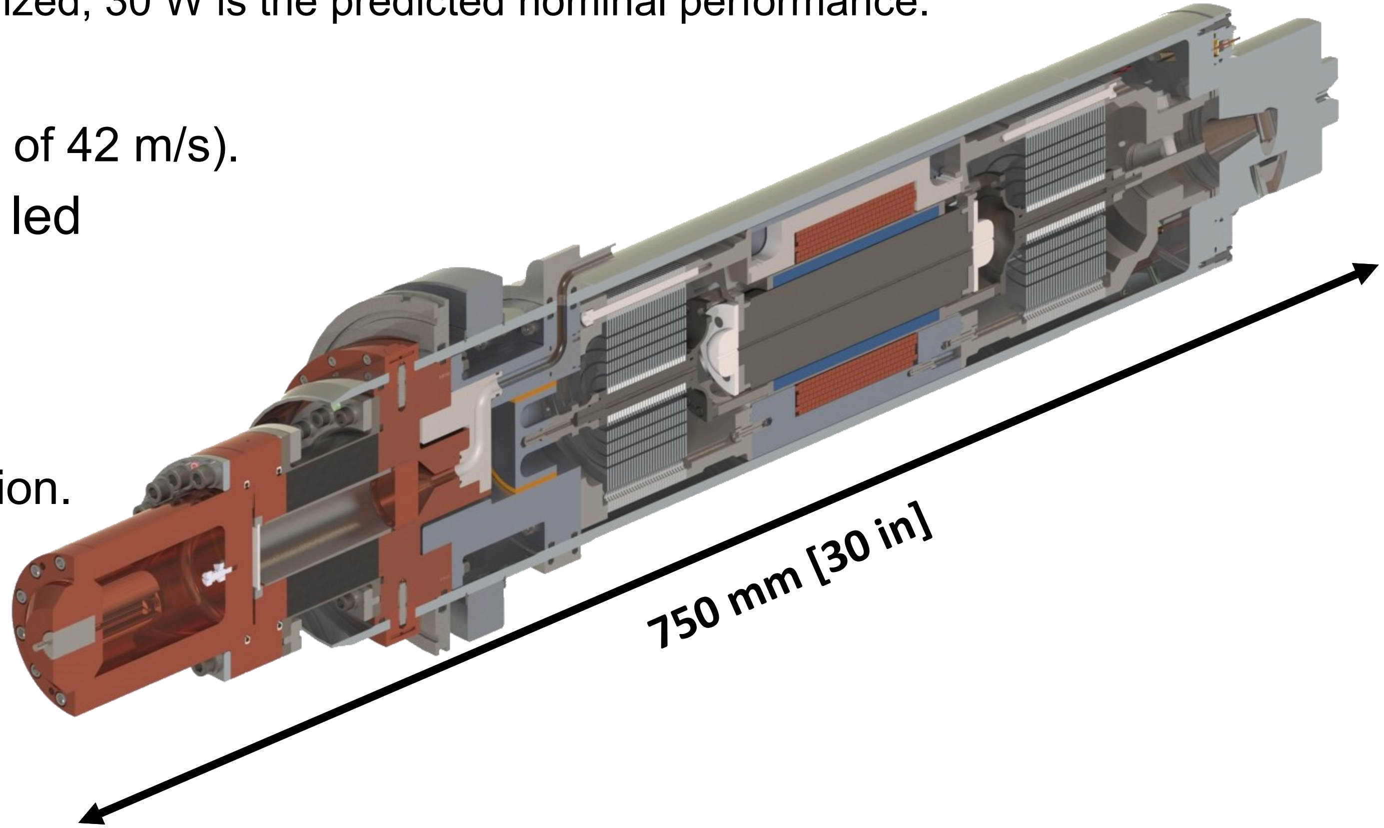
- NASA's High Efficiency Megawatt Motor (HEMM) is a 1.4 MW partially-superconducting wound-field machine intended for use in partially electrified aviation concepts [2].
- Some past superconducting concepts relied on transferring a cryogen to the rotor.
- HEMM uses a cryocooler directly attached to the rotor to cool the superconducting coils.
  - This avoids the need for cryogenic rotating seals.
  - **However, the cryocooler must rotate with the shaft at 6800 RPM.**
  - Stationary rotor cooling successfully demonstrated with off-the-shelf cryocooler [3].



2. https://www.nasa.gov/eap-resources/publications/technology-development/#hemm
3. Scheidler, J.J. et al., IOP Conf. Ser.: Mater. Sci. Eng. 1302 012020, 2024

CRYOCOOLER DESIGN REQUIREMENTS & CHALLENGES

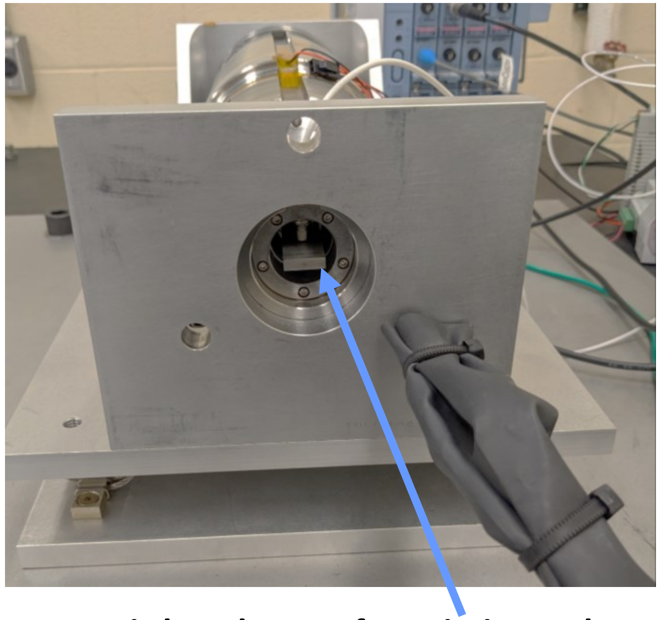
- Mounting the cryocooler inside of the shaft has advantages but introduced significant constraints.
  - Lift 50 W at 50 K.
    - 50 W was original target, but after design was realized, 30 W is the predicted nominal performance.
  - Fit within 110 mm (~4.3 inch) ID shaft.
  - Rotational speed of 6800 RPM (shaft tip speed of 42 m/s).
- Rotation requirement and early trade studies led to a few decisions [2]:
  - Rule out gas bearing, avoid cold moving parts.
    - Select coaxial pulse tube cryocooler for high compactness, single interface for heat rejection.
    - Select flexure bearing linear motor for mechanical robustness.
- Cryocooler was re-optimized following the design of a revised "V2" linear motor and regenerator stock selection.



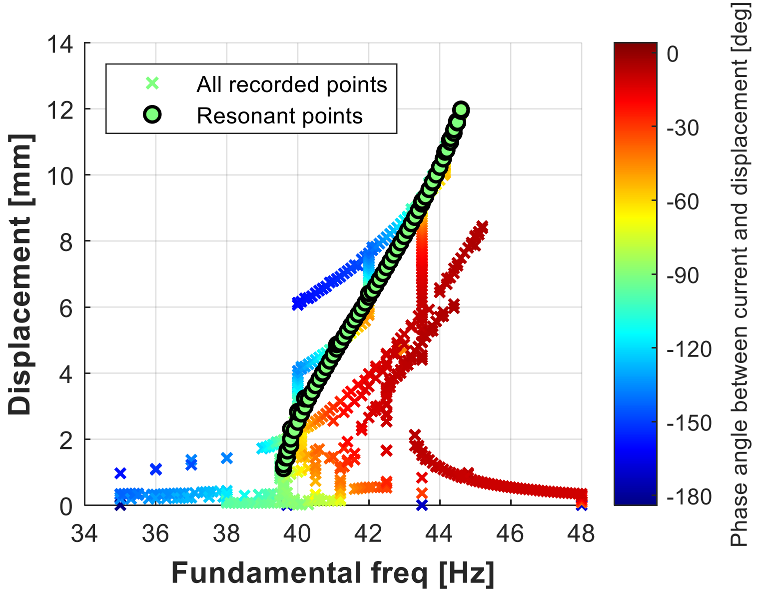
2. https://www.nasa.gov/eap-resources/publications/technology-development/#hemm

LINEAR MOTOR

- Single pole, moving magnet motor, stationary inner iron.
- Flexure bearings
  - ~100 mm OD, designed for 13 mm displacement (26 mm stroke).
- Rotational environment plays into many design features of the motor.
  - Retaining sleeve over magnets as in a rotating PM machine.
  - Heat rejection.
- Observed nonlinearity in the dynamic behavior [4].
  - Resonant frequency increases with displacement.
- **DC bench testing with load cell showed only 58% of predicted force constant [4].**
  - Possibly due to issues with the magnetization [4].
  - For the proceeding testing, we reduced charge pressure to compensate. Expect only 1/3 the lift at 50 K.



Dynamic bench test of proximity probe.

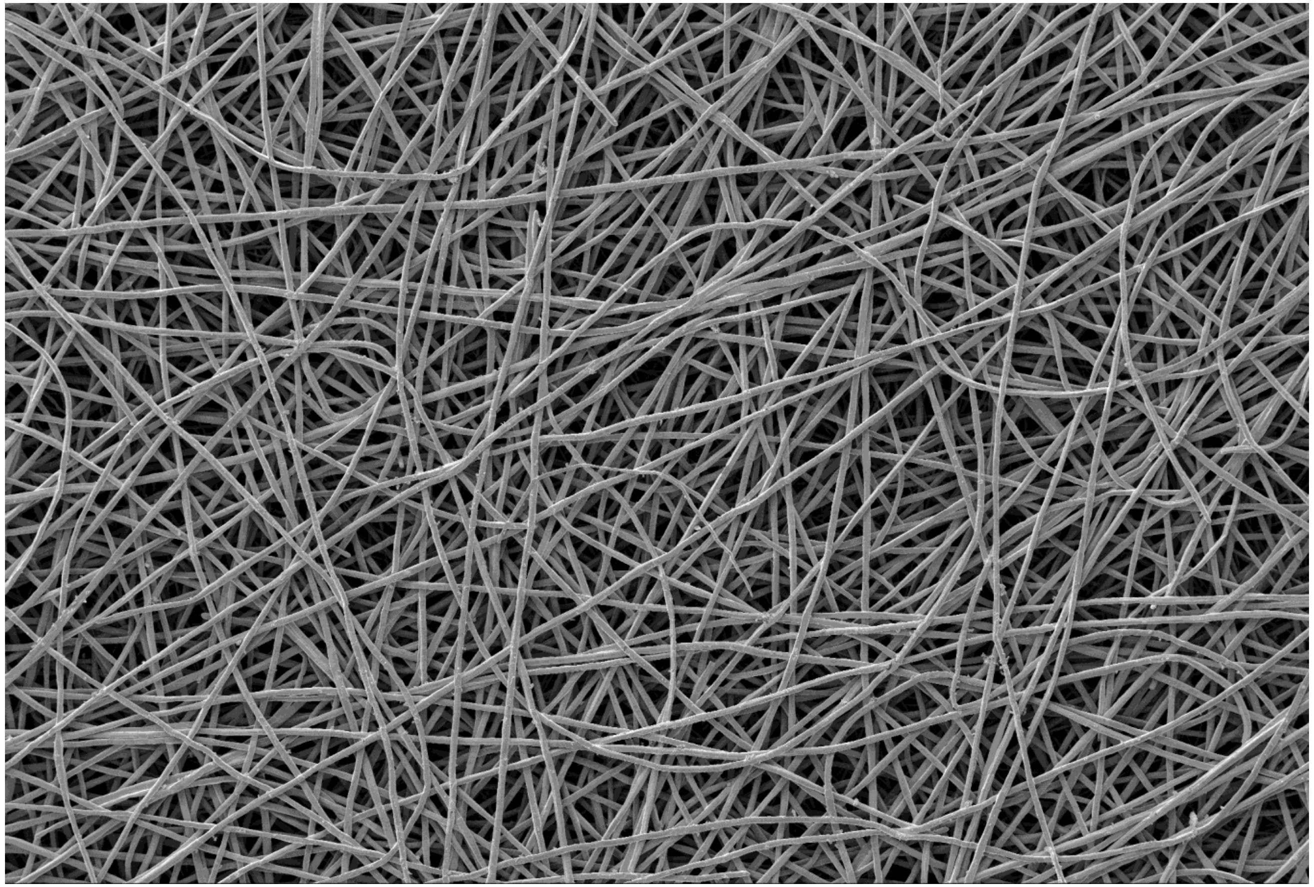


Motor dynamic testing in air; no-load resonant behavior.

2. https://www.nasa.gov/eap-resources/publications/technology-development/#hemm
4. Anderson, A.D. et al., Proc. of IEMDC 2025, doi: 10.1109/IEMDC60492.2025.11061092

REGENERATOR

- Random fiber regenerator
- ~12 µm dia 316L stainless steel fibers
- ~75% nominal porosity
- High pressure necessitated smaller regenerator feature size than screens.
  - Specific surface area for performance.
  - Thermal penetration depth at cold end.

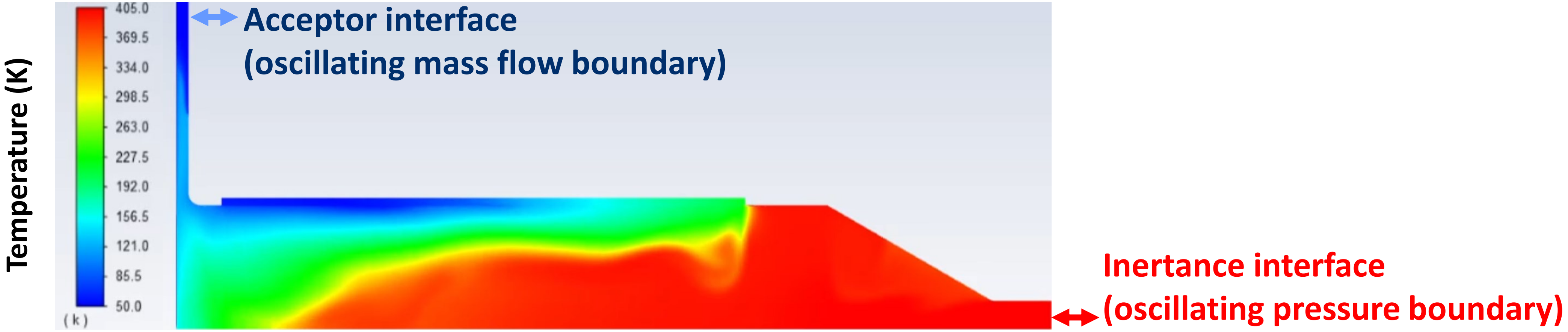


SEM of stock sintered regenerator material.

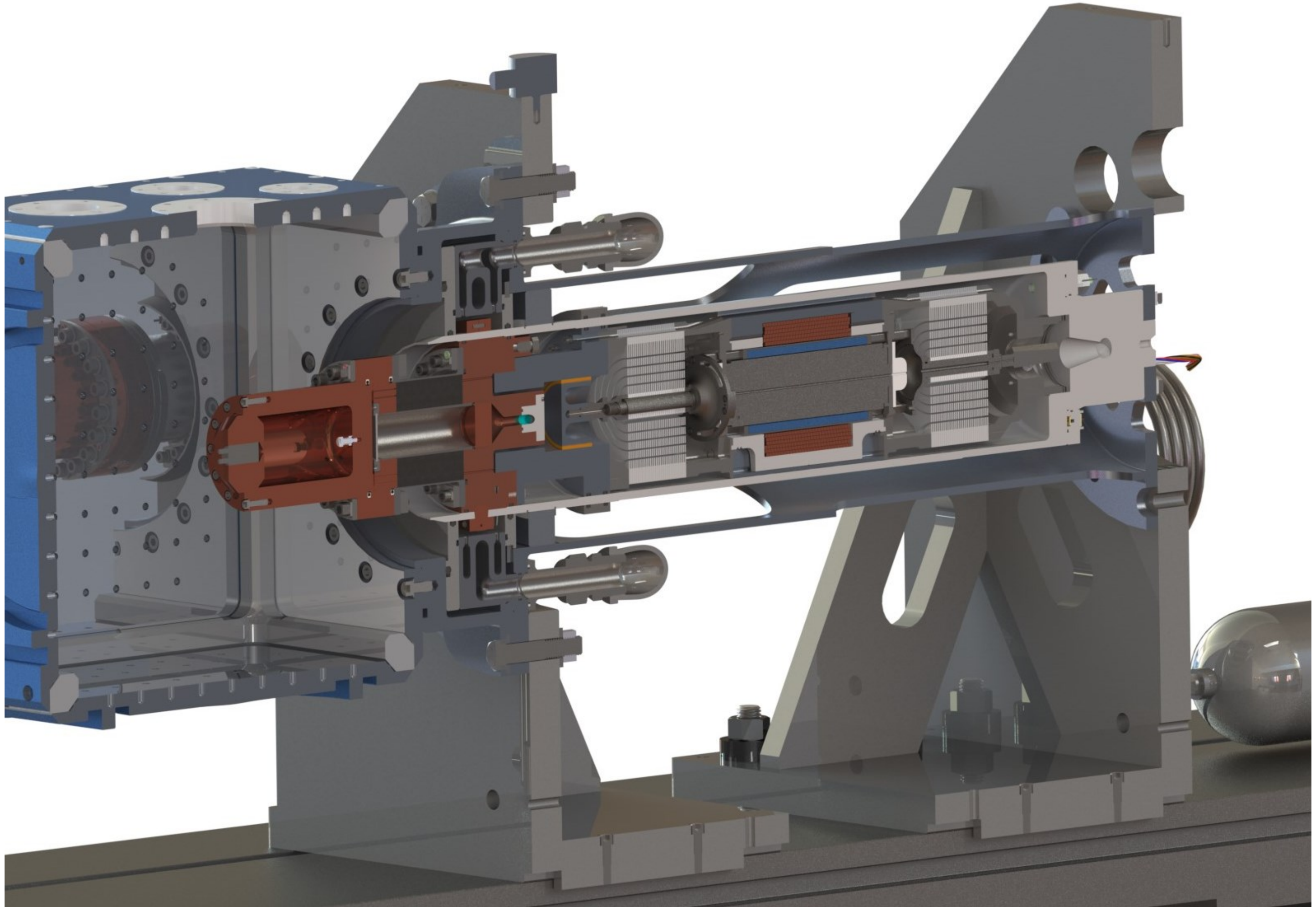
ROTATING PULSE TUBE ANALYSIS

- A downside to the coaxial configuration is the flow turning between the acceptor tube bundle and the pulse tube.
- When rotating, the Coriolis and centrifugal forces can dominate.
  - A cold-end flow straightener is necessary and the warm-end secondary heat rejector must also be carefully sized as a flow straightener for the inertance tube.
  - The cold gas entering the pulse tube from a larger radius and the hot, high velocity gas from the inertance tube on the axis of symmetry makes the pulse tube susceptible to flow stratification while rotating.

Axisymmetric, transient CFD example of a thermally stratified pulse tube due to rotational body loads (6800 RPM)



CRYOCOOLER ASSEMBLY



Cryocooler test setup cross section

Cryocooler before integration with test stand

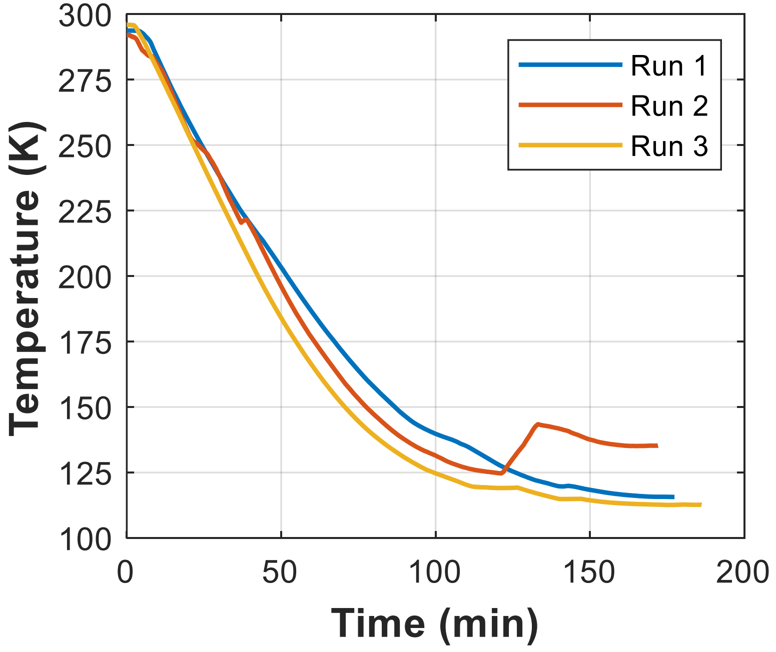
CRYOCOOLER STATIONARY TESTING

- Key Measurements
  - Piston displacement measured dynamically by a proximity probe & tapered target on the motor (calibrated statically).
  - Dynamic pressure in the compression space, bounce space, and reservoir.
  - Temperature at the cold tip, aftercooler, and motor coil.
- Open-loop control
  - Voltage & frequency controlled, sinusoidal output power supply.
  - Measure current, and the phase between displacement and current.
  - Manually control voltage & frequency to stay on resonance and obtain desired operating point.
- Charge system
  - Gas panel with turbomolecular pump to evacuate the cryocooler & charge with helium.
- Cooling system: oil jet impingement on the aftercooler.
  - MIL-87252 PAO oil coolant; same fluid as the HEMM stator.
  - Was optimized for minimal drag while rotating, while still being effective during stationary startup.

FIRST COOLDOWNS

- Passed pneumatic pressure test & other functional tests.
  - No remaining detectable leaks after fixing leaks in electrical feedthroughs.
- Running at lower than design pressure due to reduced motor performance.
- Initial cooldown rates looked promising.
  - Cold tip sized for steady state to minimize superconductor temperatures.
  - Large thermal mass (~5 kg of copper).
- Did not reach target temperatures.
  - Target 50 K, reached only 112 K.
  - Vacuum chamber pressure higher than ideal.
  - Chamber pressure rises when motor is running.
  - Apparent helium leak, likely due to oscillating pressure.
- All signals functional.
  - High speed (50 kHz) pressure, displacement, voltage & current

Initial cooldowns of the cryocooler

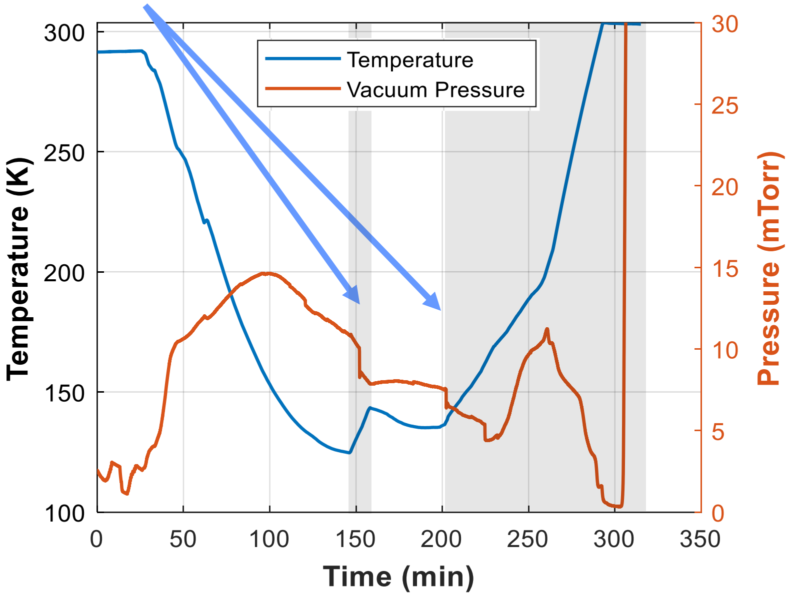


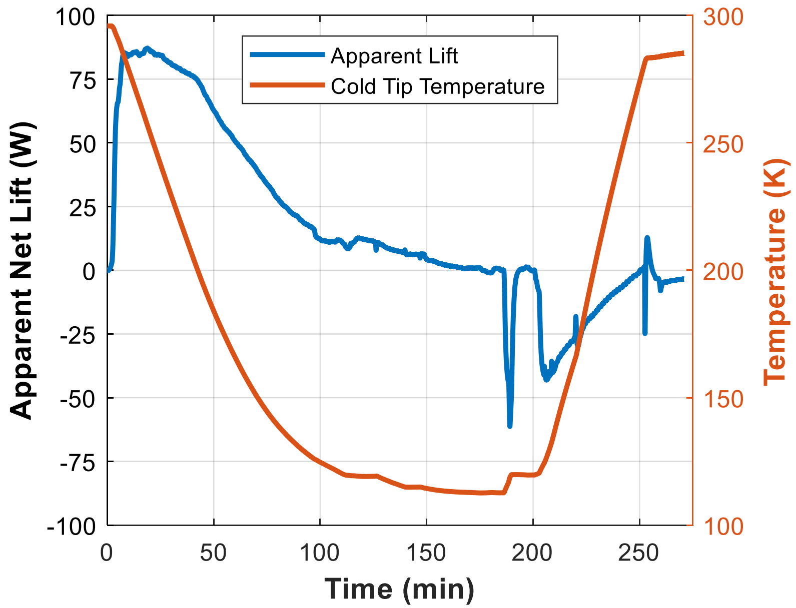
HELIUM LEAK & HEAT LEAK PROBLEM

- Cryocooler is not hermetically sealed; wanted prototype to be reconfigurable.
  - PTFE spring energized seals on the cryogenic components.
  - FKM seals on the warm components.
- Observed helium leak small enough that the pressure drop in the cryocooler is negligible, but large enough to cause significant convection (~10 mTorr).
- Estimate total heat leak via thermal mass of the cold tip and observed temperature derivatives, when motor powered off.

$$\dot{q}_{net} = \dot{q}_{heater} + mc_p(T)\frac{dT}{dt}$$

Pressure drops when motor turned off

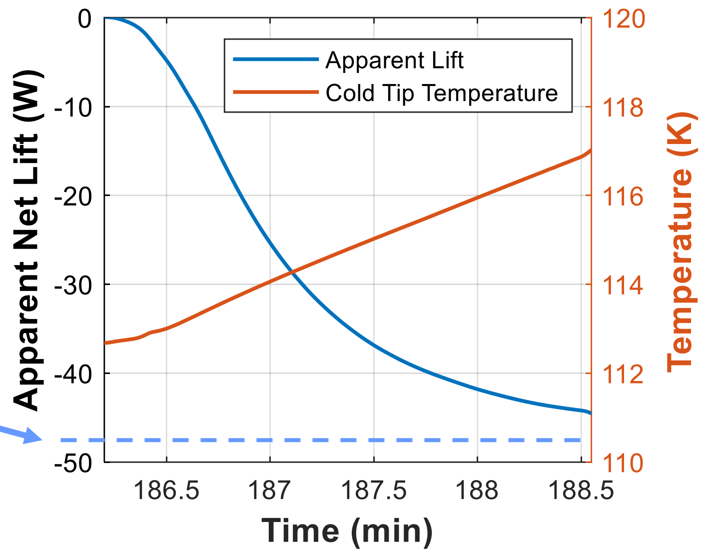




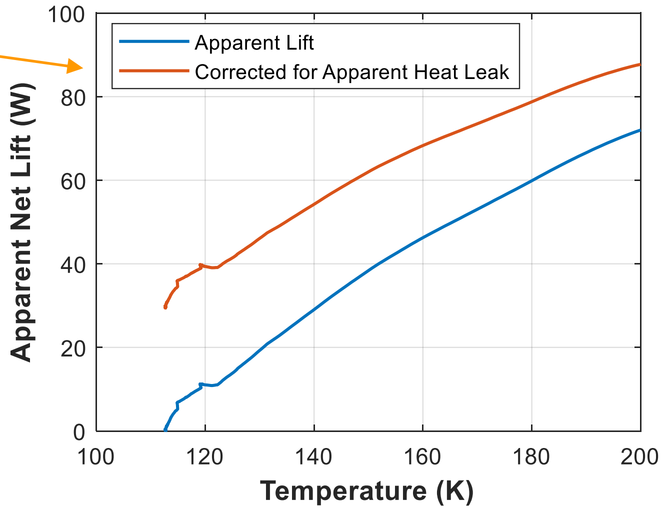
ESTIMATED HEAT LEAK & LIFT

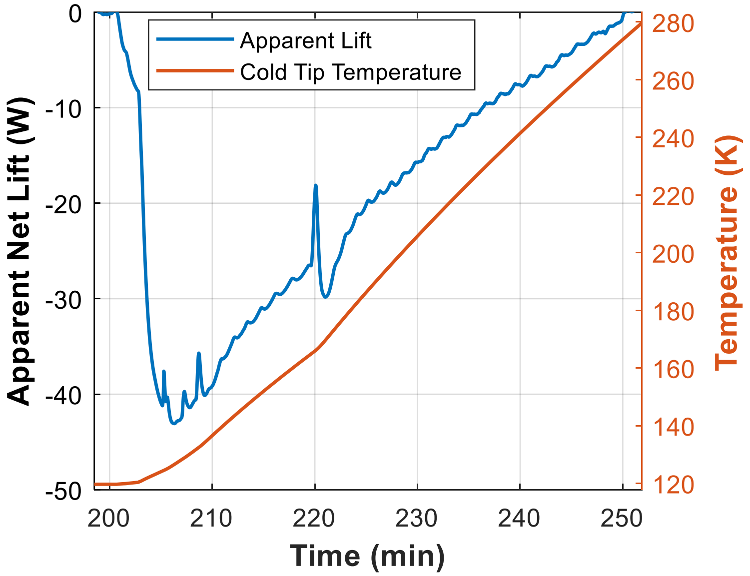
- At 115 K, shut off motor and observed temperature rate of rise.
  - From known cold tip thermal mass, observed ~45 W total heat leak
    - Previously predicted ~15 W of internal conductive heat leak.
    - Therefore, ~30 W total external convective & radiative losses at 115 K.
- Estimate corrected heat lift assuming a linear heat leak of 30 W at 115 K, and 0 W at 293 K.

$$\dot{q}_{lift,corrected} = \dot{q}_{leak}(T) + \dot{q}_{heater} + mc_p(T)\frac{dT}{dt}$$



Short shutdown at ~115K





Heated warm up

CONCLUSIONS

Working Well

- Expected compressor performance.
  - Pressure ratio ~1.37
  - Tight piston clearance as designed.
- Thermal management.
- Data system & signals (mostly) performing as expected.
- Piezoelectric pressure transducer working well.
- Achieved 10 W of actual lift at 120 K
  - ~40 W, if we include the apparent vacuum-side heat leak.

Needs Improvement

- Helium leak & total heat leak into cold tip.
- Quartz diaphragm pressure sensors measuring compression space/bounce space obtain a pressure offset after exposure to helium.
  - Seemingly still OK for transient pressures.
  - Ignore offset.
- Proximity probe for displacement noisy.
  - Might be mechanical dynamics or electromagnetic interference causing the issue.

FUTURE WORK

- Immediate term – improve & complete stationary baseline testing.
  - Locate and fix helium leak.
  - Consider larger turbopump to further reduce chamber pressure.
  - Add MLI.
- Longer term goals.
  - Rotational test to understand pulse tube & other components' dependence on rotation.
  - Dynamic balancer.
  - Revised linear motor to fix known design problems (magnet, flexure undersize, thermal management).