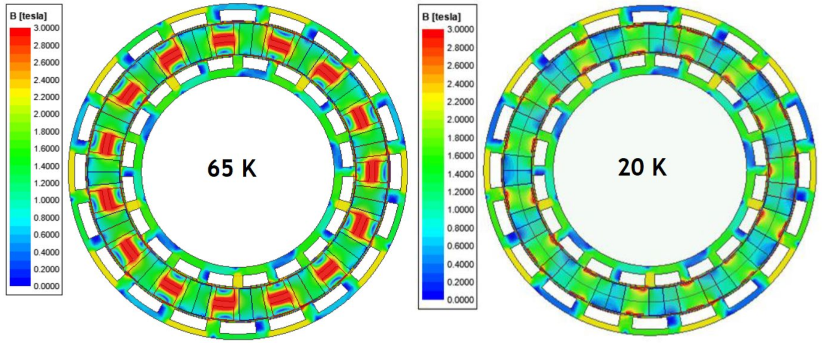
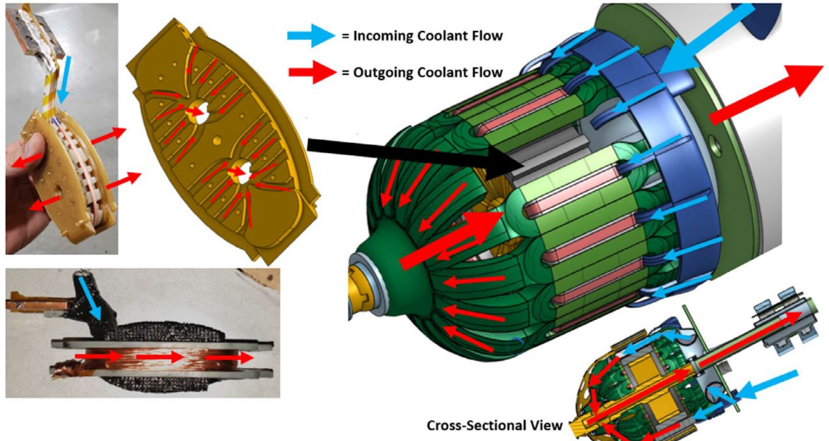
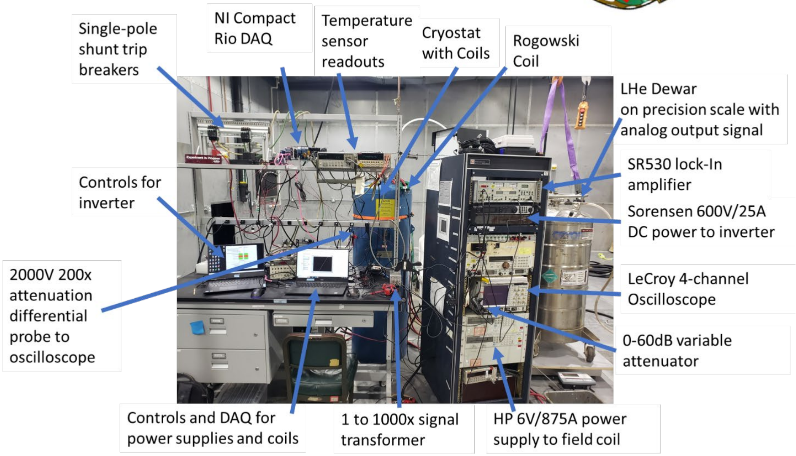






A Double Rotor Flux Switching Machine with HTS Field Coils for Transportation Applications

Chris Kovacs[1], Saeid Saeidabadi[2], Leila Parsa[2], Keith Corzine[2], Timothy Haugan[3], Brice Hall[3], Charles Ebbing[3], George Panasyuk[3], Tom Bullard[3]

[1]Scintillating Solutions LLC, [2]University California Santa Cruz, [3]Air Force Research Laboratory

ICMC 2023

July 11, 2023

Summary

- US Department of Energy ARPA-E ASCEND
- UCSC cryogenic flux-switching motor, HTS air-core with Litz armature
- Motor mechanical and thermal management design and integration
- Statorette derisking task design, Mk. I and Mk. II
- Mk. I and Mk. II testing
- Conclusions

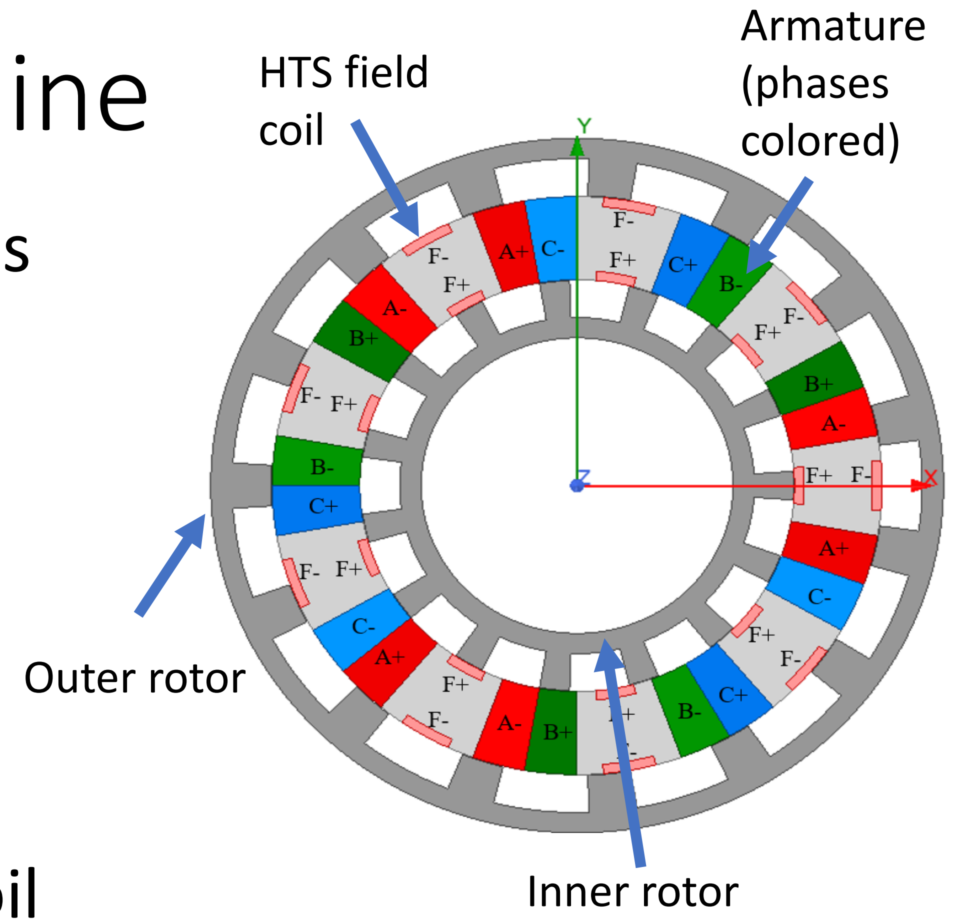
ARPA-E ASCEND

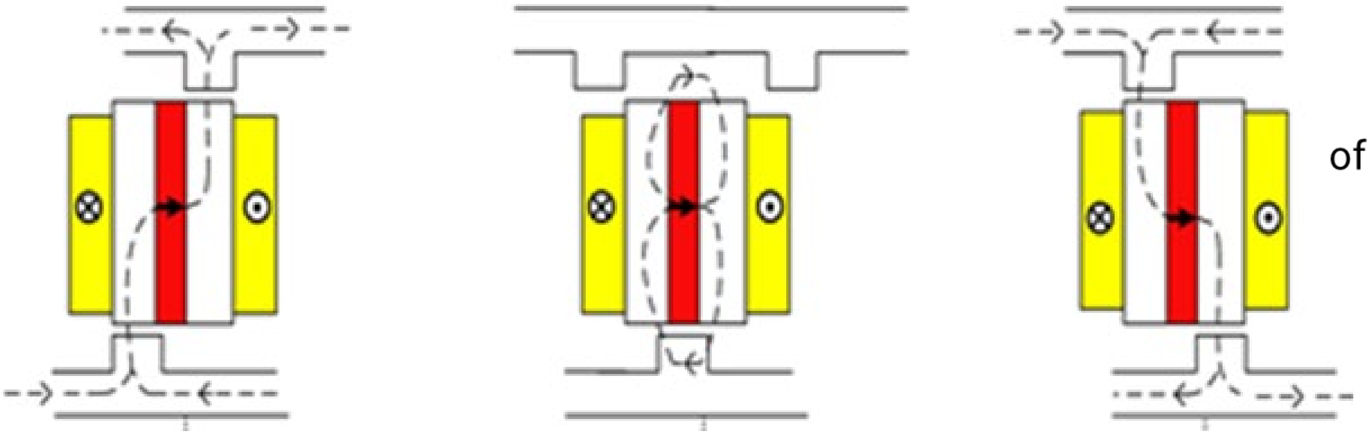
- Aviation-Class Synergistically Cooled Electric-Motors with Integrated Drives
- Development of lightweight and ultra-efficient electric motors, drives and thermal management systems
- Total powertrain >12 kW/kg
- Efficiency > 93%
- End of Phase I, a demonstration of subscale >250 kW powertrain with thermal management.

- Prime Recipient: Univ. Calif. Santa Cruz
- PI: Prof. Leila Parsa
- Program Manager: Dr. Peter De Bock

UCSC: Flux-Switching Machine

- A flux-switching machine (FSM) belongs to a class of doubly-salient machines
- Both the HTS field (air-core) and Litz cable armature excitation are on the stator
  - Simplifying cryogenic thermal management
- A variable flux path from a change in rotor inductance due to the motor dynamic position.
- Flux switches direction when passing the field coil



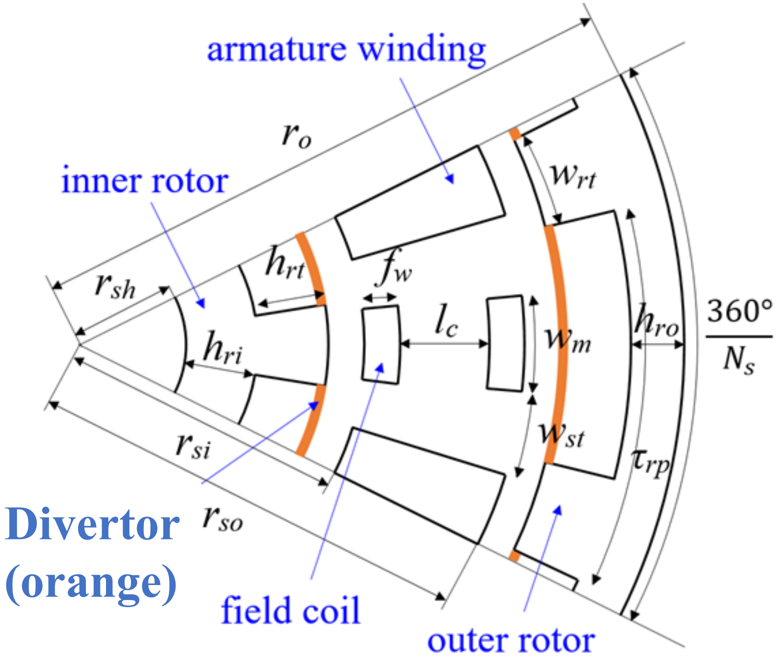


- Feasible pole-slot combinations of an FSM with HTS field coil:

$$N_p = N_s\left(2 \pm \frac{n}{2N_{ph}}\right)$$

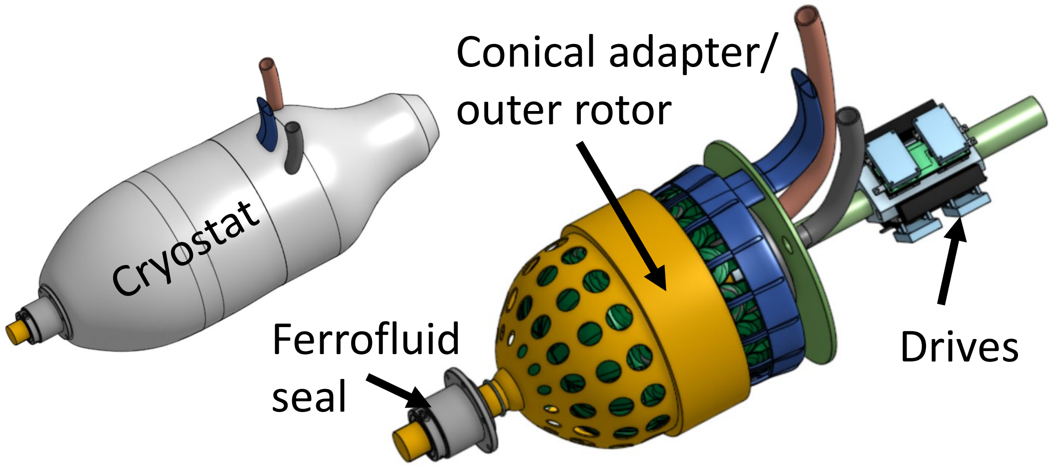
FSM with SC Flux Divertors

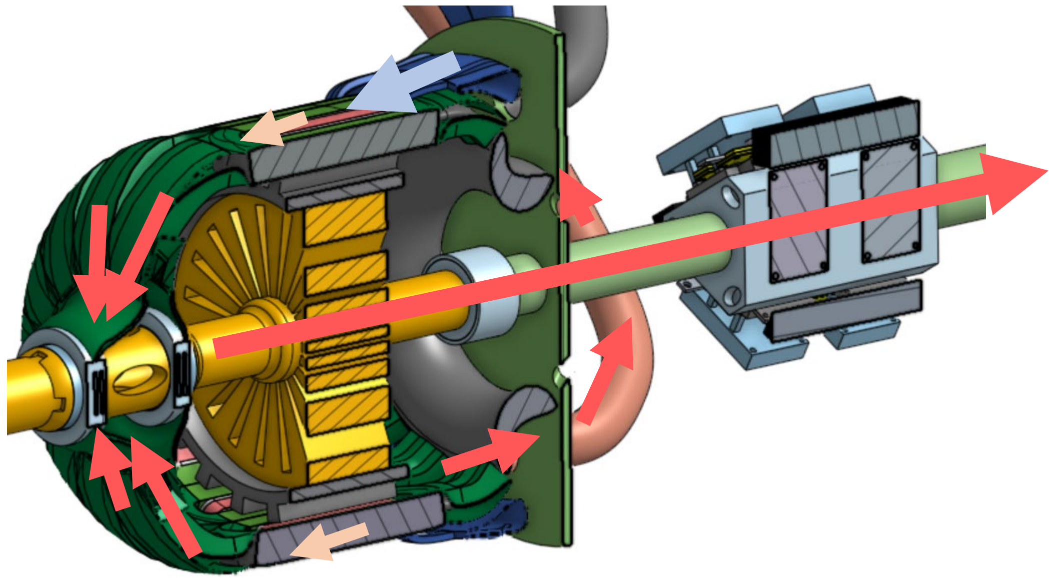
- High frequency designs needed, 1000+ Hz armature
- Early motor designs possessed system power densities which slightly exceeded ARPA-E goals (12.3 kW/kg)
- It was found flux leakage could be decreased substantially for the FSM using superconducting divertors between poles
  - Boosted power density further, >20 kW/kg
- Pending Patent “An Air-Core Flux-Switching Machine with HTS Field Coils and Superconducting Shielding”
- It is possible lower frequencies can still reach very high power densities when utilizing SC flux divertors



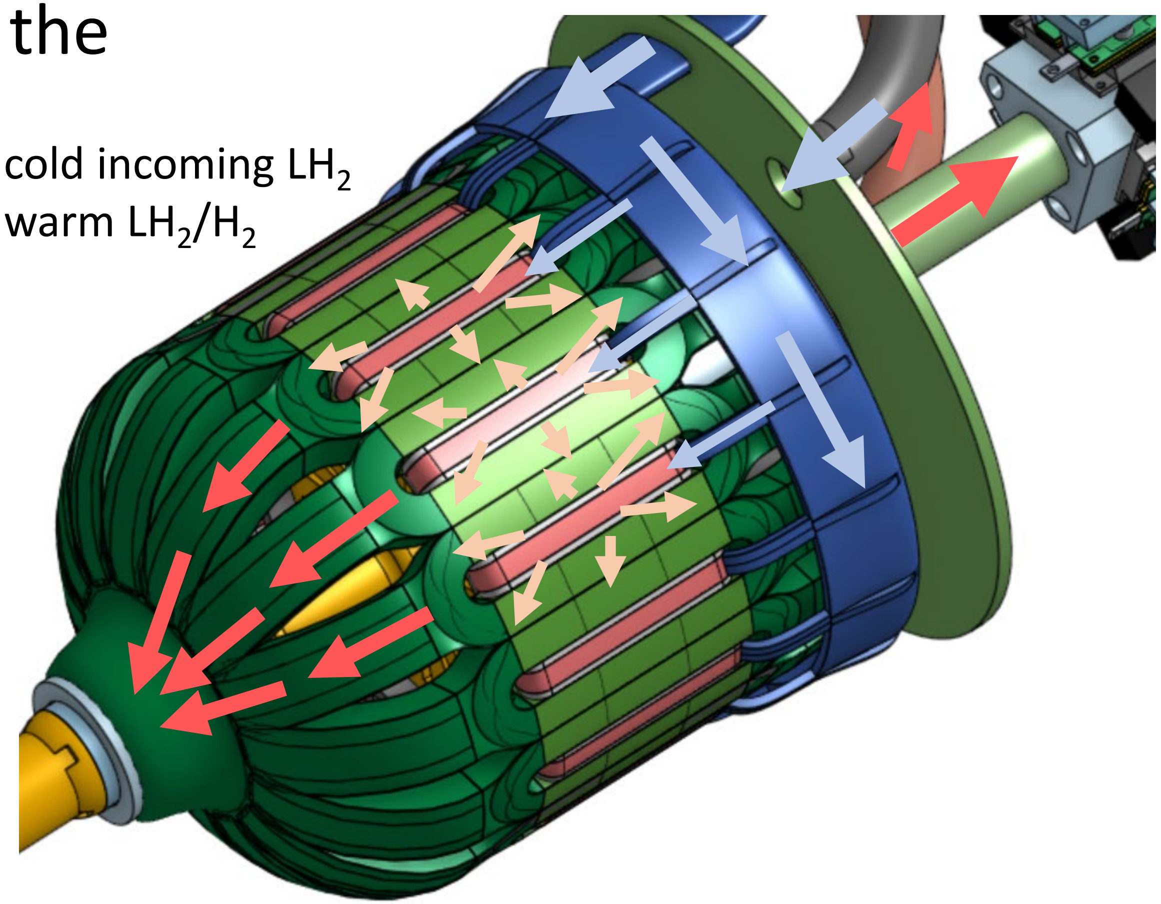
UCSC: LH_2 FSM with TMS

- LH_2 Mk. II design with shields shown (1 MW, 20-pole/15-slot)
- Total drivetrain power density 27.7 kW/kg
- Majority of the system mass comes from the rotors and mechanical structure



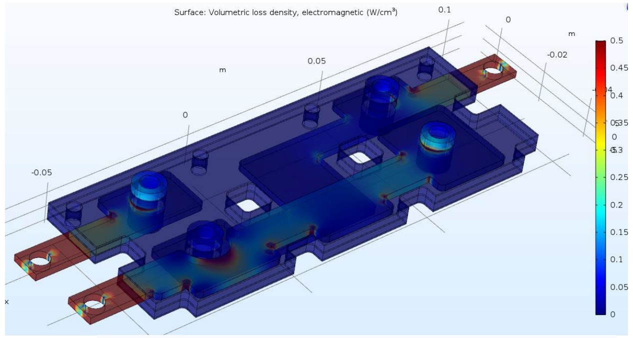


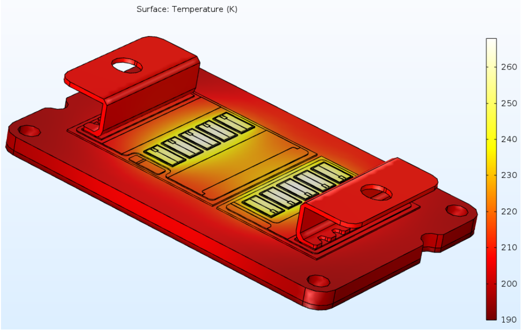
= cold incoming LH_2
= warm LH_2/H_2



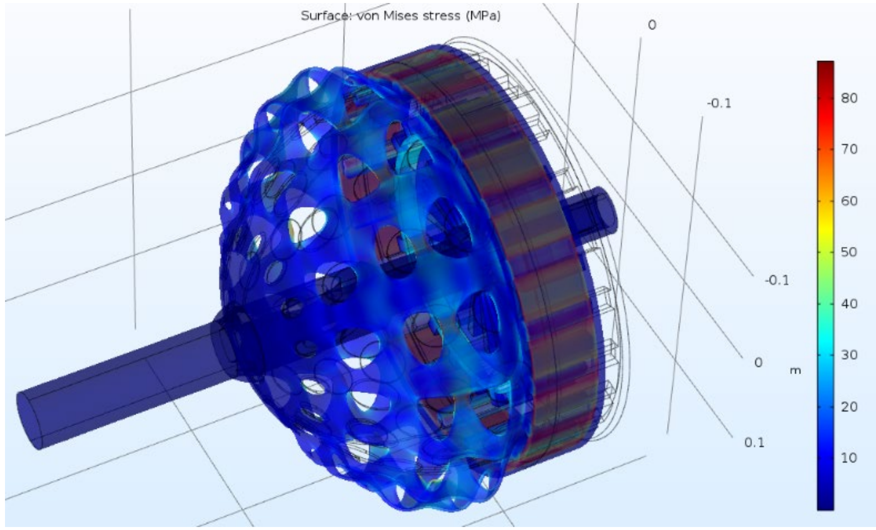
FEM Simulations: Mechanical and Thermal

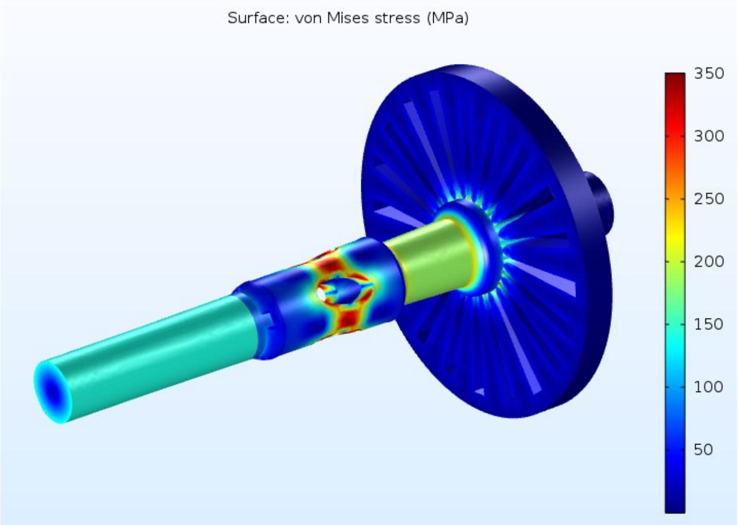
- Mechanical simulations were performed on the outer rotor conical adapter, rotors, and driveshaft. These critical components were lightweighted
- Thermal (CTE and Del T) simulations on the electrical drive components
- Driveshaft had stress concentrators at opening in hollow driveshaft for LH_2/H_2 exhaust





Analytical calculations were used for the motor TMS





Motor TMS: Analytical Calculations

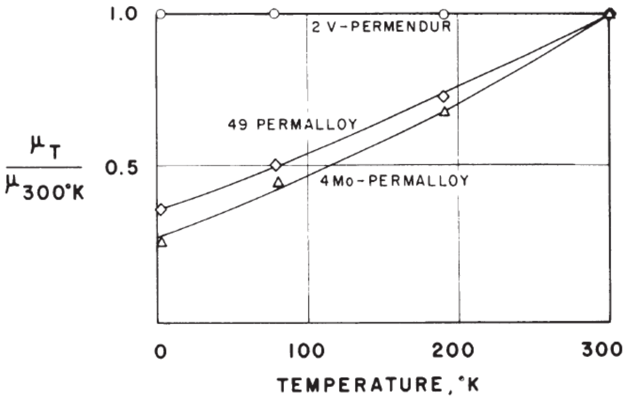
- Knowing the fuel consumption rate, power balance analytical calculations were performed
- Primary goal, reduce thermal load
- Rotor (eddy and hysteretic heating)
- Armature AC Loss (eddy and ohmic)
- Field coil AC Loss (hysteresis, coupling, and eddy in stabilizer)
- SC flux divertors (hysteresis and eddy in stabilizer)
- Cryostat and current lead heat leak
- Other components in within strong AC field were high performance polymeric composites

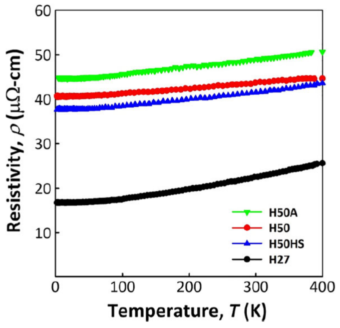
	Cessna U206B	Beachcraft Bonanza G36	Comanche C/R PA-39	Cessna Grand Caravan EX-pod	Beachcraft KingAir 205	DeHaviland Dash 8 Q200
Max Occupants	6	6	6	13	10	40
Propulsion Power (kW)	224	224	238	647	1268	3200
Avgas Fuel Burn @ Full Power (gpm)	0.46	0.41	0.46	1.69	2.81	4.76
Bio LNG Fuel Burn (gpm)	0.61	0.54	0.72	2.23	3.71	6.29
LH2 Fuel Burn (gpm)	1.68	1.49	1.98	6.13	10.20	17.30
LH2 Fuel Burn Normalized to 1 MW (gpm)	7.49	6.63	8.32	9.48	8.05	5.41

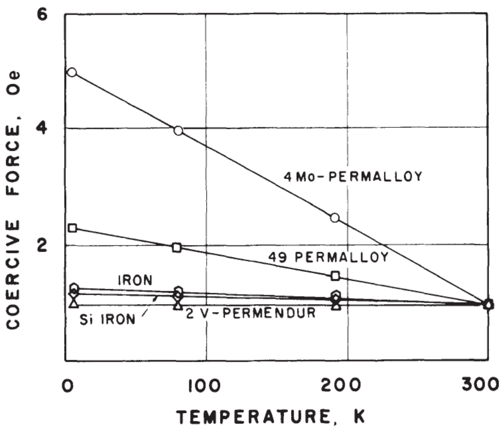
Device	Cooling Options	Inlet Temp (K)	Outlet Temp (K)	Cool ΔT (K)
HTS Field Coils	H_2 liquid --> gas	20	25	5
Al-Litz coils	H_2 liquid --> gas	25	50	25
HTS Shields	H_2, gas	50	75	25
Core, Hiperco-50	H_2, gas	75	150	75
Drive+Vessel	H_2, gas	150	300	150

Motor TMS: Analytical Calculations

- Carpenter Technology Hiperco-50 chosen (49Fe49Co2V)
- Losses assumed insensitive to temperature, and interpolated from RT data
  - Hiperco-50 = “2V-Permendur”
  - Electrical resistivity, coercivity, and permeability relatively constant for Hiperco 50







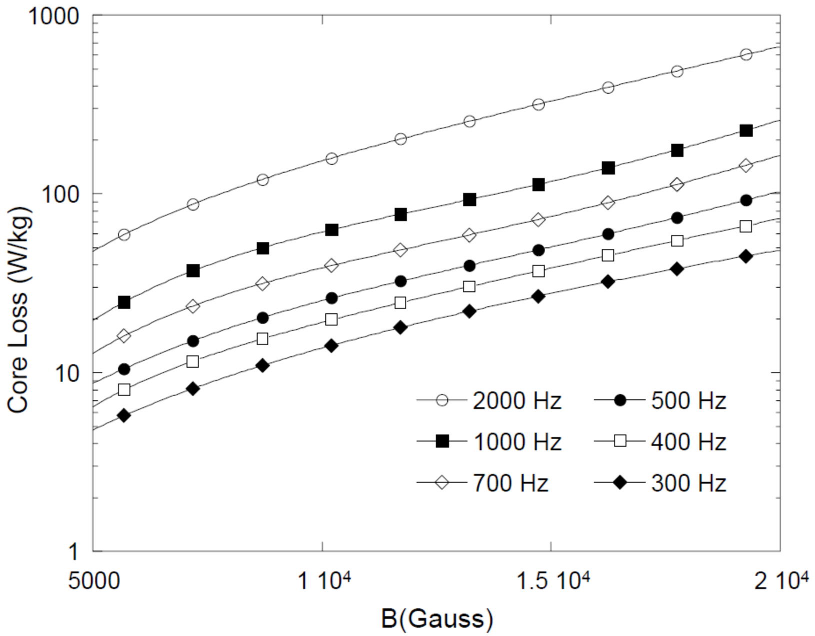


Figure 3.1.7 Core losses of unaged Hiperco 50 alloy taken at room temperature

Ackermann “Magnetic Properties of Commercial Soft Magnetic Alloys at Cryogenic Temperatures” (1971)
Horwath AFRL-PR-WP-TR-2006-2176 (2006)
Kozlowski “Thermal Transport Properties of Fe-Co Alloys” (2020)

Motor TMS: Analytical Calculations

- Litz armature plays a big role in total motor heat loss
- Fine filaments are great, but expensive and lower portion of cable area (metal packing factor) for very fine filaments (insulation few micron)
- Balance of ohmic and eddy current loss leads to an intermediate, not infinitely high, RRR as best option for different temperatures

$$\frac{dP_{Total}}{d\rho} = 0 \rightarrow$$

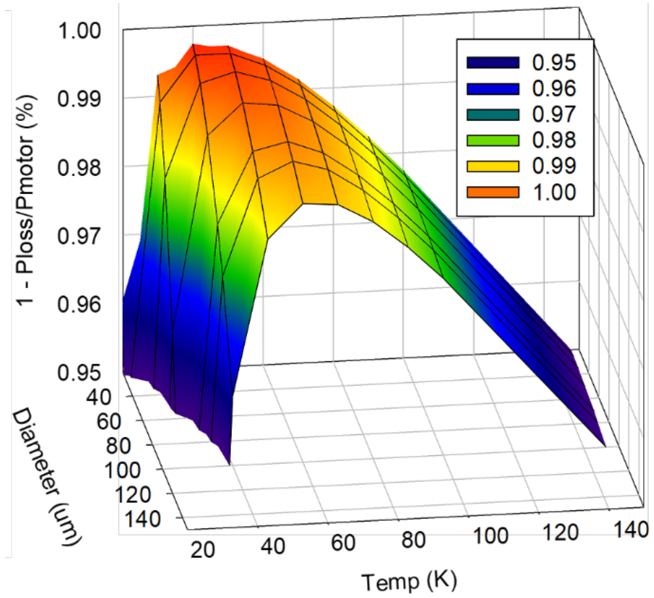
$$\boldsymbol{\rho_{optimum} = \frac{\pi^2 n d^3 f B_0}{I\sqrt{128}}}$$

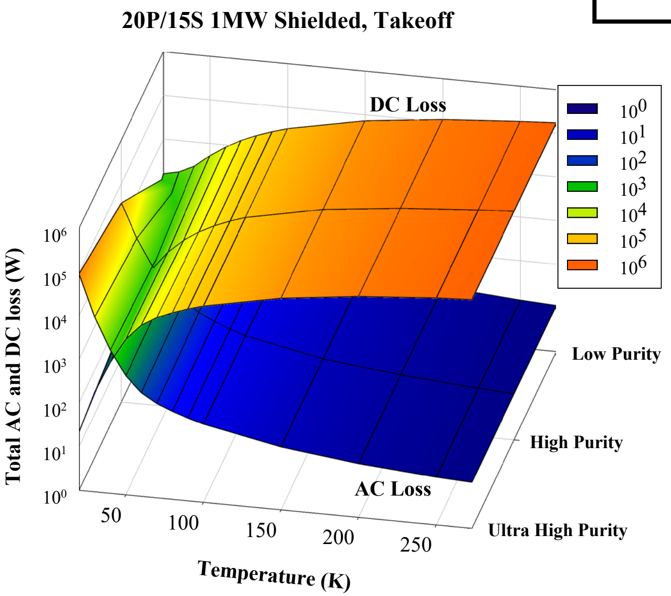
$$\boldsymbol{\rho_{optimum} = \frac{\pi d f B_0 \sqrt{2}}{4 J_{Litz}}}$$

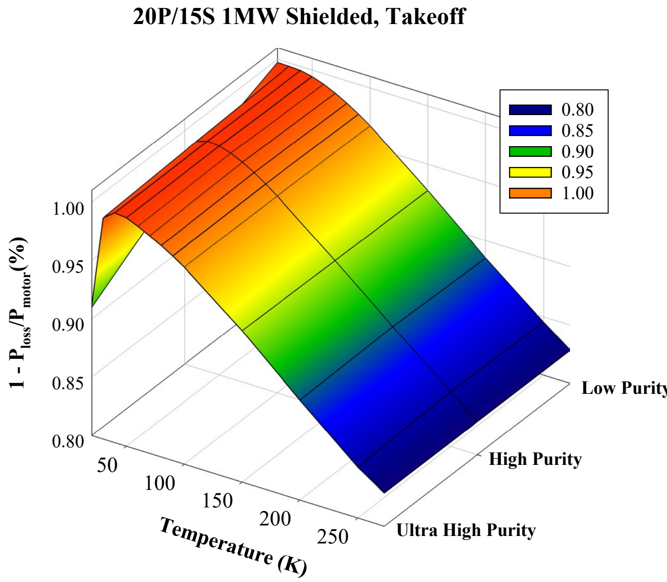
$$P_{Ohmic} = I^2 \frac{\rho}{\pi n d^2/4}$$

$$d < \delta = \sqrt{\frac{\rho}{\pi f \mu_0}}$$

$$P_{Eddy} = \frac{\pi^3}{32\rho}(fB_0)^2 d^4 n$$







Sullivant "Simplified Design Method for Litz Wire" (2014)

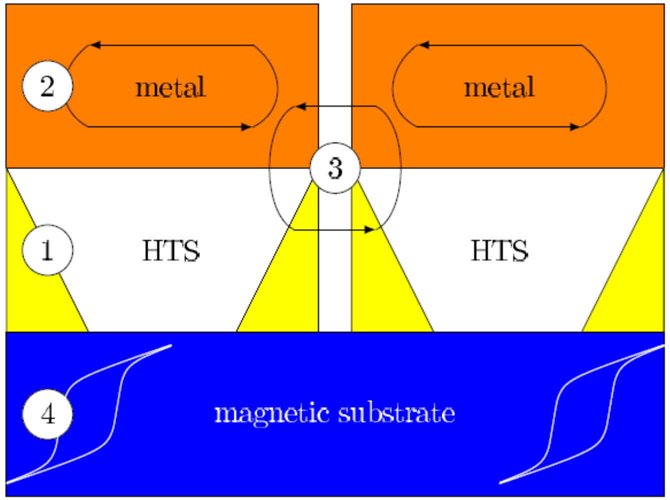
Motor TMS: Analytical Calculations

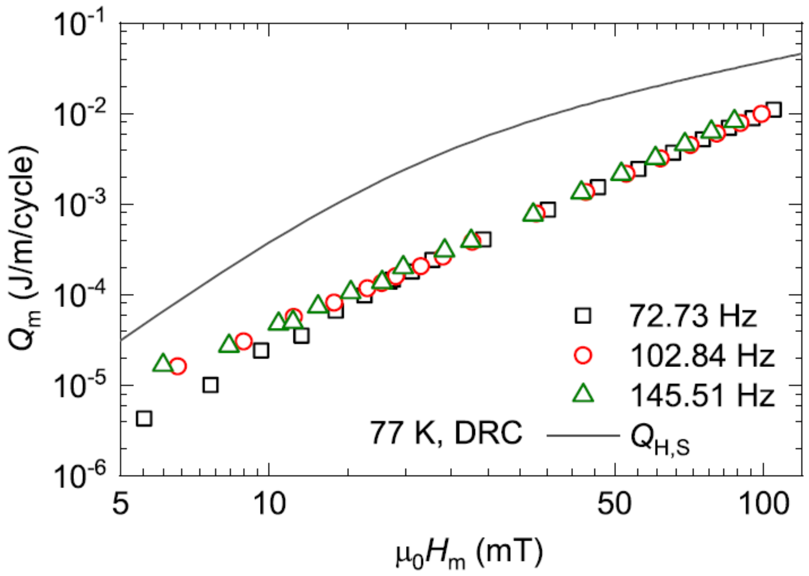
- High surface area Litz armature coils can safely carry high current density under flowing cryogen (LN_2 used experimentally)
- ~0.5 gpm LN_2 flow into 1.5 m long Litz coil wound manifold
  - Cable 80um, 810 filament Cu Litz cable
  - 373 A before insulation burnout, 92 A/mm^2

		Cu @300K J_e (A/mm^2)	Al @300K $J_{e\text{-Ohmic}}$ (A/mm^2)
Air Cooling		8	6.3
Cooled Plate		22	17.5
Spray Cooling		28	22.2
Direct Cooling, Hollow Wires		30	23.8

Motor TMS: Analytical Calculations

- Field coil is a no-insulation REBCO or BSCCO-2212
- REBCO field coil AC loss estimations changed dramatically whether assuming a single tape or a coil winding
- Loss estimates were too high assuming “single tape” hysteretic loss for current state of the art high J_e REBCO coated conductor
- Loss estimates were acceptable assuming coil winding hysteretic loss for current state of the art high J_e REBCO coated conductor and low loss Bi-2212 cable from Solid Materials Solutions (North Chelmsford, MA)
- Coupling losses will play a large role in our frequency range

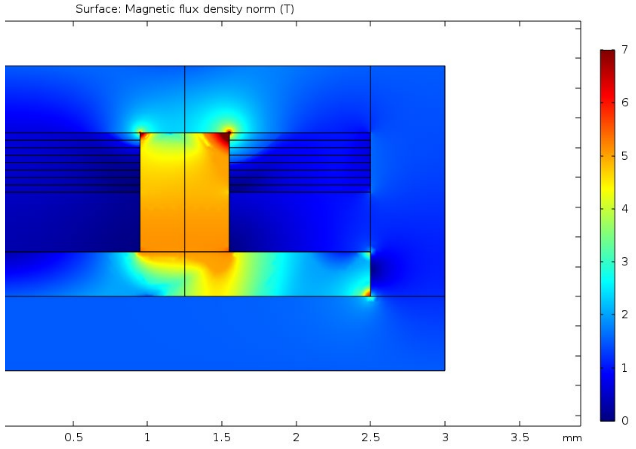


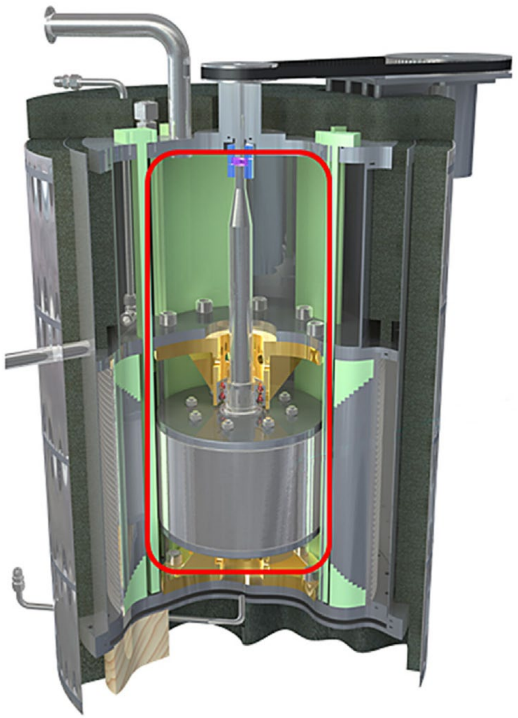


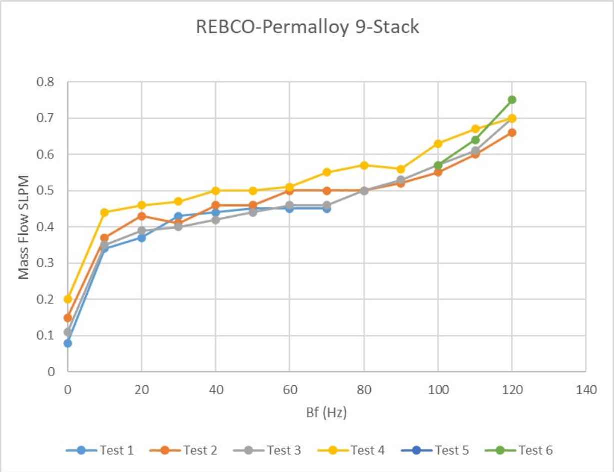
Sun “Dynamic Resistance and Total Loss in Small REBCO Pancake and Racetrack Coils Carrying DC Currents Under an AC Magnetic Field” (2023)
Iwasa “Case Studies in Superconducting Magnets: Design and Operational Issues (2nd Ed.)” (2009)

Motor TMS: Analytical Calculations

- Predicted loss from SC flux divertors was largely estimated because the amount of shielding required is an unknown and higher field/frequency extrapolations from experiments
- AC loss was measured using LN_2 calorimetry of REBCO coated conductor stacks in the AFRL SAM rotating machine (0.65 T, 120 Hz)
- Solid melt-textured REBCO puck (14 mm thick) flux divertor was too powerful and induced large vibrations in the sample chamber, reducing signal quality

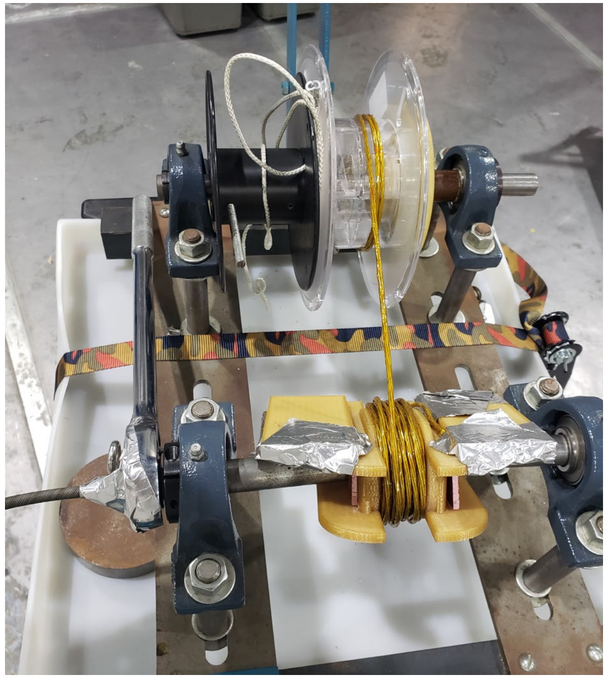


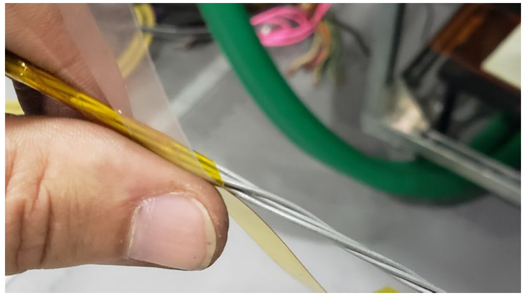


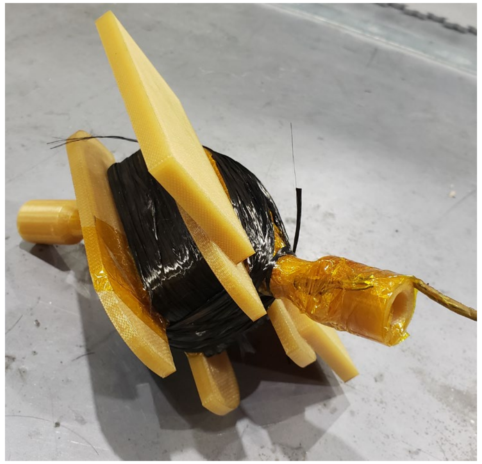


Mk. I Statorette

- 12 kW subsection of 250 kW motor
- For this test, the armature and field coil had the support structure integrated into one Ultem 1010 3-D printed coil former
- [No HTS first run] 4-strand, 4-filament, OD: 1mm HPAL cable (11.5m, 67 turns)
  - Insulated with 50% overlap of Kapton tape
  - Should be able to carry ~1000 A in flowing LHe
- 3-D printed Ultem was weaker than expected, so carbon fiber reinforcement was applied throughout the structure, below windings and outside of manifolds.
- S-glass/Stycast 2850 (with Catalyst 23LV) used for impregnation. VPI avoided first run, afraid of leakage into winding

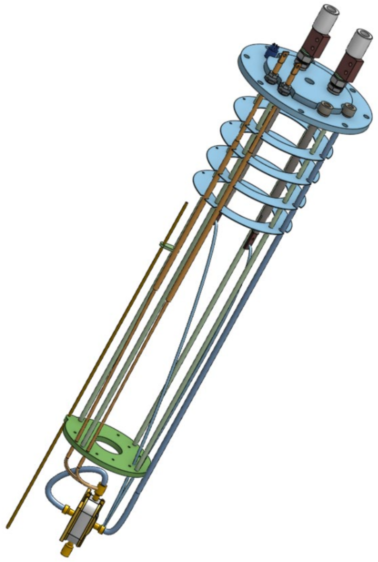


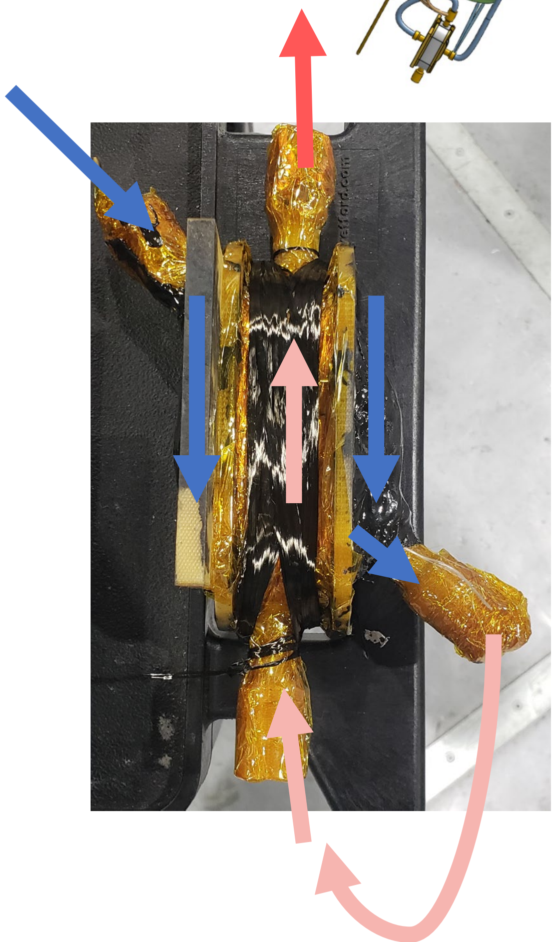


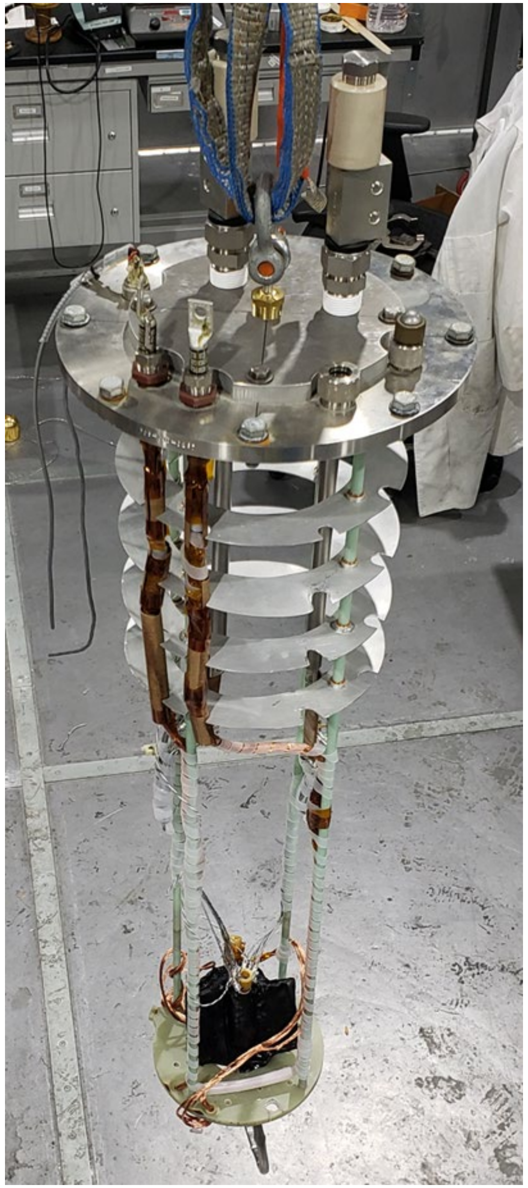


Mk. I Statorette

- Cu-Litz armature (50 um, 610 filaments)
  - Polyurethane insulation (rated 300 V at room temp)
- 1 kA, 1 kV rated vapor-cooled DC leads for the field coil
  - Exhaust from leads is a threaded connection for vapor collection
- Tapered Cu-Litz leads for armature
  - Previous experiments have shown not using Litz in AC leads produces excess heat
- Flow first into HPAL field coil
  - Connecting tube then circulates into armature coil and out the exhaust







Mk. I Statorette

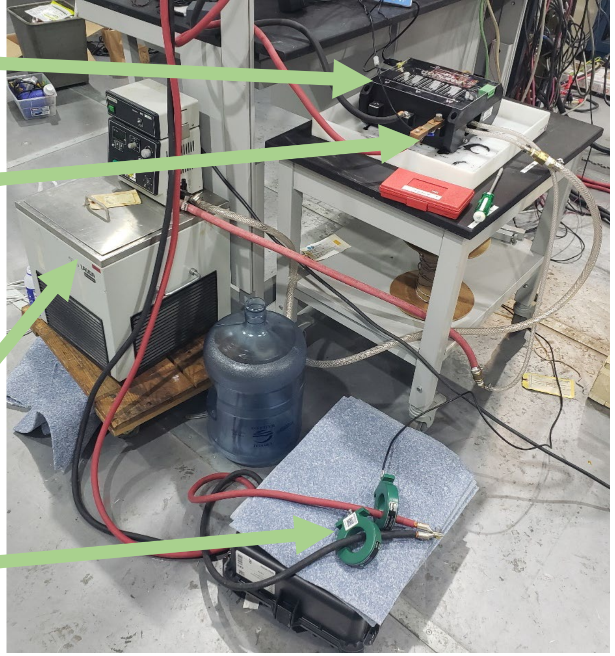
- Inductive AC-loss method
  - $P = I \times V\cos(\varphi)$
- 1000 Hz room temp impedances
  - Field coil: 164 µH, R = 543 mΩ
  - Armature: 648 µH, R = 514 mΩ
- Protection circuit for armature and field coil using shunt trip breakers, triggers, and oscilloscope
- High voltage differential probes

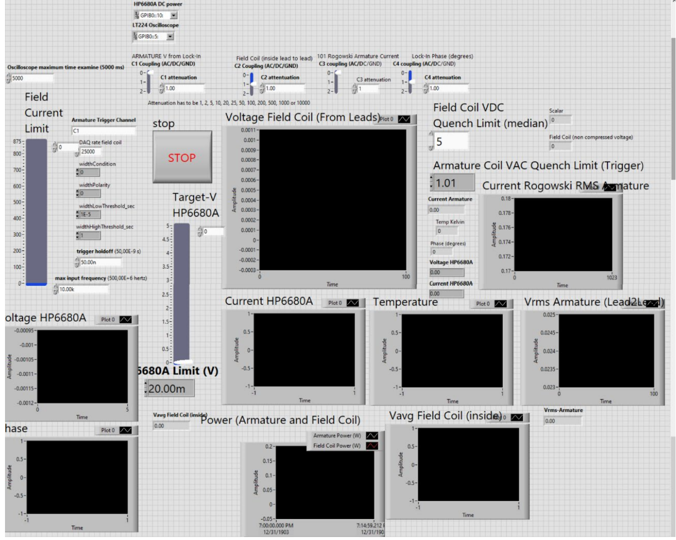
Inverter

Non-inductive shunt resistor

Chiller/ circulator

Rogowski Coil





Shunt Trip breakers

Function generator

SRS Lock-in

300VDC-20A to Inverter

4-ch Oscilloscope

875A DC to field coil

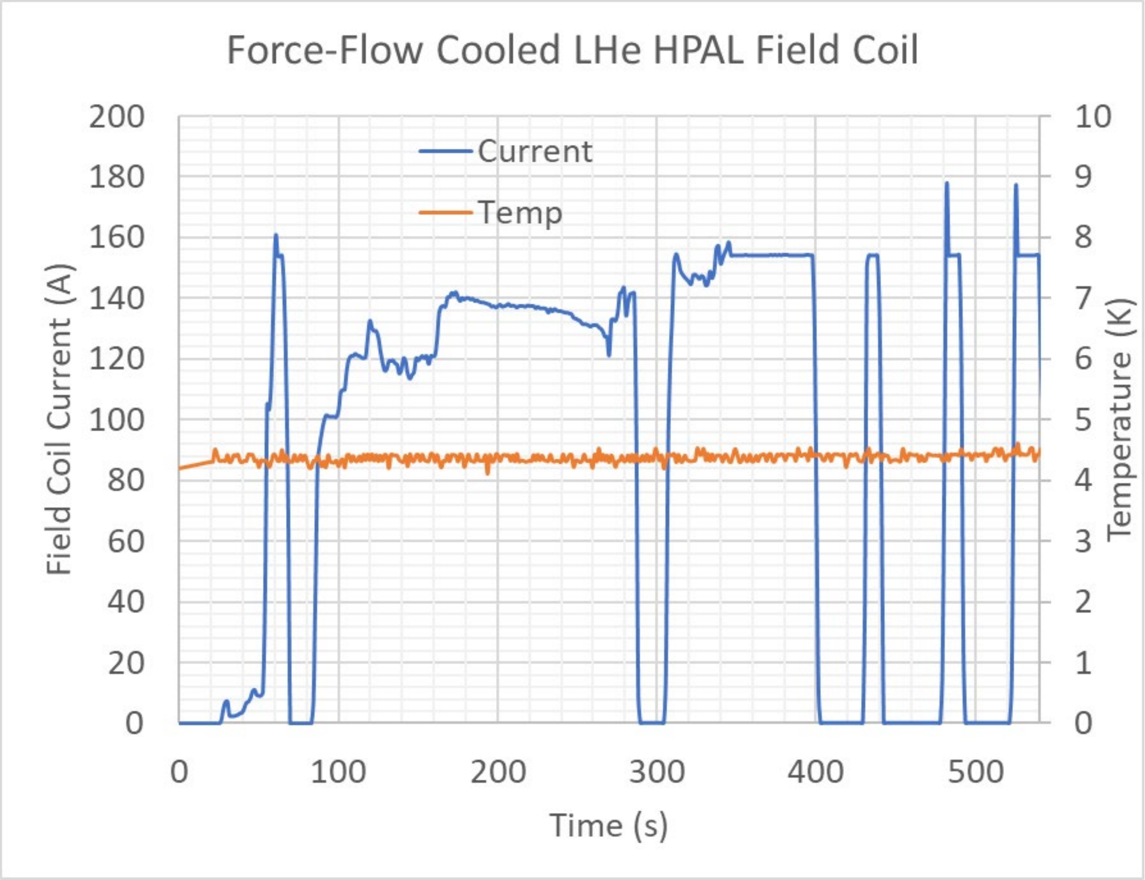
NI-cDAQ modules

DAQ computer

Inverter computer

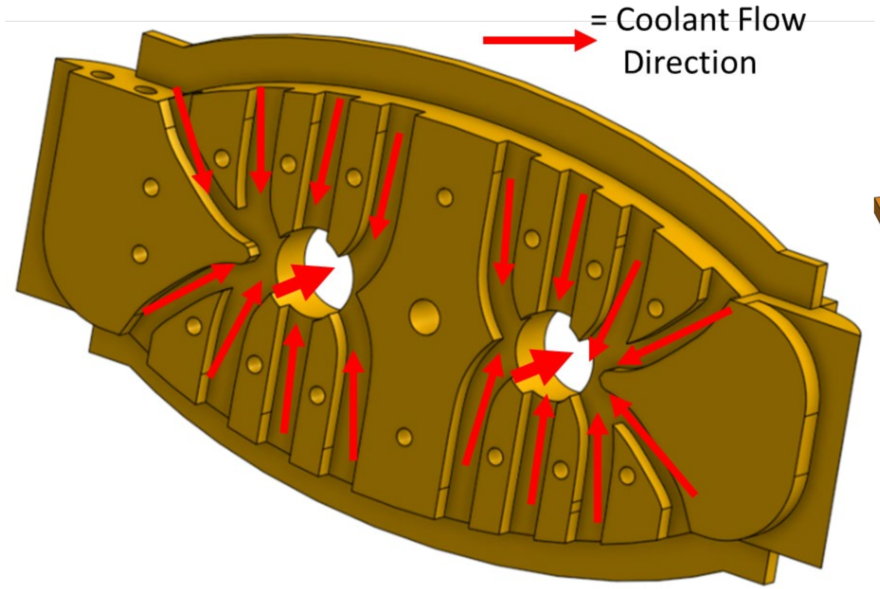
Mk. I Statorette

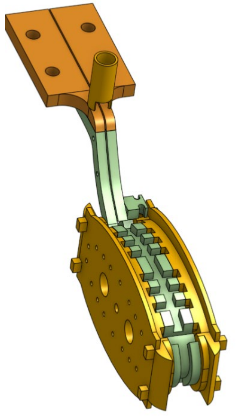
- During preliminary LN_2 flow testing, while trying to get lock-in, pushed armature coil too hard (~80A_{rms}/mm^2) and burnt it out (loose protection wire).
- All that was left was DC testing of the HPAL field coil, which was lower than expected
- Voltage control mode of field coil allows slow approach to ampacity
  - Only 50 A/mm^2
  - Much lower than expected, Kapton insulation wrap a possible culprit
  - Pressure drop was unknown, but was high as determined from backpressure when transfer line was disconnected
  - Flow pathway non-ideal

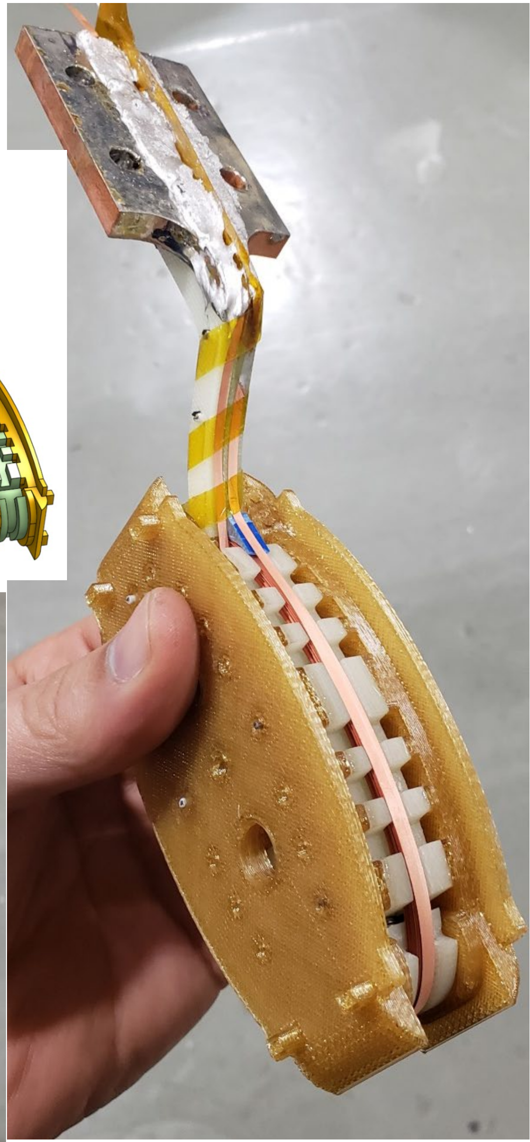


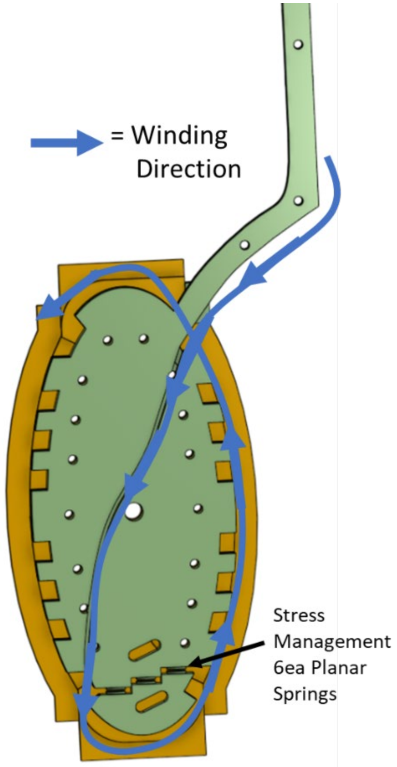
Mk. II Statorette

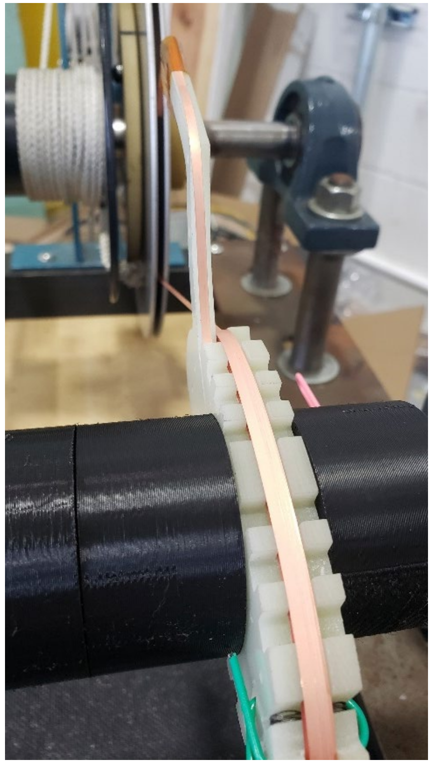
- HTS Field coil with new cooling channels and optimized coolant flow
- NI REBCO coated conductor coil
  - Superpower coated conductor
  - 9 fil (200 um wide nom)
  - 2 mm tape
  - Cu 10 um each side
  - Hastelloy 30 um
  - 50 turns, 12 m
  - 5 N winding tension
  - 10 N stress management
- I_c data proprietary

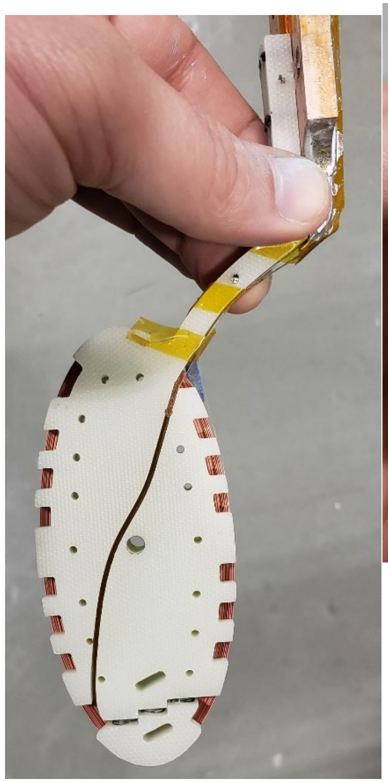






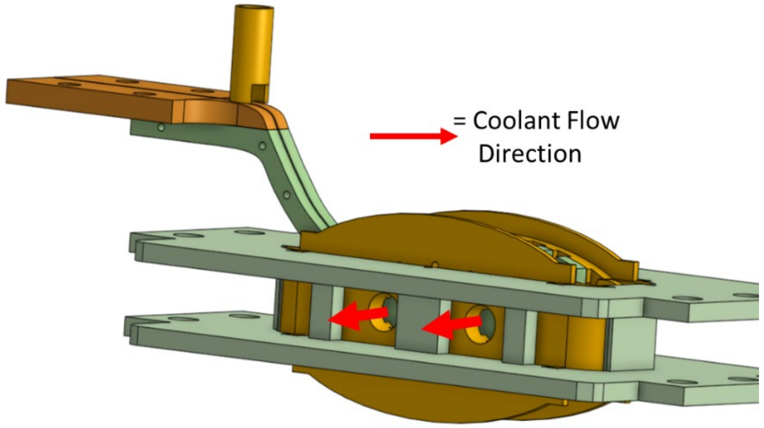


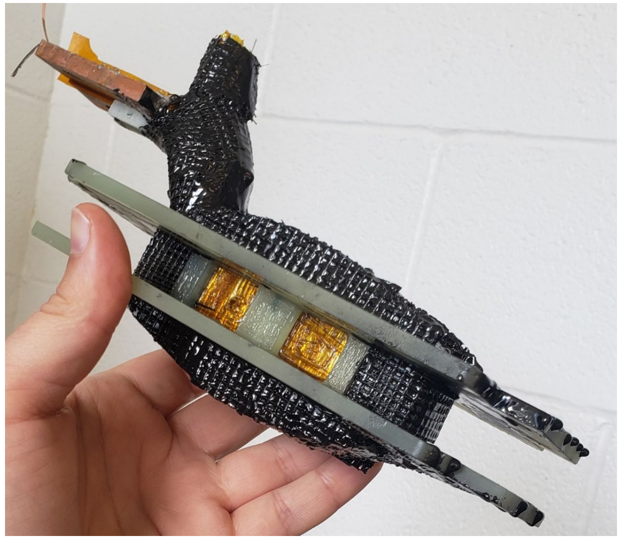




Mk. II Statorette

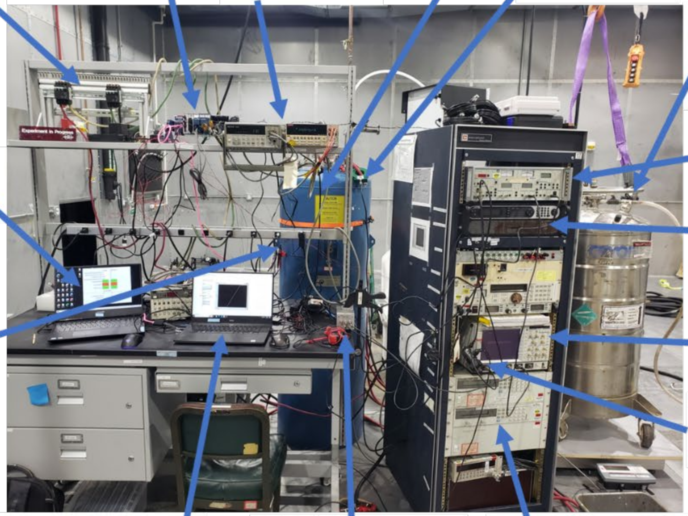
- Armature manifold excluded for ease of replacement for test runs
- Same 50 um, 610 filament Cu Litz cable
  - 75 turns, 24 m
  - 90 A/mm^2 @ LN$_2$ should be > 400 A/mm^2 LHe
- Room temperature voltage rating of the armature pushed to the brink, zero safety factor (300 V)
- Large scale to measure LHe flow rate during testing
- CERNOX sensors on outer layers of armature (exhaust)

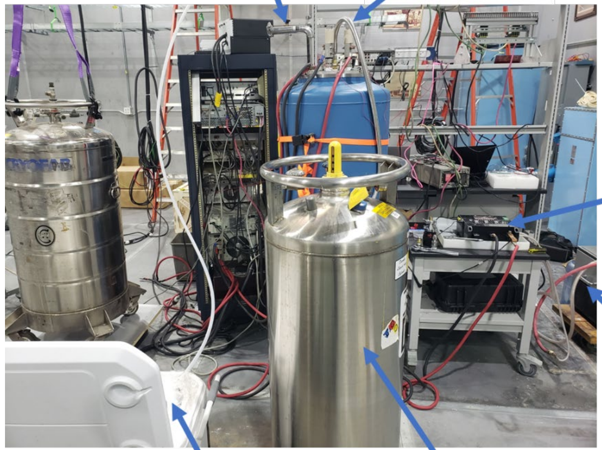




Mk. II Statorette

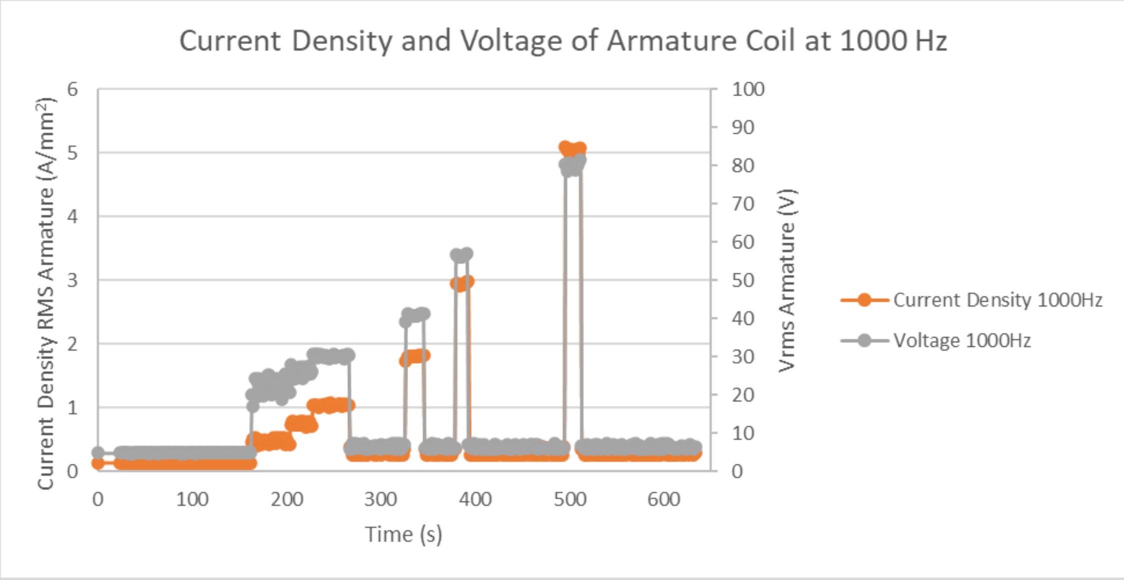
- Low excitation testing at multiple frequencies and field coil fields
- ~20 K maintained at exhaust by controlling LHe flowrate
- While ramping to intermediate excitation, armature insulation breakdown

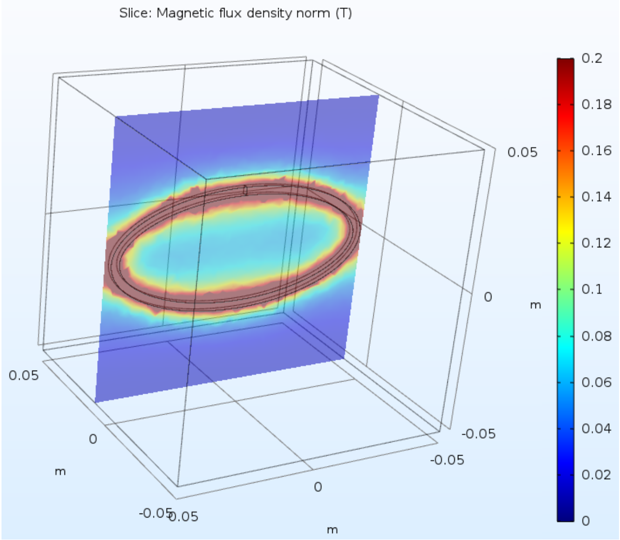


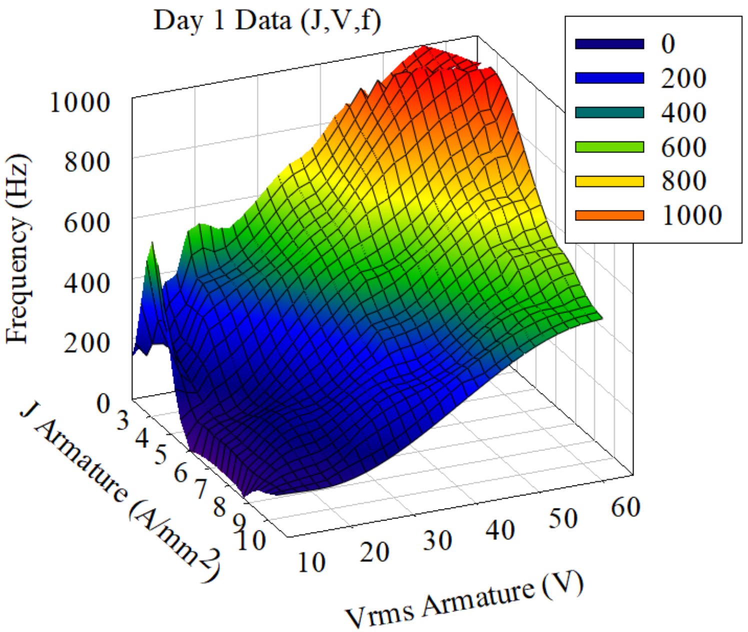


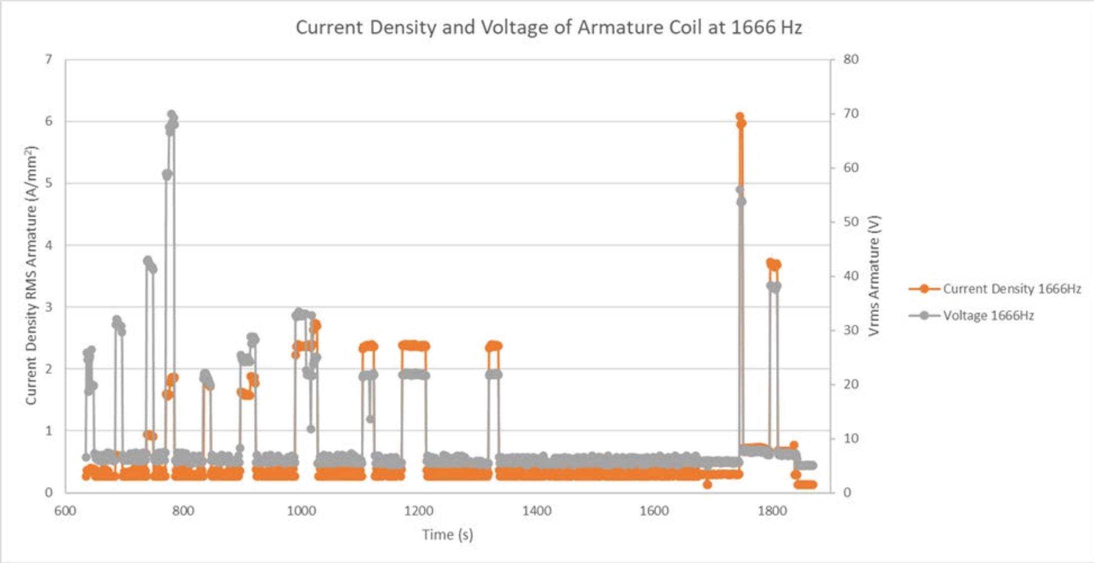
Mk. II Statorette

- DAQ (lock-in) insufficient for inductive loss calc
- Very loud buzzing/humming during testing, audio dependent on frequency
- Eventual burnout of an instrumentation cable after breakdown of armature insulation
- Low excitation testing: field coil ~ 0.5 I_c (and much lower I_c than thick film REBCO in simulations) and armature well below ampacity









Future Work

- Mk. III Statorette, HV polyimide Litz
- Subcooled LN_2 boil-off calorimetry
- Al Litz
- Higher J_e HTS
- Testing BSCCO-2212 coil (from Solid Materials Solutions)
- Proof of flux leakage reduction and power density increase with SC shielding in linear or rotating machine

Thank You CEC-ICMC 2023!

"Hawaii is one of those places that keeps topping itself. Just when you think you'll never see another sunset as beautiful, there comes a sunrise that only Gauguin could imagine."

-Thomas Sullivan Magnum IV (1982)

CEC ICMC 23 HONOLULU JULY 9-13 HAWAII CONVENTION CENTER