

[Invited] Progress on a 100-kW superconducting propulsion unit for zero emission aviation

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Airbus Upnext

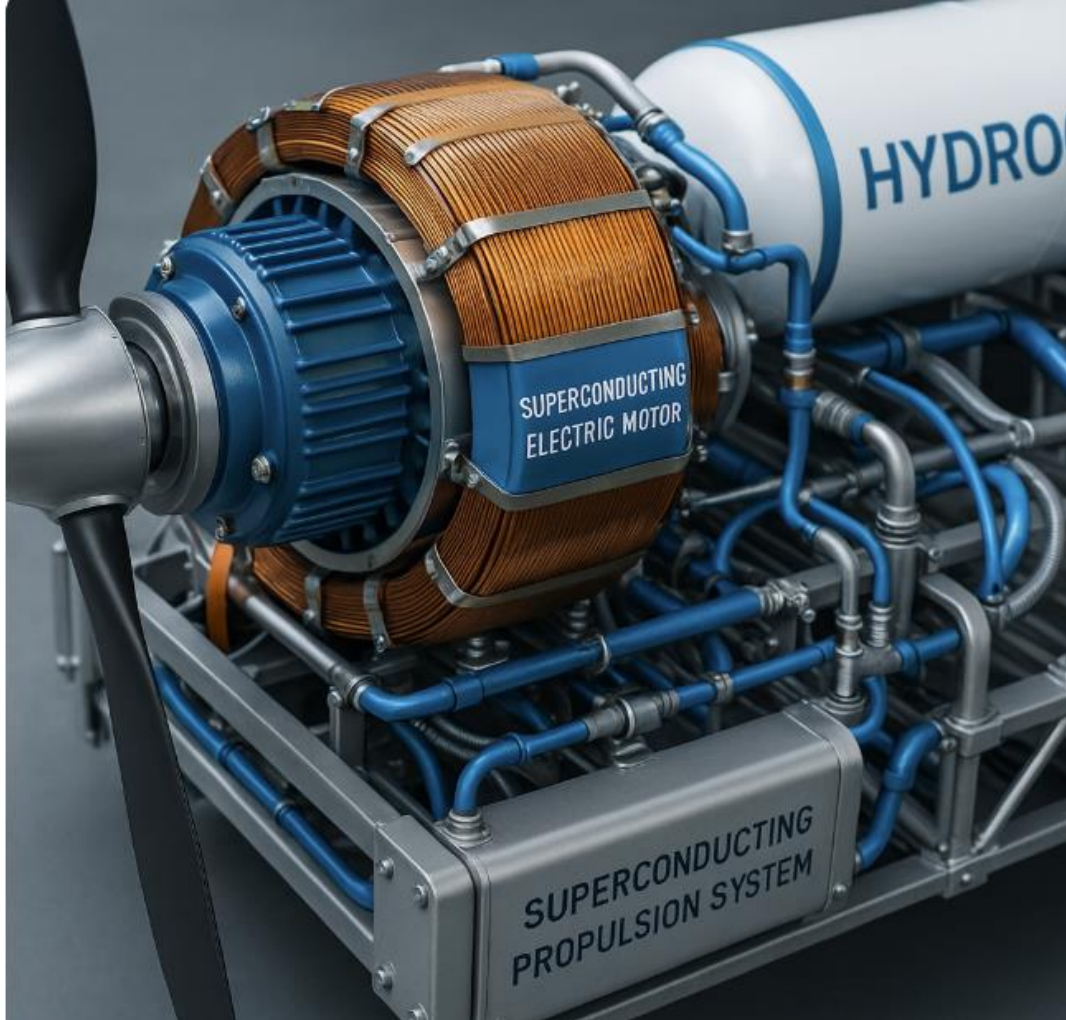
This work covers the update from:

- “ZEST1 Zero Emissions for Sustainable Transport 1”, funded by Innovate UK
- “Superconducting Machines for Zero Emission Aviation”, selected by ERC and funded by UK Research and Innovation

Content

- Introduction
- Fully HTS motor design updates:
 - Cooling system
 - HTS stator design
 - HTS brushless rotor design
 - Rotational motor tests up to 1500 rpm
- Cryogenic inverter design updates

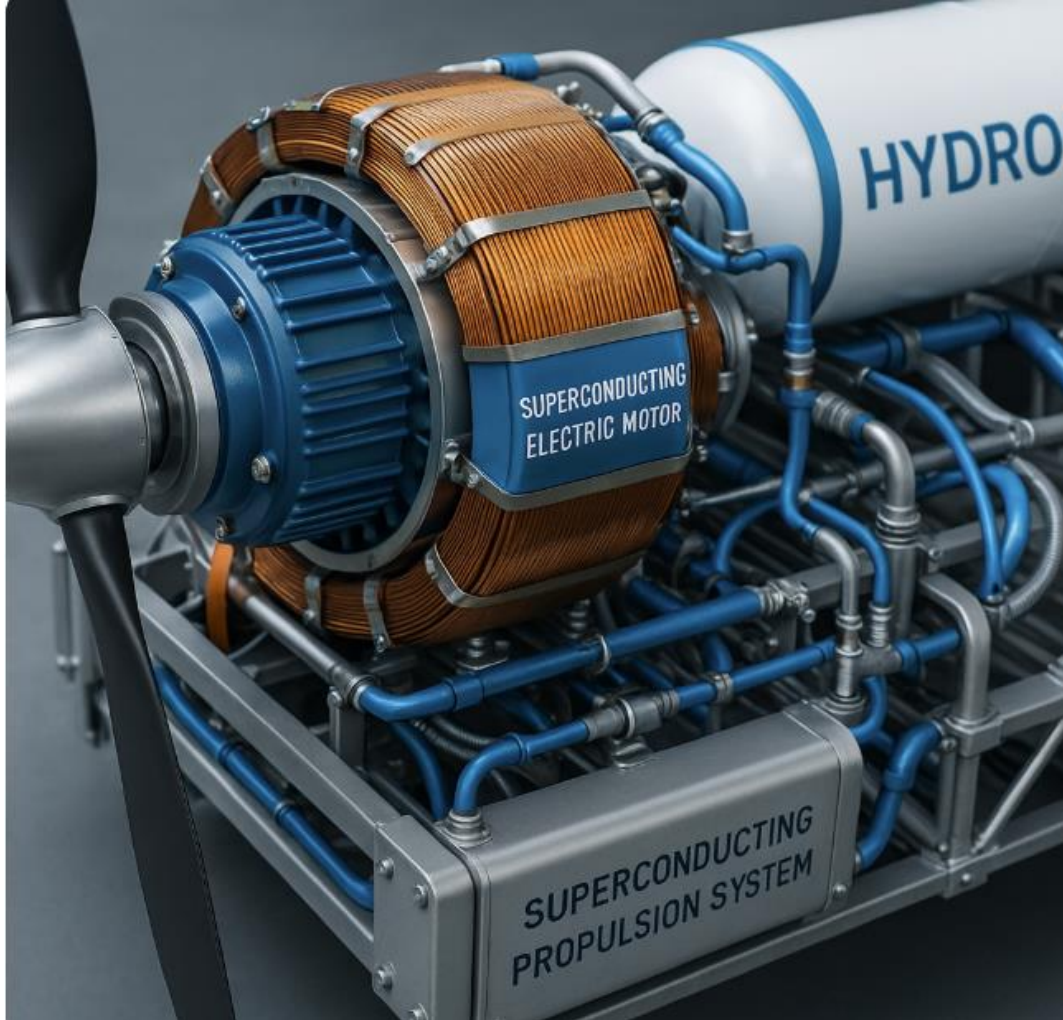
WHY



- Emission
- Electrification
- Limitation on existing machines

Chatgpt: a superconducting propulsion system for hydrogen aircraft

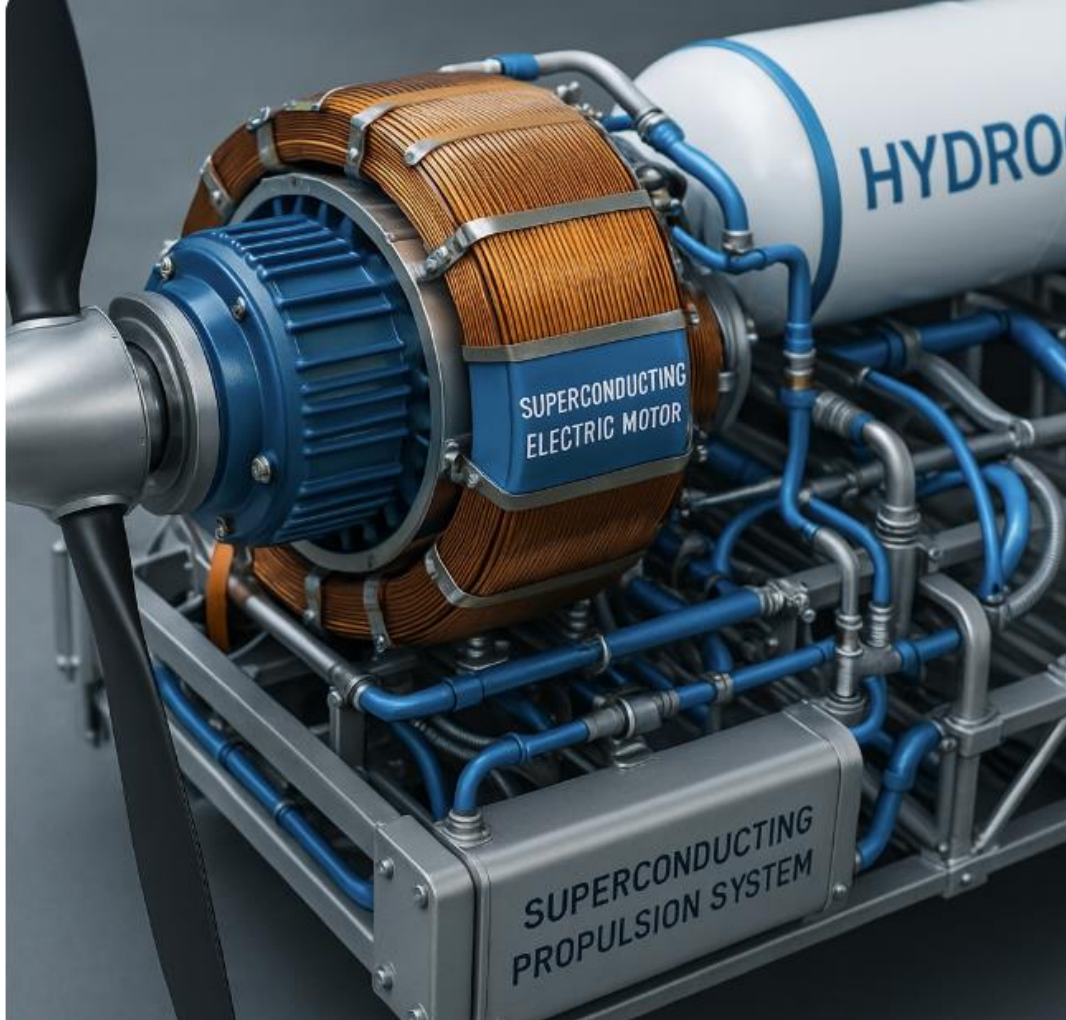
WHY



- X Too expensive
- X Technology not mature
- X Reliability issue
- X No supply chain
- X No regulation
- X No certification

Chatgpt: a superconducting propulsion system for hydrogen aircraft

WHY NOT



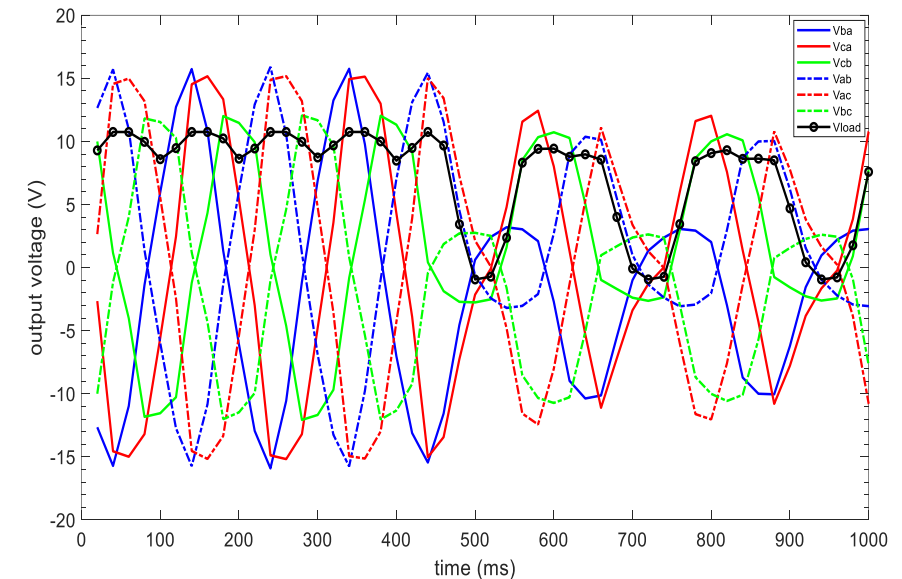
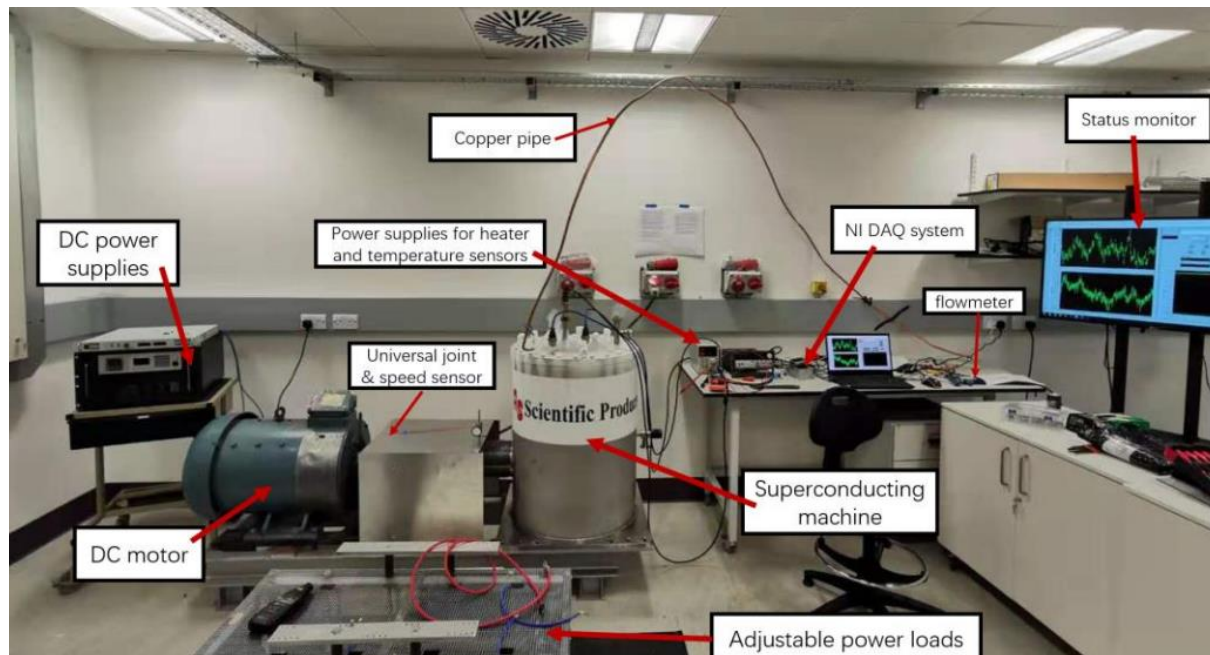
- X Too expensive
- X Technology not mature
- X Reliability issue
- X No supply chain
- X No regulation
- X No certification

Without technology demonstrations, we will never get to address these questions/concerns

Chatgpt: a superconducting propulsion system for hydrogen aircraft

WHY NOT

2017-2020: 15 kW partially HTS motor



1. AC loss of HTS coils in a rotational field: SUST 33 (10), 104002
2. Transient response of the partially HTS motor: IEEE Access 9, 59628-59636

2022-2025: ZEST 1, in collaboration with Airbus



100 kW cryogenic inverter

Sub-cooled LN2 for stators

Commercial drive system



Neon Thermosiphon
cooling for rotor

Vacuum pump

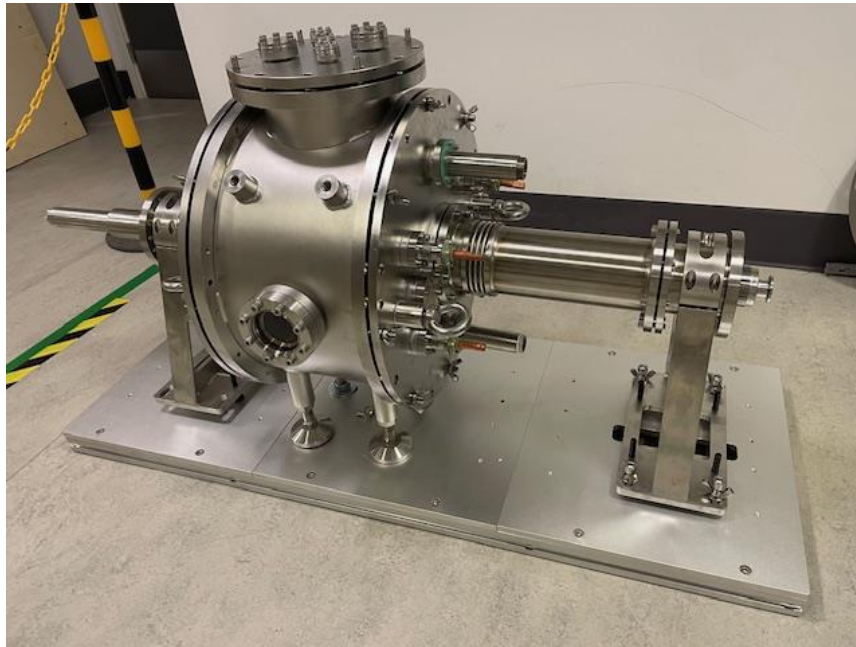
1. Demonstrate step change for cryogenic/superconducting technologies
2. Demonstrate voltage reduction below 800Vdc for a multi-megawatt applications

2024-2029: ERC SUPERMAN

100 kW fully superconducting motor

Axial flux motor

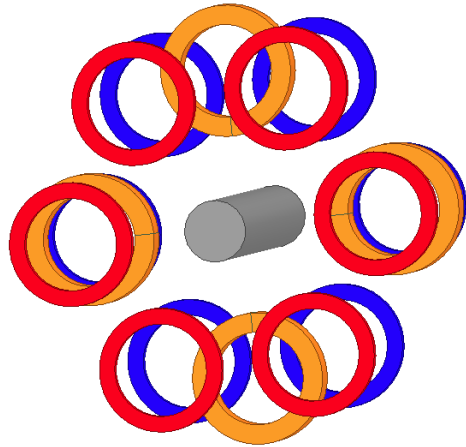
- HTS brushless rotor : Neon conduction cooling at 40-50 K
- HTS stator* 2: circulated subcooled LN2 at 70-77 K



Motor Parameter	Unit	Value
Rated Power	<i>kW</i>	100
Rated Phase voltage	V_{rms}	300
Rated Speed	<i>rpm</i>	1500
Airgap	<i>mm</i>	5
Slot/Pole	--	6/4

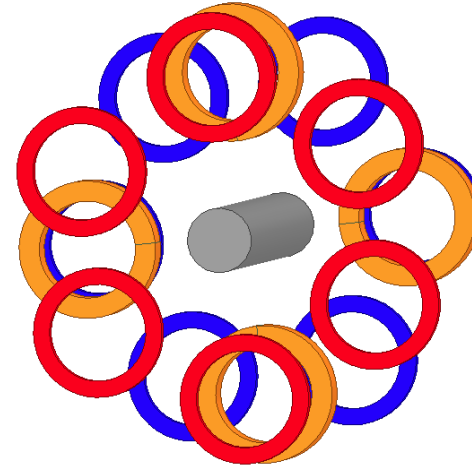
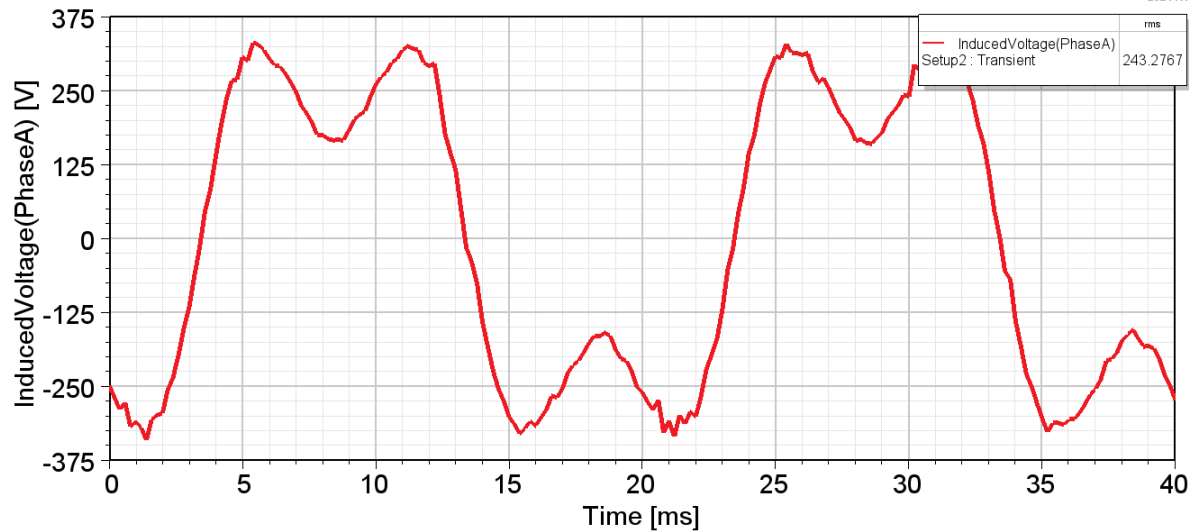
100 kW fully superconducting motor

There are two ways to arrange the two HTS armatures:



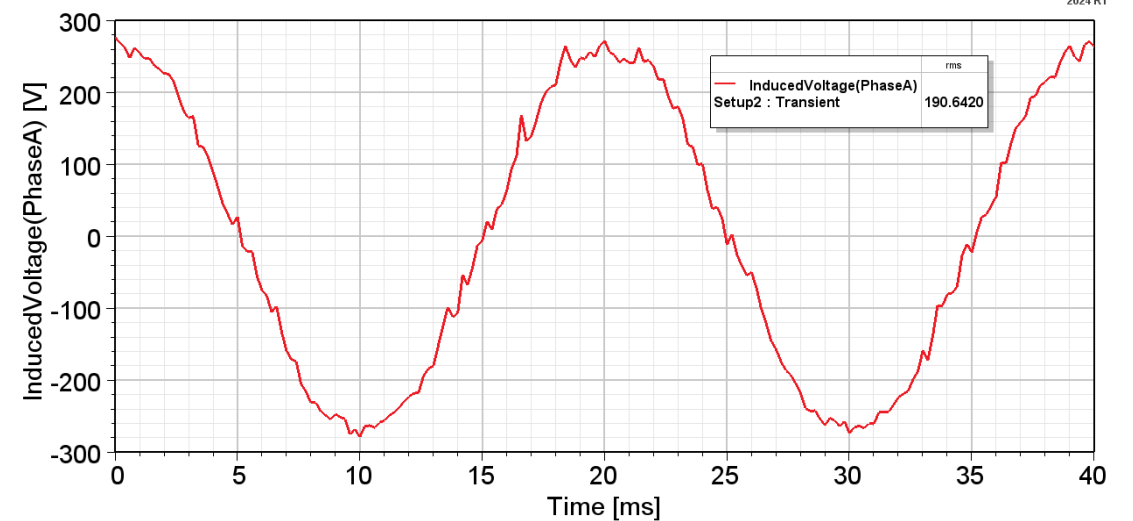
Face-face

Winding Plot 1



30 deg shift

Winding Plot 2



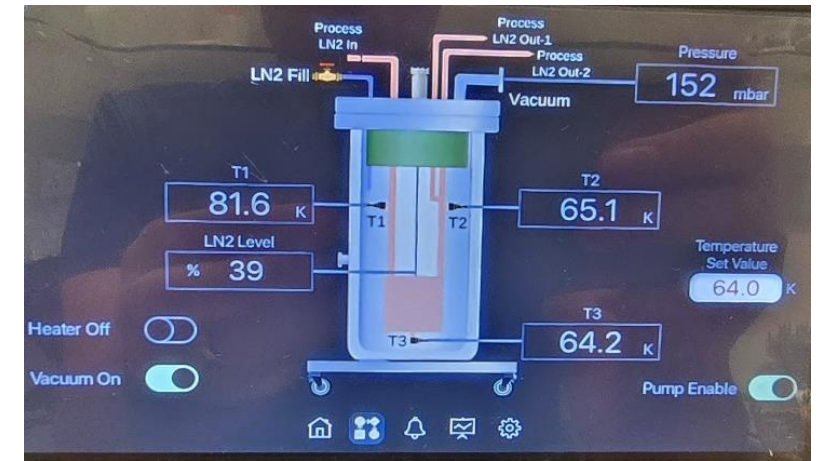
100 kW fully superconducting motor

Cooling system

➤ Motor casing leakage test passed

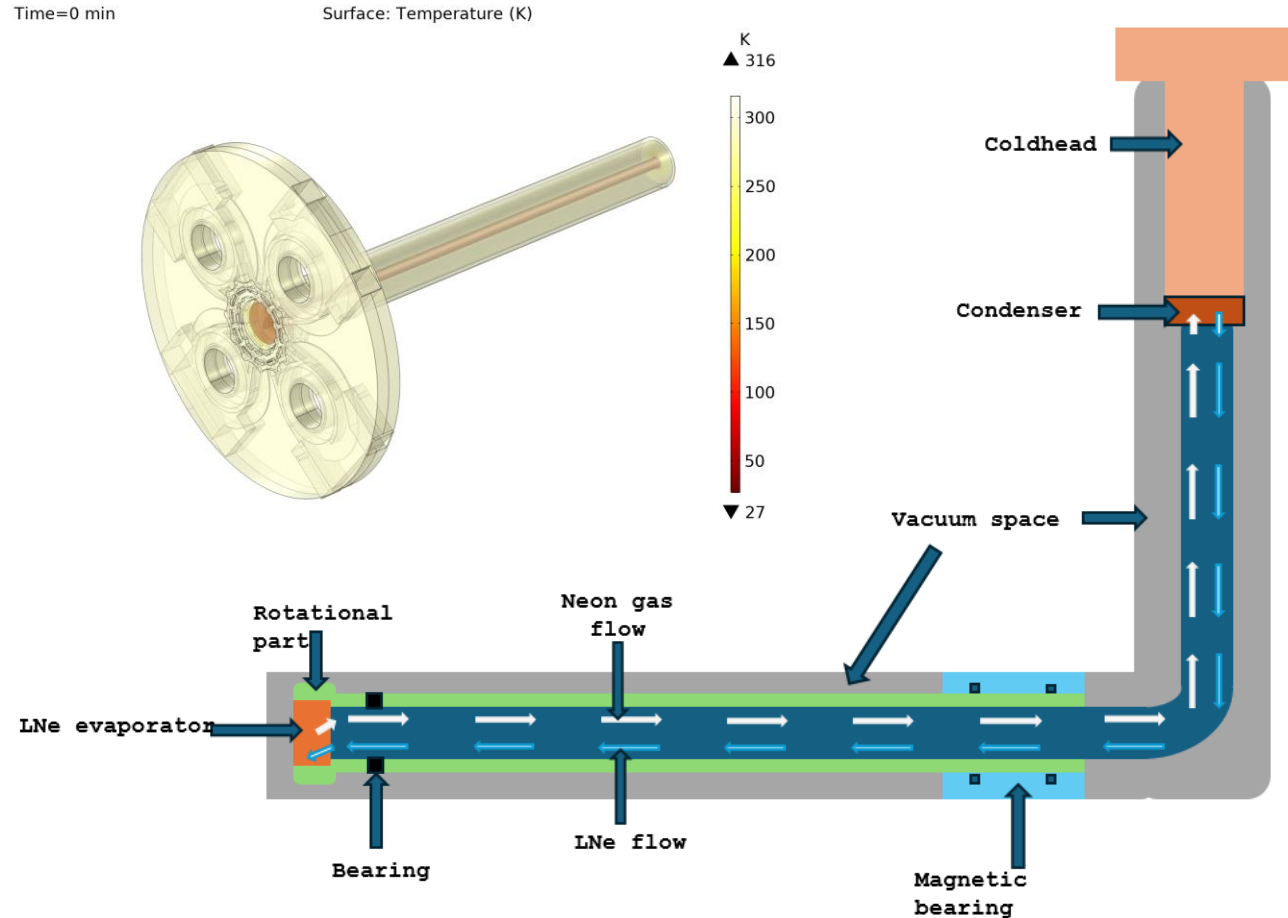


➤ Sub-cooled LN2 circulation for HTS armature:



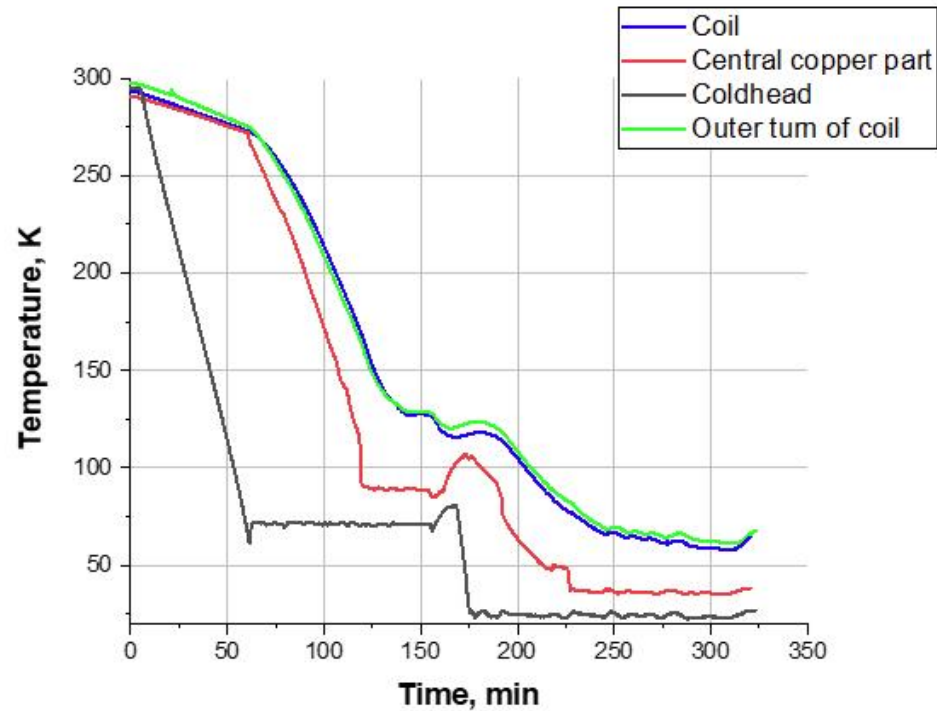
100 kW fully superconducting motor

➤ Rotational thermosiphon cooling for HTS rotor:

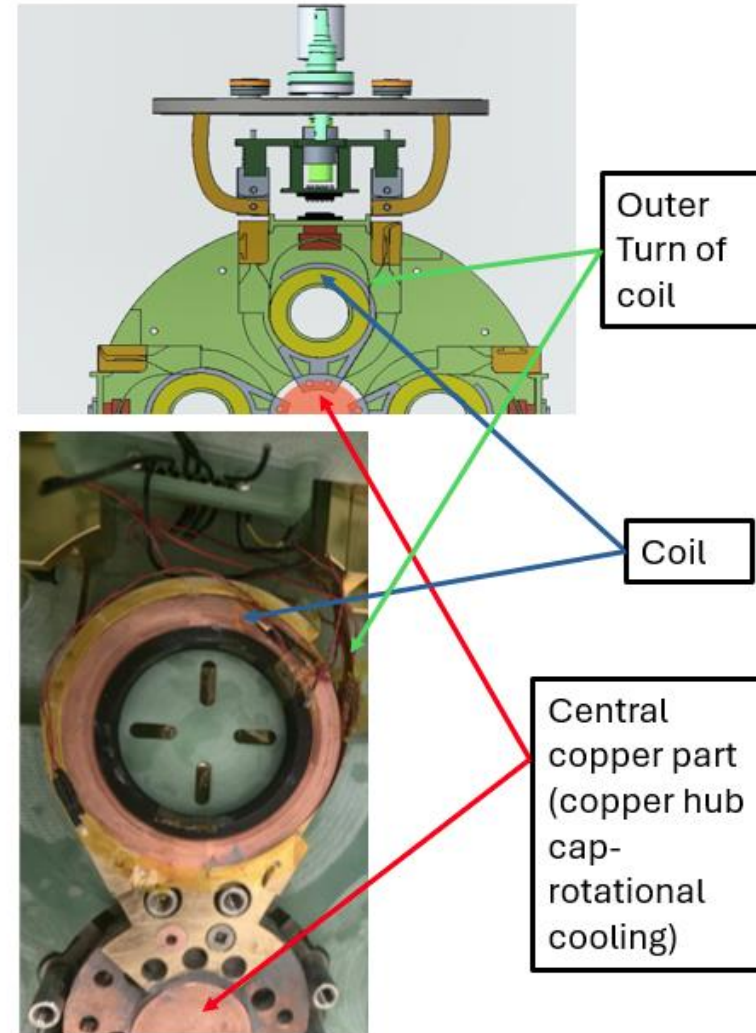


100 kW fully superconducting motor

➤ Cooling the rotor without thermal insulation layers:



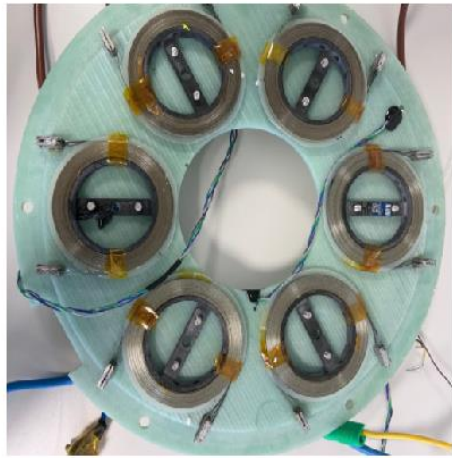
Location	Minimum stable temperature with active cooling (K)
Coil	58.24
Central copper Hub	35.34
Coldhead	23.26
Outer turn of Coil	62.54



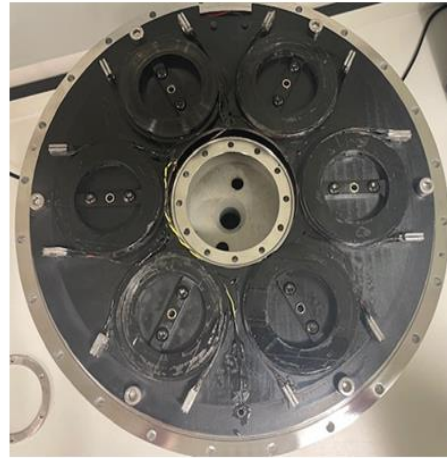
100 kW fully superconducting motor

HTS stator/armature:

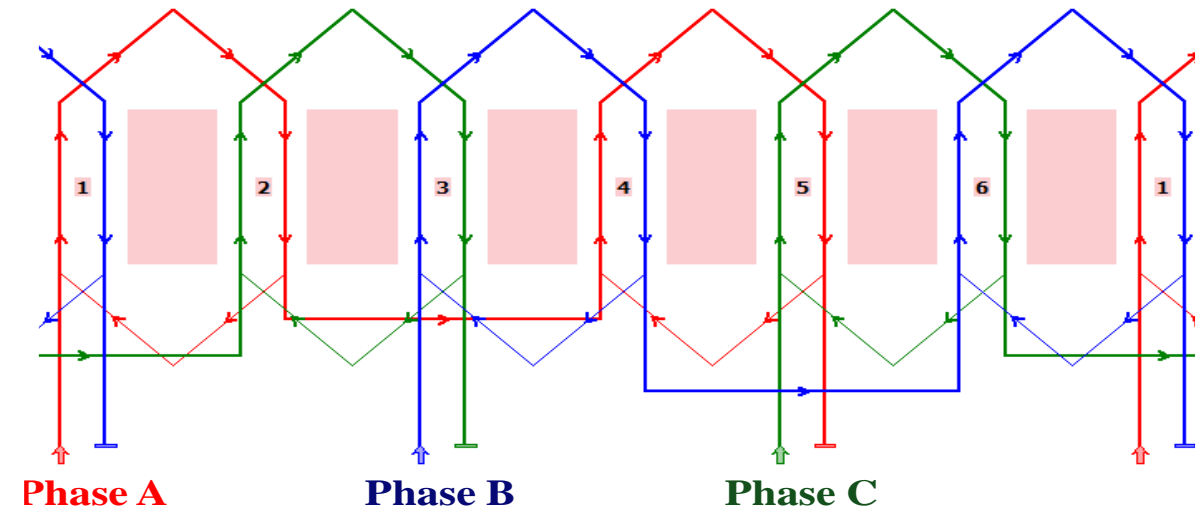
- Two stator disks were developed and tested: dry winding vs wet winding



(a)



(b)

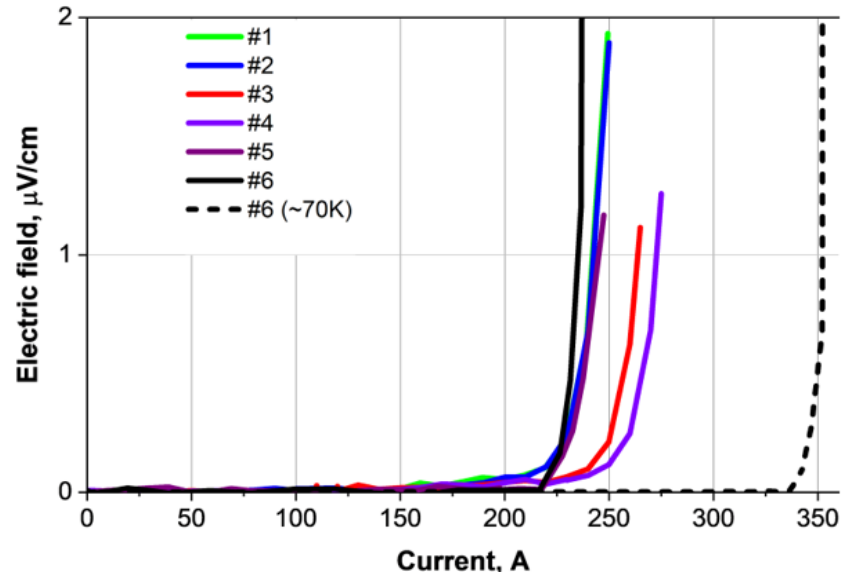


Each cable turn has four 4mm HTS coated conductor

Motor design updates

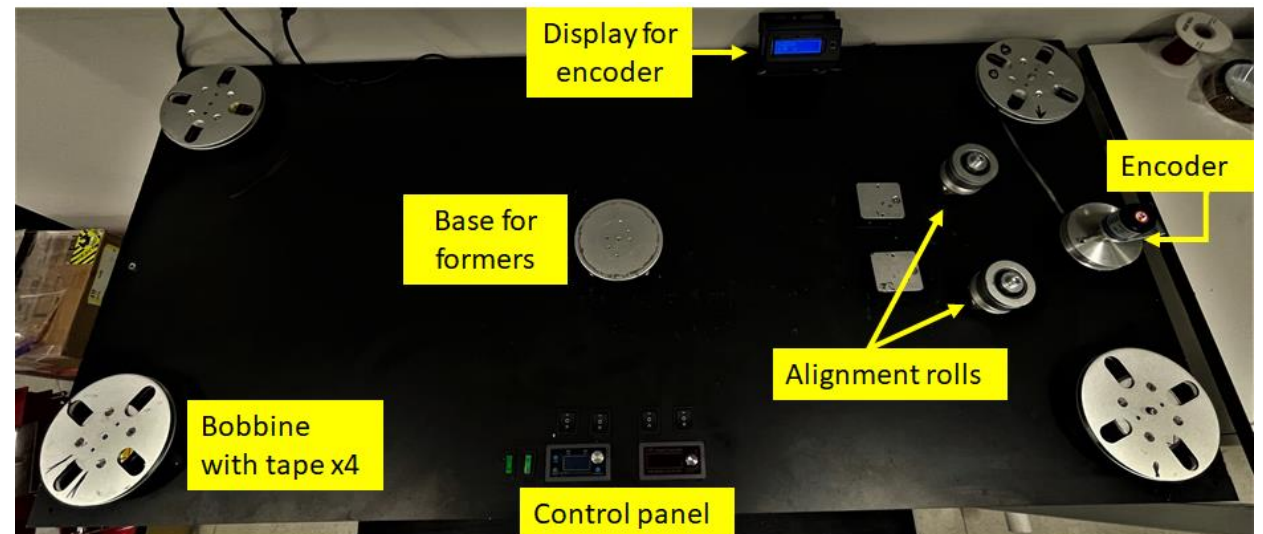
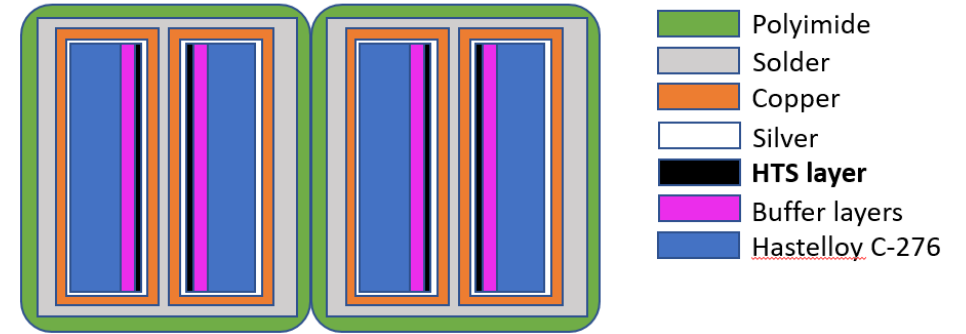
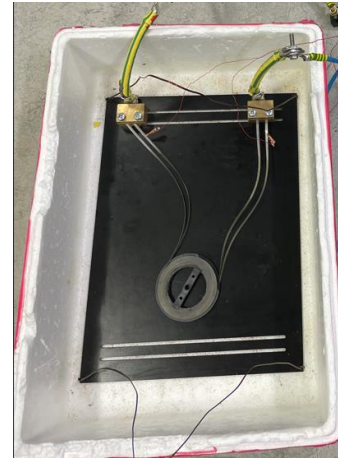
HTS Stator

➤ Ic tests at 70 K and 77 K:



All coils have I_c above 220 A at 77 K.

When further cooled down to 70 K, I_c is above 350 A.

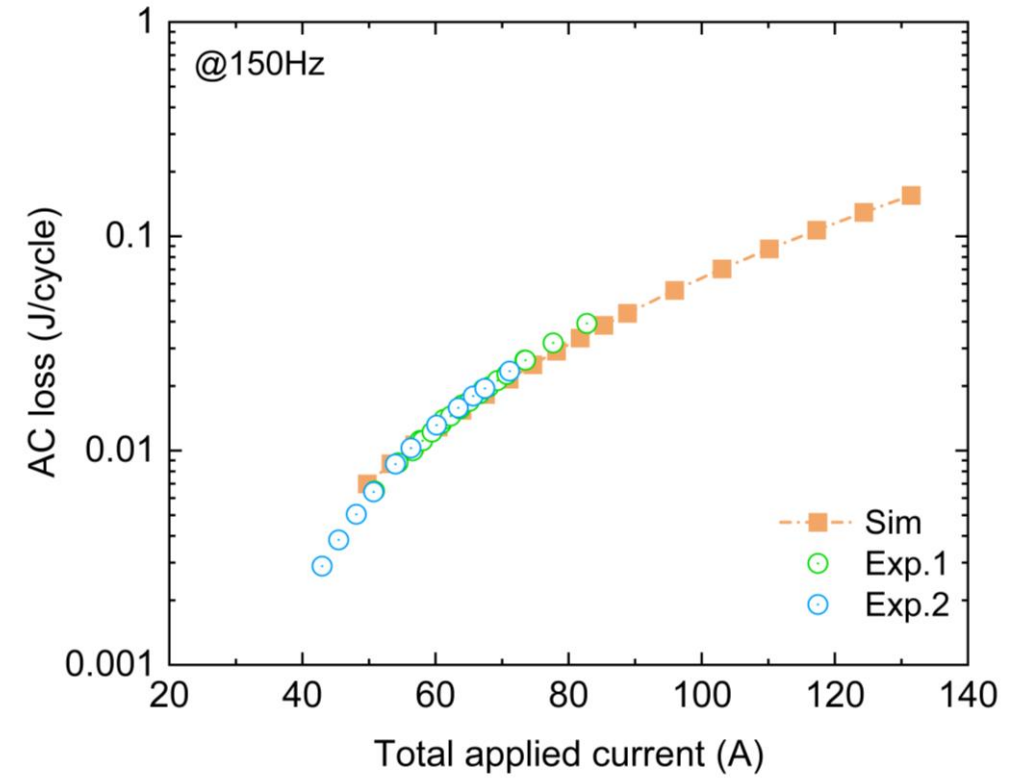
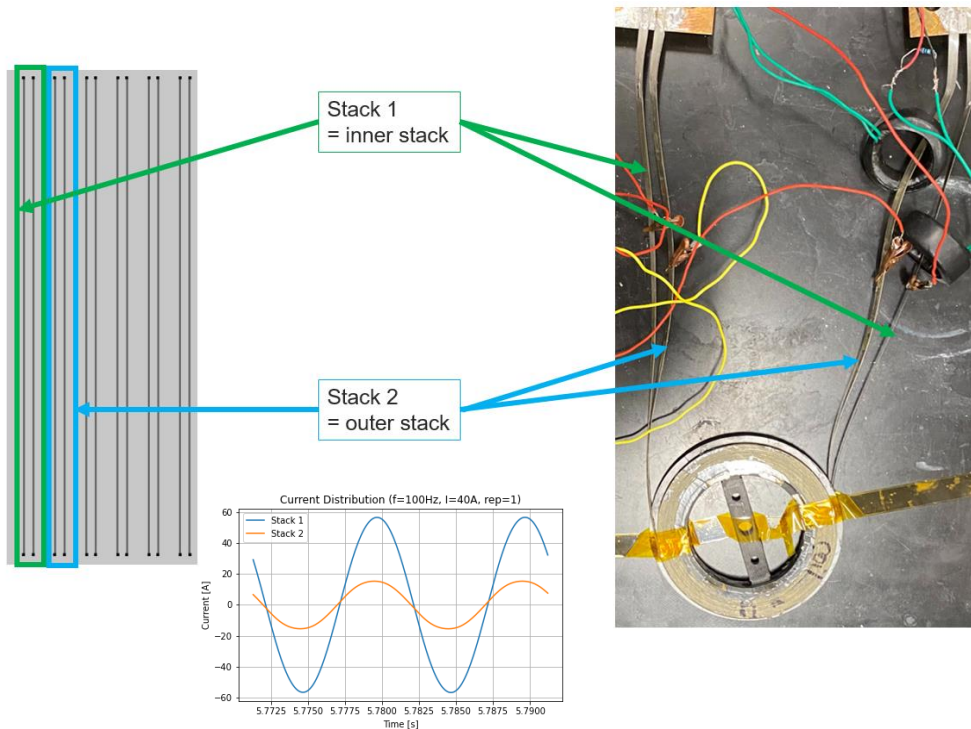


Motor design updates

HTS Stator

- AC loss measurement and calculation at 20-77 K *:

Sat-Af-Or5-06: AC loss measurement for parallel-wound HTS coils

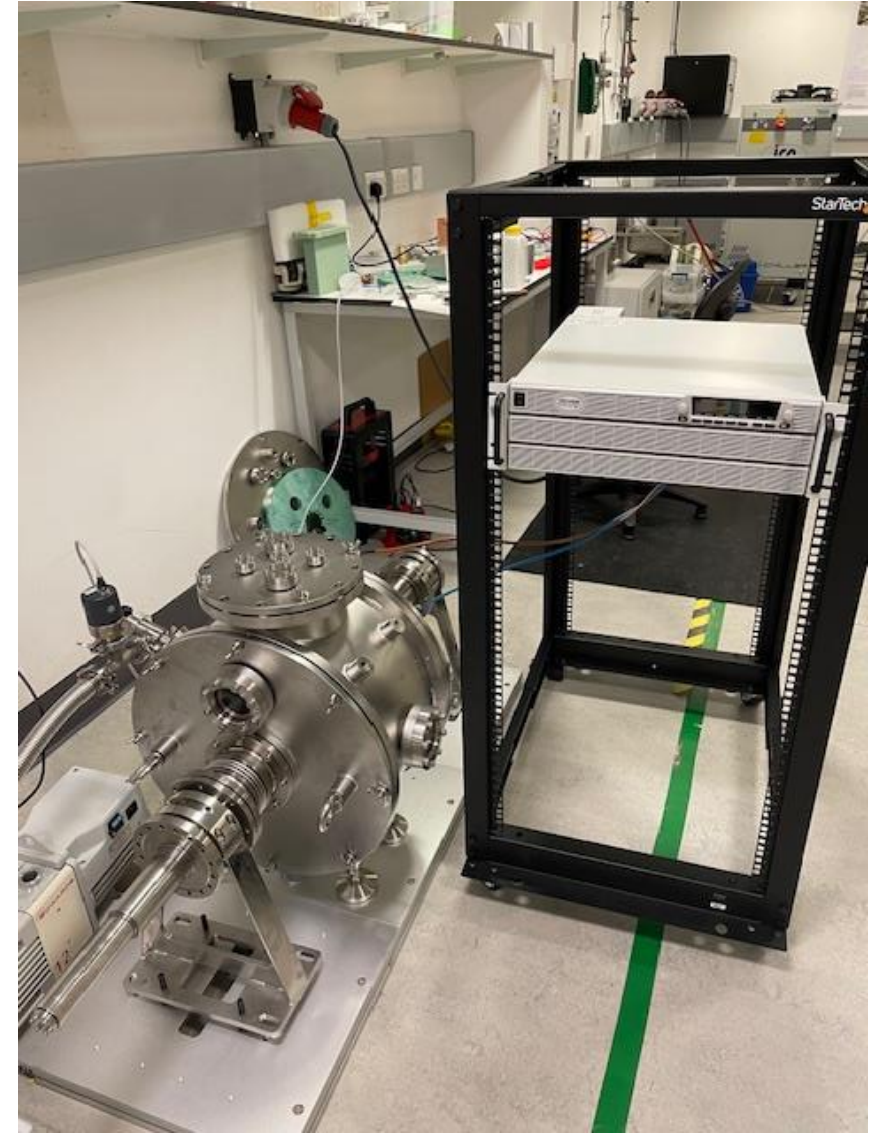


Motor design updates

➤ Insulation test up to 1kV:

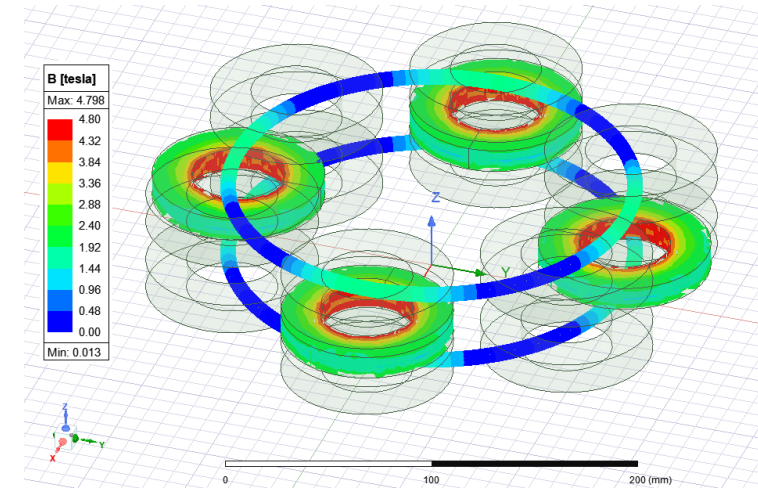
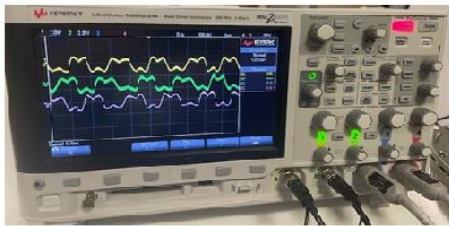
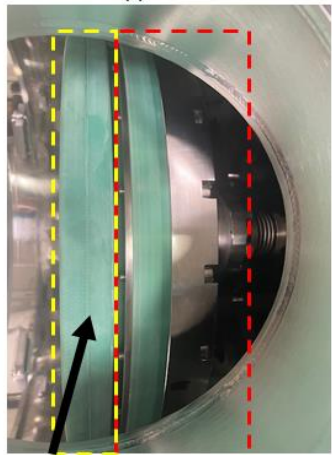
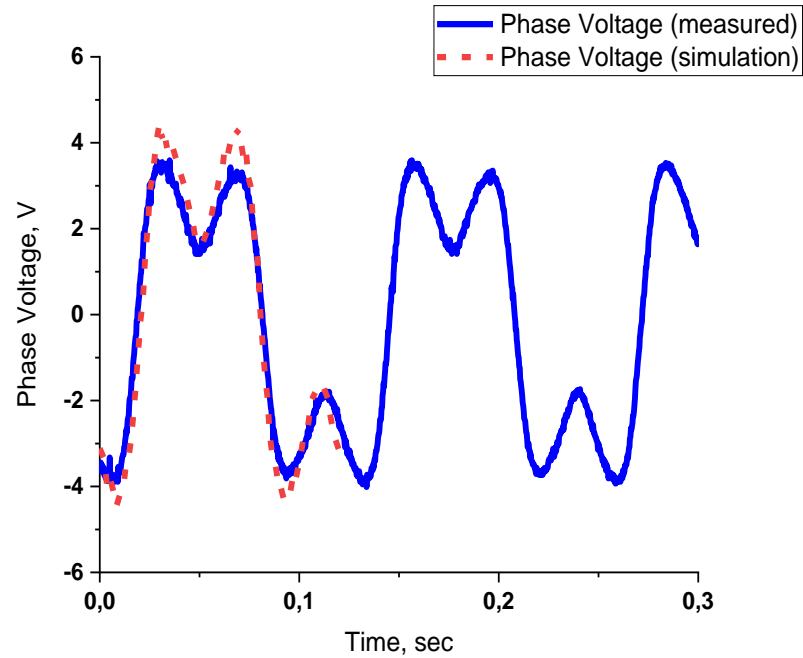
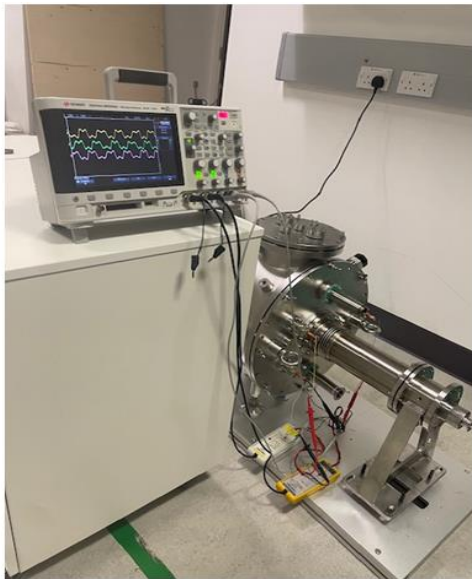
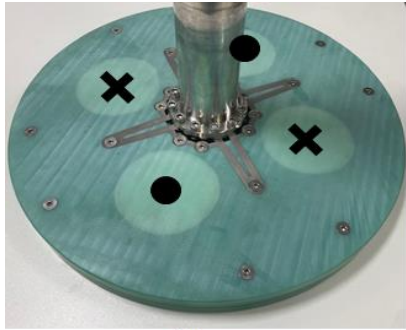
Voltage applied between armature
and motor casing

No leakage current up to 1 kV



Motor design updates

➤ Room temperature rotational test with a PM rotor:



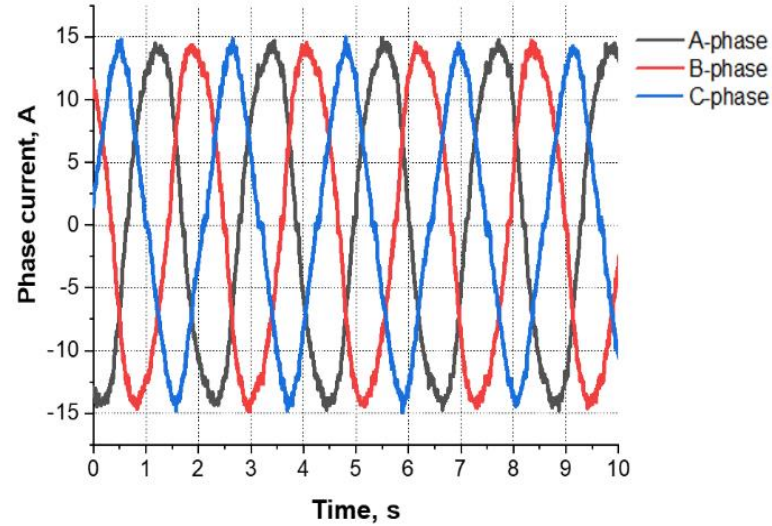
Open voltage output agrees with FEM 3D simulation

Motor design updates

➤ First 77 K first test failed:



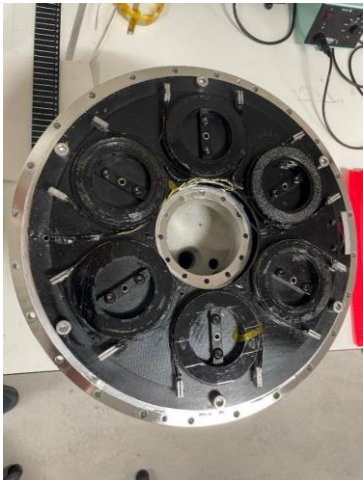
(a)



(b)



- Coolant leakage due to G10 casing sealant problem. Top coil was burnt

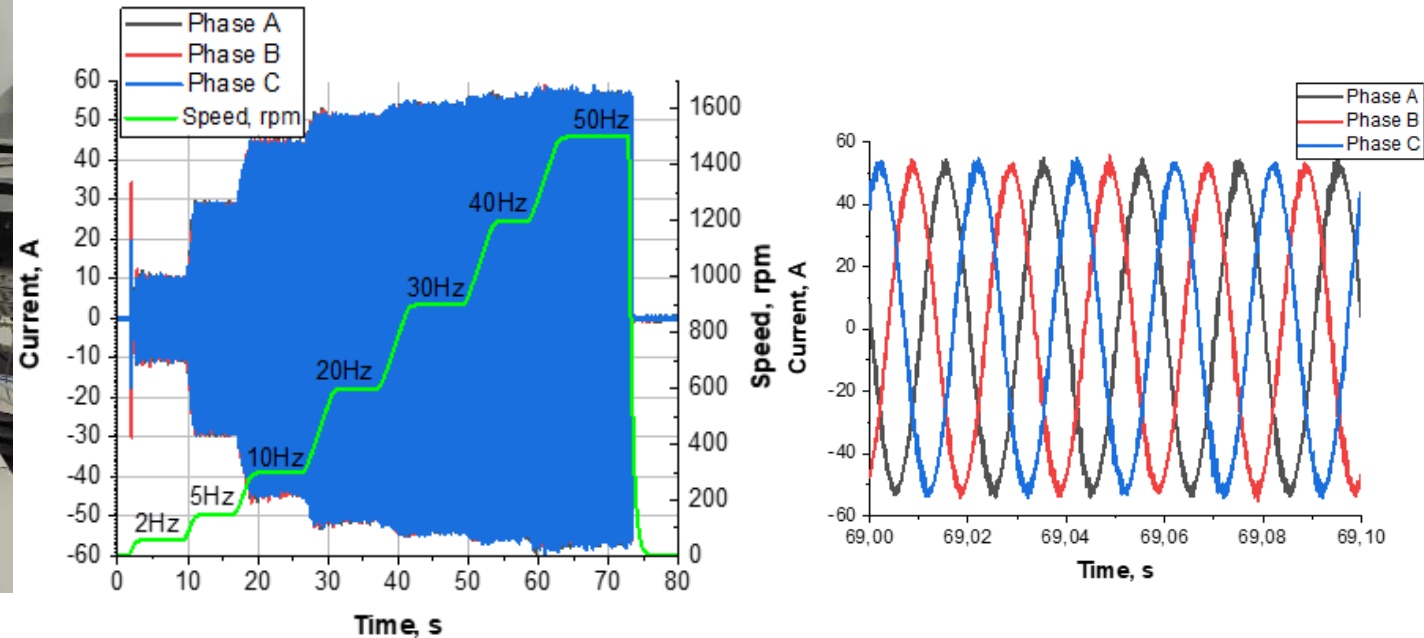
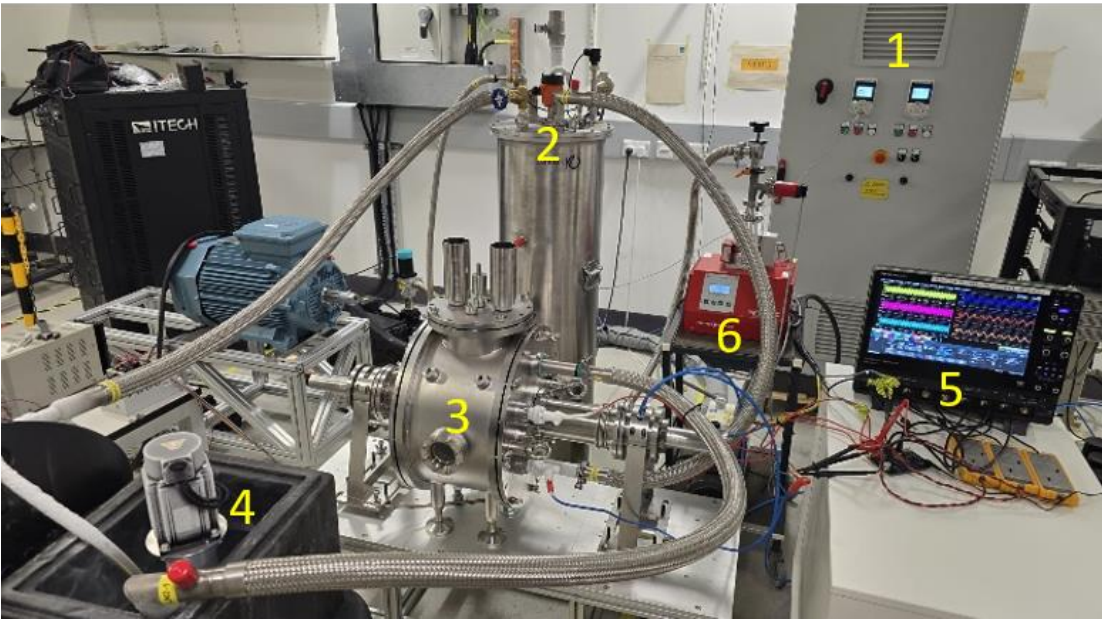


Lessons learnt:

1. Better sealing
2. Real-time T monitoring

Motor design updates

- Second rotational test was successful @ 70 K, 1500 rpm:

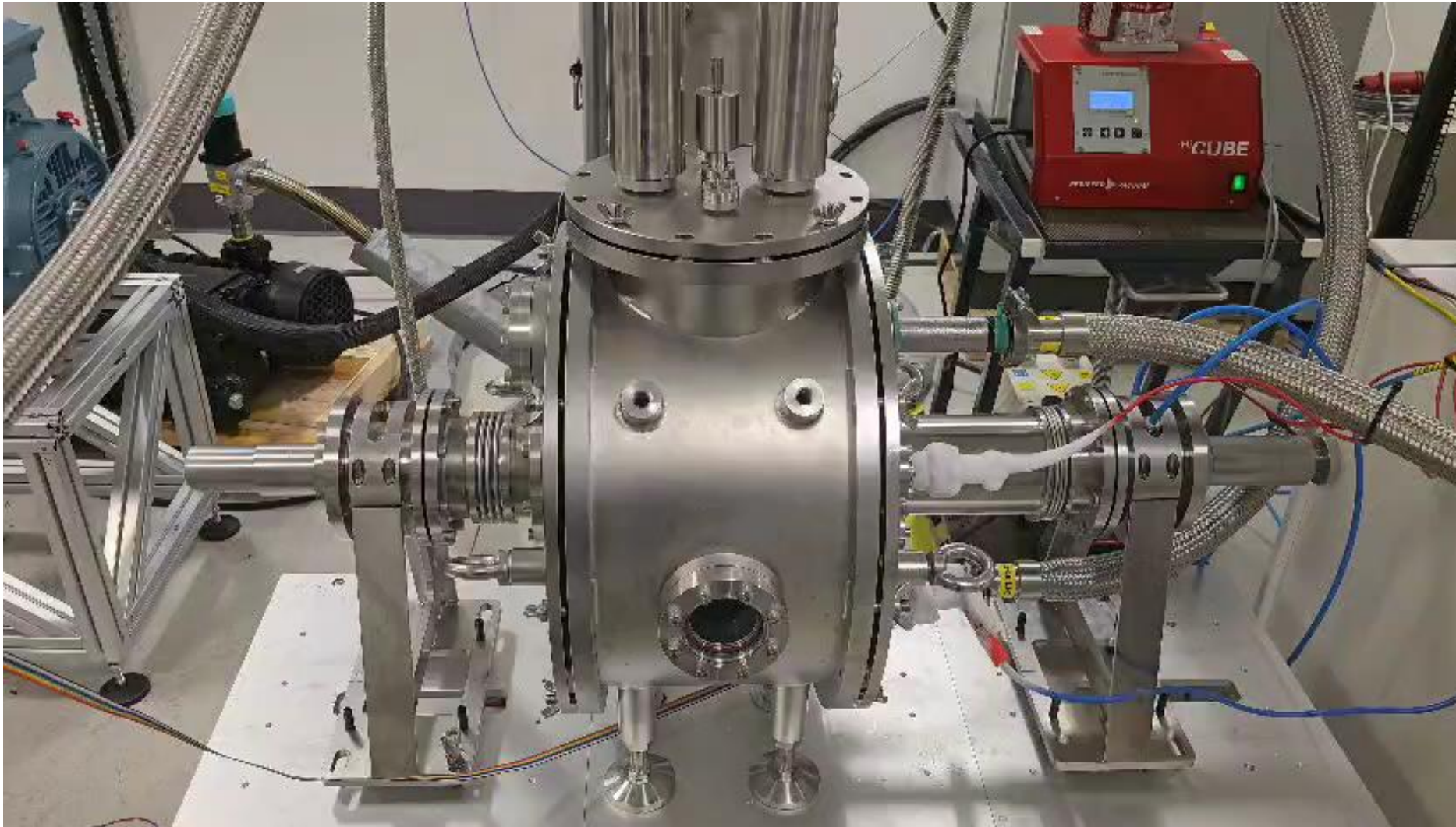


Test setup with closed loop subcooled LN₂ circulation and PM rotor: 1) inverter, 2) subcooled LN₂, 3) HTS motor with a PM rotor, 4) cryogenic pump and LN₂ reservoir, 5) oscilloscope, 6) vacuum pump.

Closed loop circulation with flow up to 10 l/min and subcooling down to 70K which was achieved during the test.

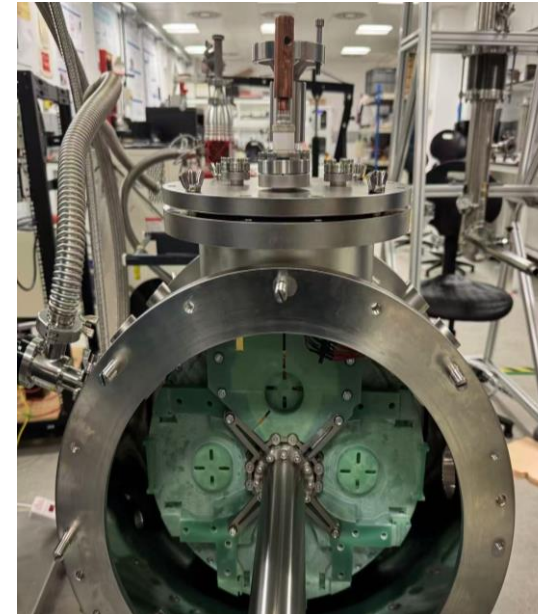
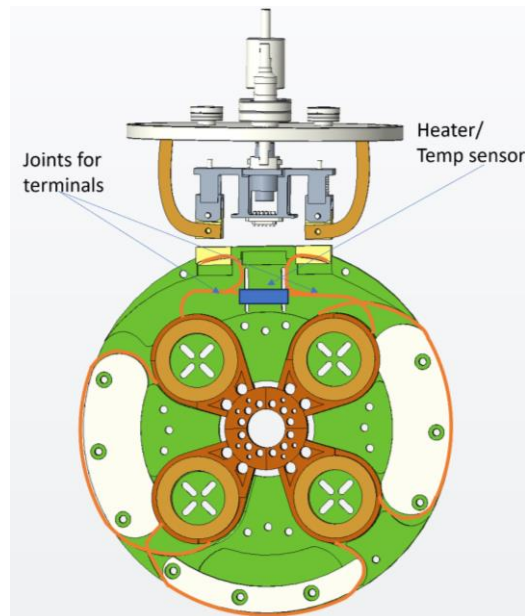
Motor design updates

HTS motor operation at 1500rpm



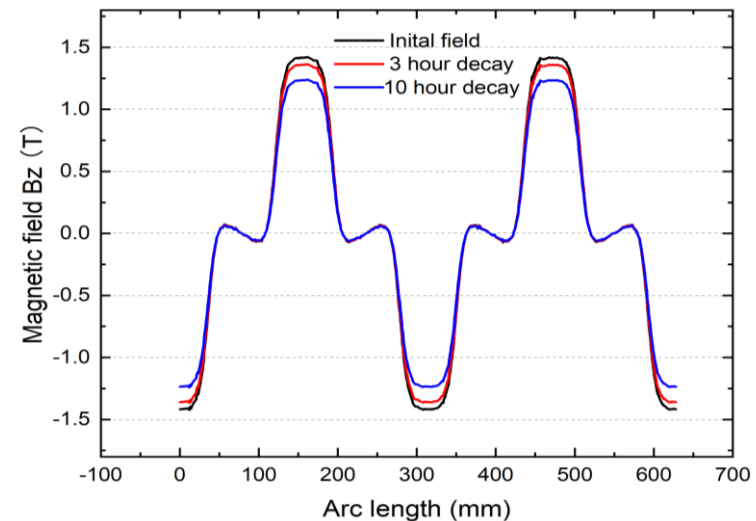
Motor design updates

HTS rotor: Low joint HTS resistivity + direct charging/dynamo-flux pump



- We need nΩ level HTS joints for this rotor at 50 K

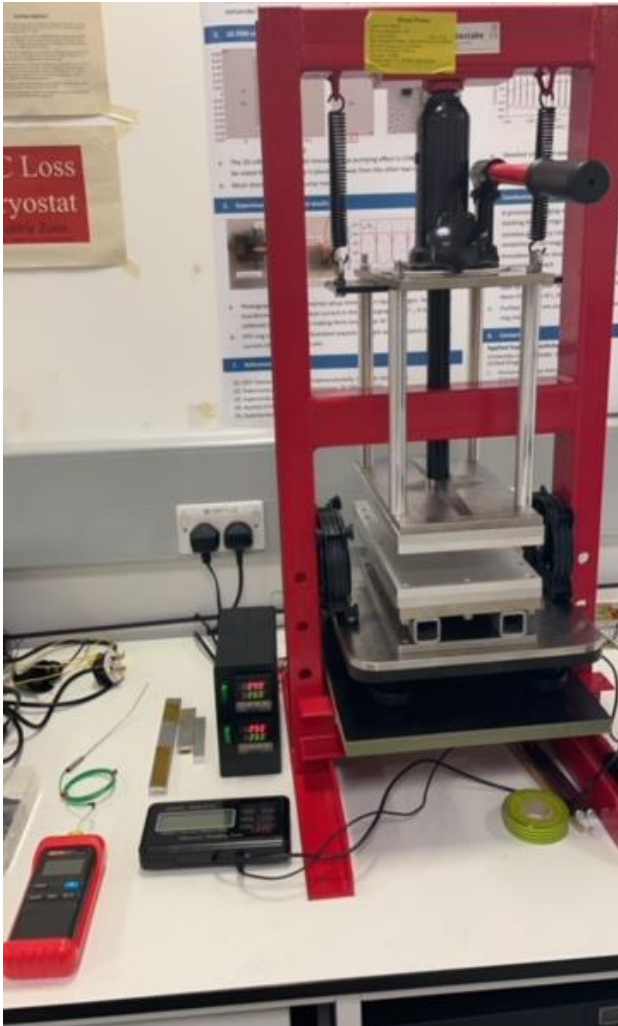
Charged current	500 A
Inductance	2640 μH
Resistance	10 nΩ
Temperature	50 K
3 hour decay	1.48T -> 1.42T 4.1%
10 hour decay	1.48T -> 1.29T 12.8%



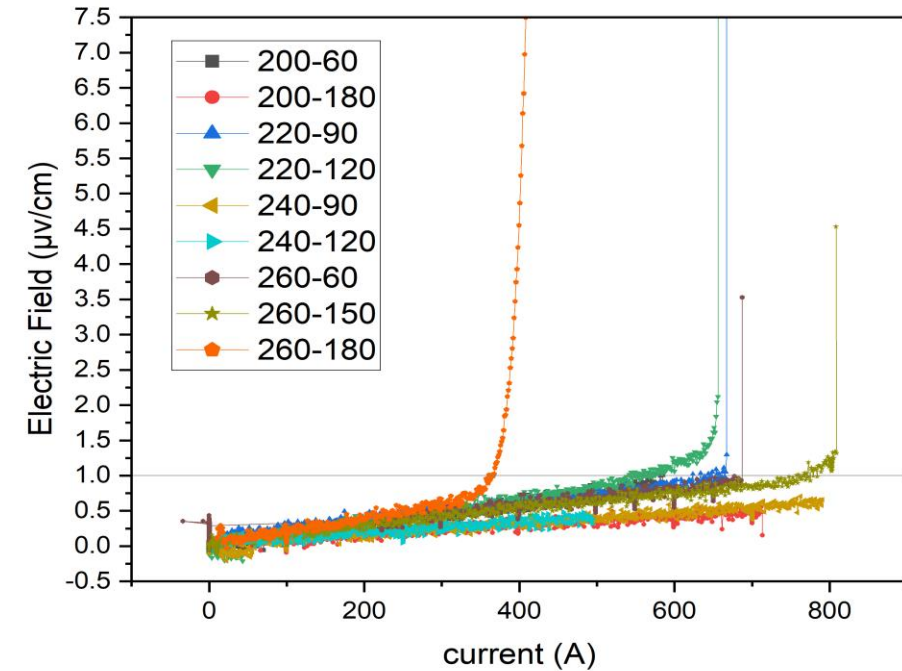
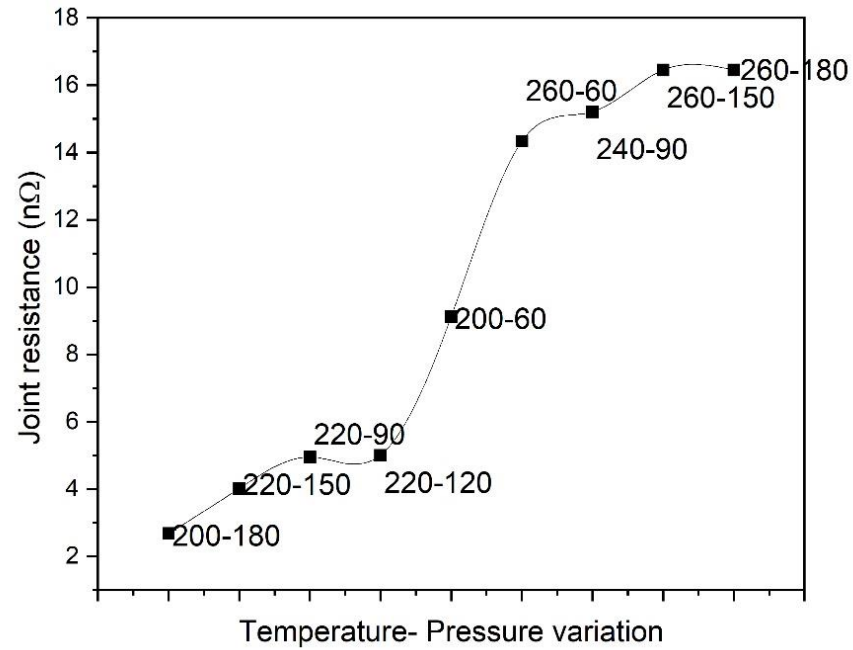
Motor design updates

HTS rotor:

Customized heating-press



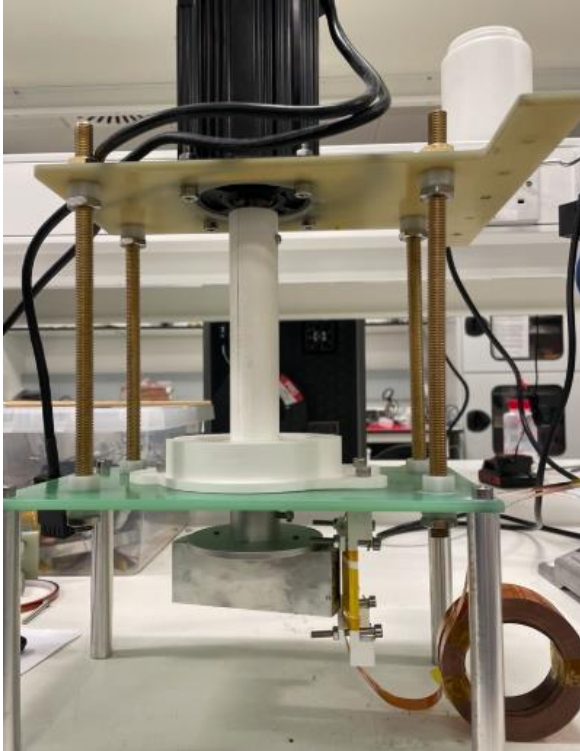
Temperature-pressure optimization for 5 cm long soldered joints with 12mm HTS tape



- nOhm level resistance was achieved at 77 K
- I_c measurements were performed for all joint samples

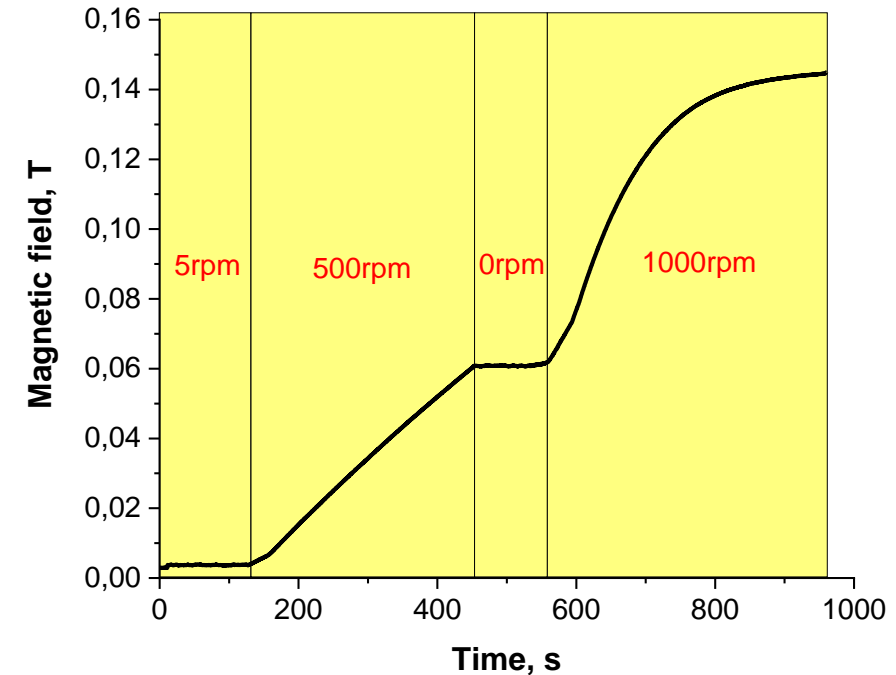
Motor design updates

HTS rotor: Dynamo-flux pump for demagnetization



**Wireless charging
during rotation of
rotor**

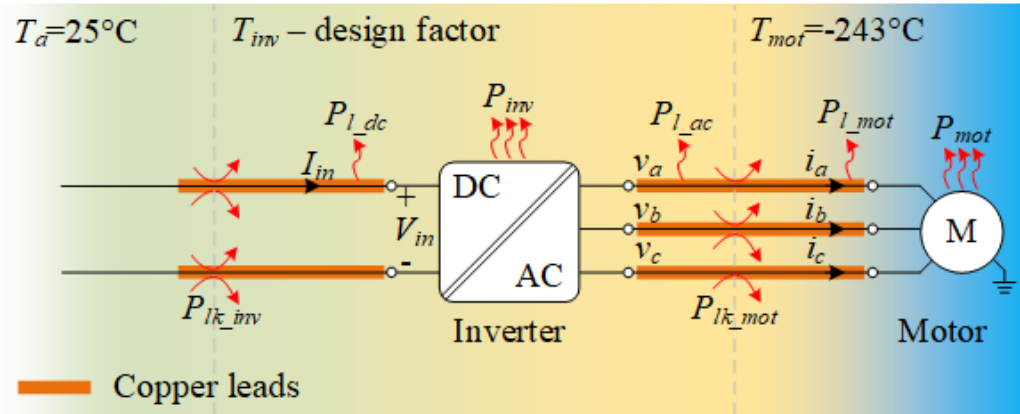
Results of the HTS coil charging
with persistent current mode



- No degradation of current at 0 rpm for low resistance of the joint.
- At 77 K, 0.04 T/100 s
- Feedback control will be used for field stability [1]

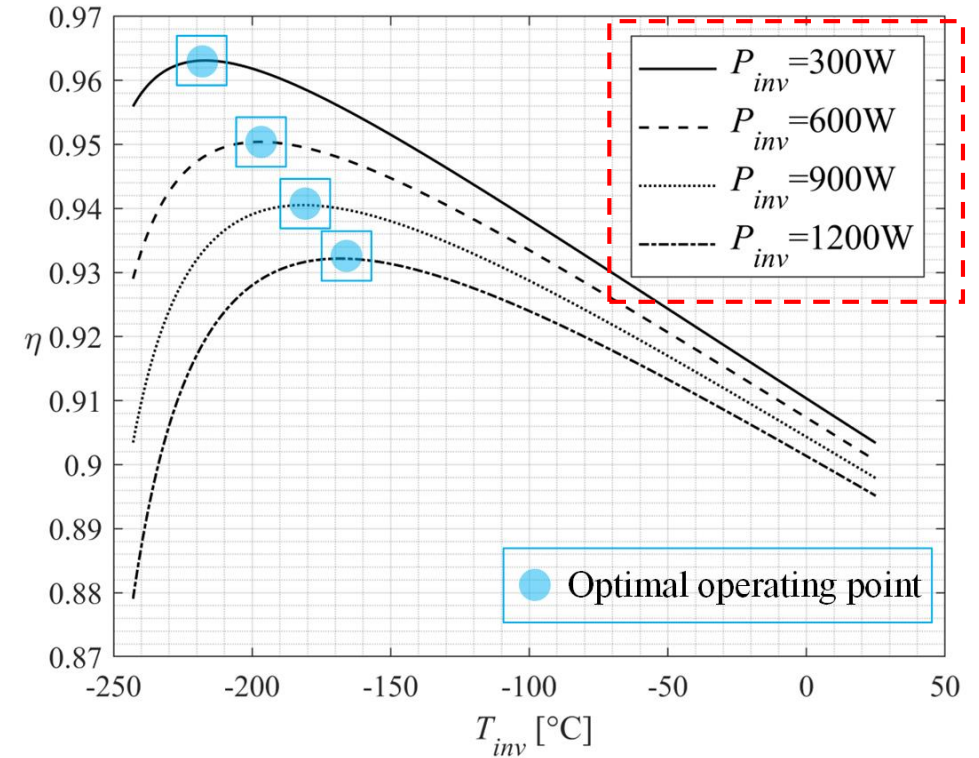
[1] [Feedback-controlled flux modulation for high-temperature superconducting magnets in persistent current mode](#), M Iftikhar, M Zhang, W Yuan, Superconductor Science and Technology 36 (5), 055008

Cryogenic inverter: why cryogenic?



Inverter's loss is mainly affected by:

- Topology of circuit
- Type of power semiconductor
- **Coolant temperature!**



Cryogenic inverter: component overview

Specification:

- DC bus voltage: 730V
- Operating temperature: 77K
- Efficiency: >96%
- THD: <4%
- Switching frequency: 5kHz

Topology:

- Three-level voltage source
- Si IGBT power module

Customized gate drive circuit:

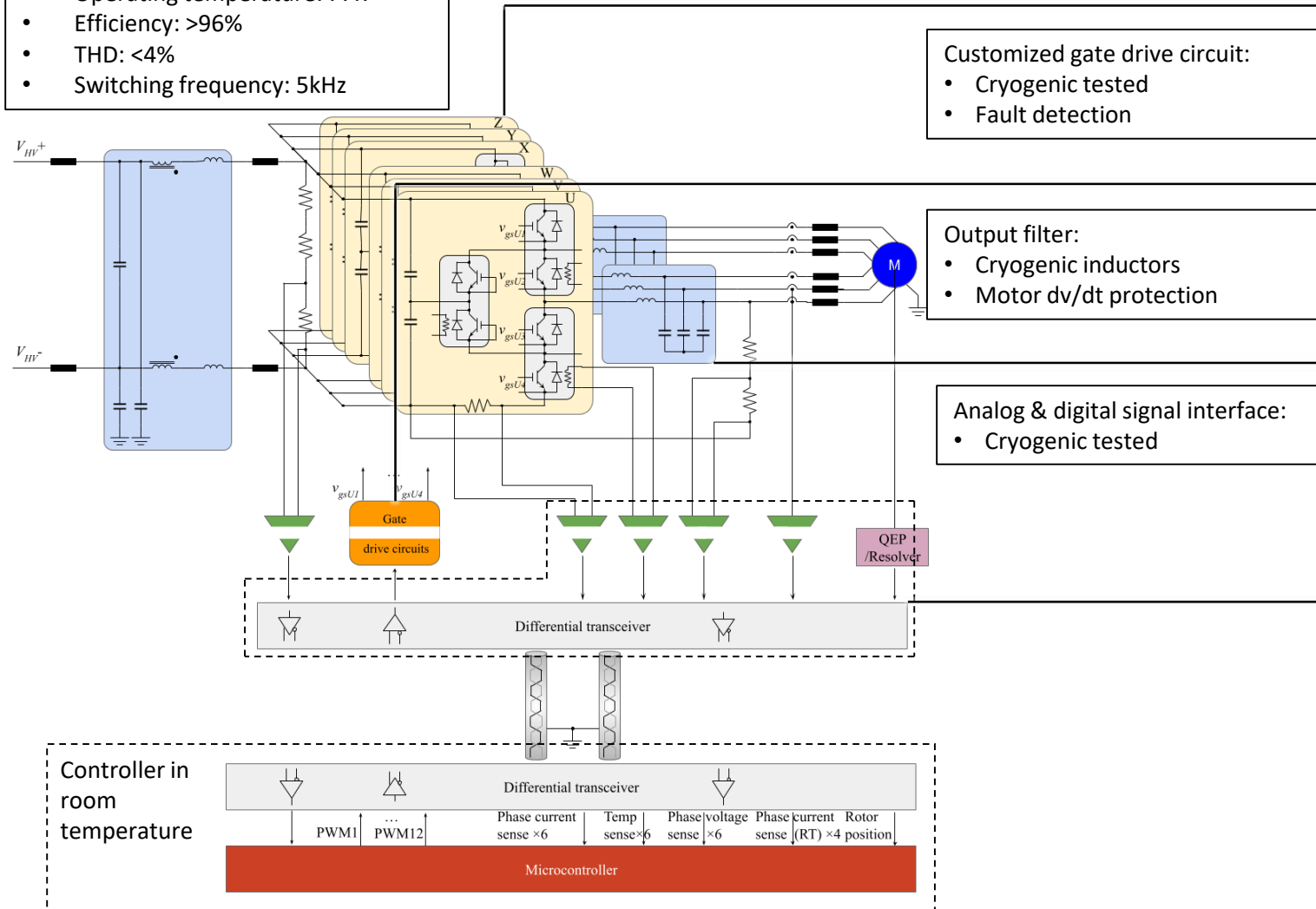
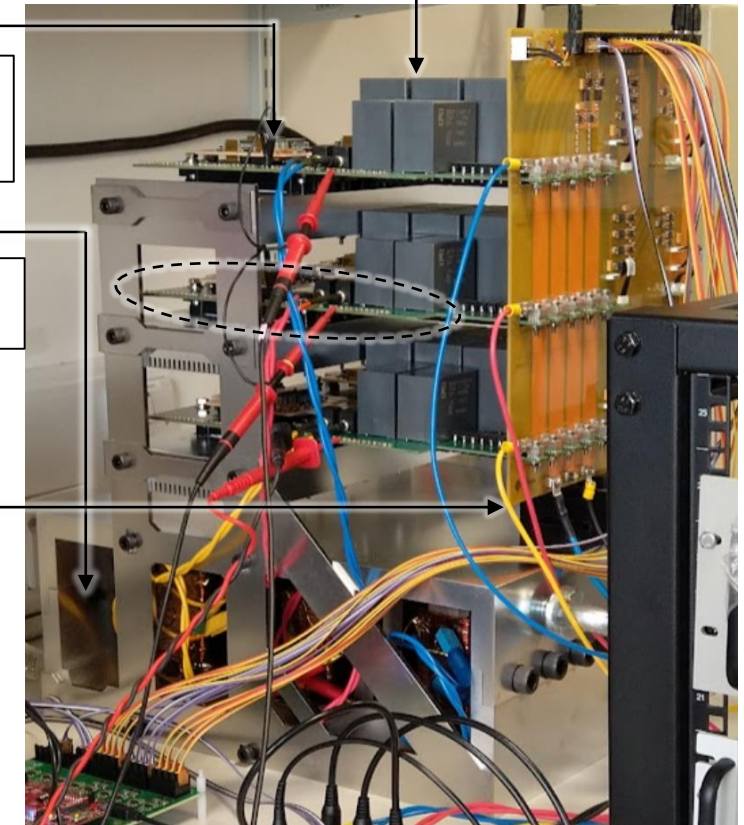
- Cryogenic tested
- Fault detection

Output filter:

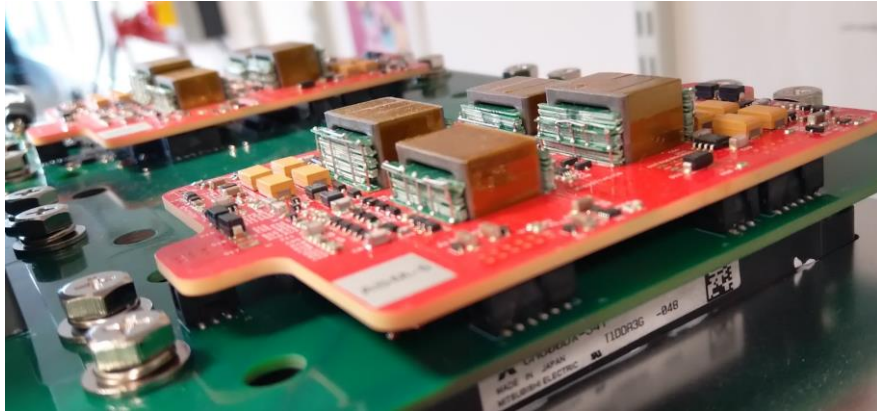
- Cryogenic inductors
- Motor dv/dt protection

Analog & digital signal interface:

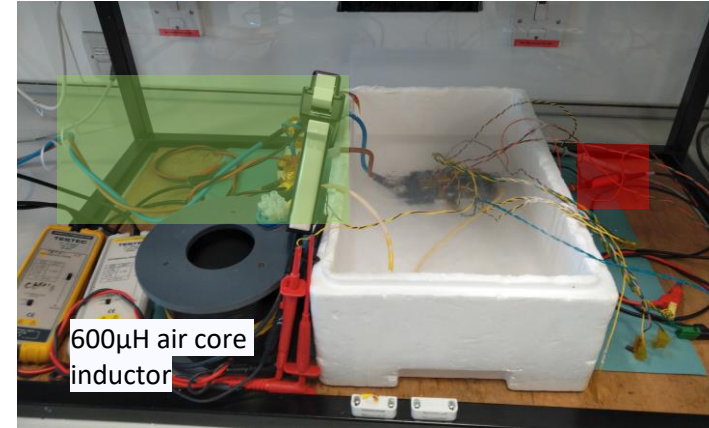
- Cryogenic tested



Cryogenic inverter: cryogenic isolated gate drive

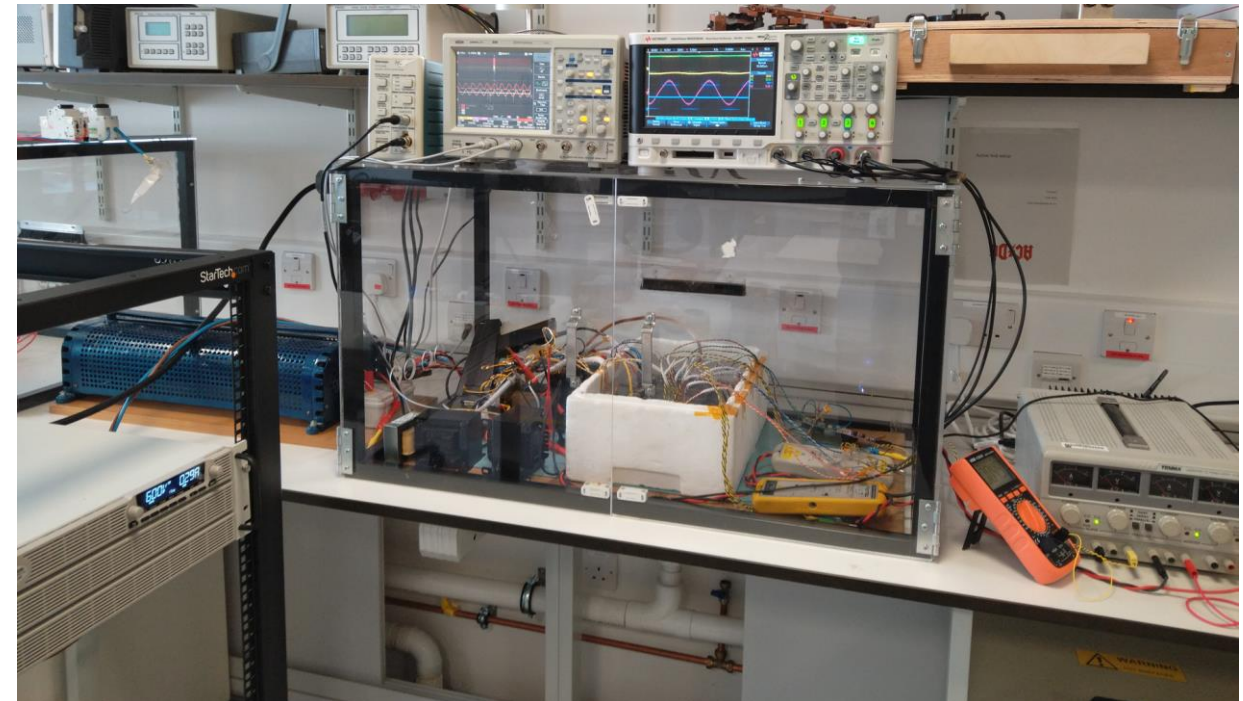


Two gate drive boards (version 2)
mounted on a phase board of
the inverter

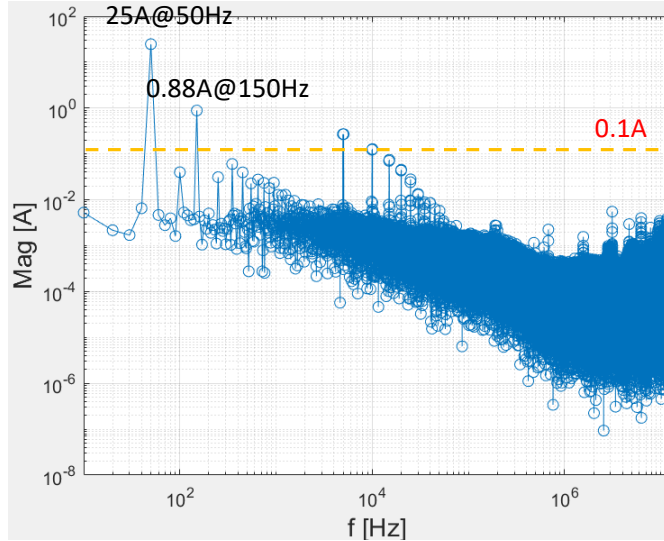


IGBT power module tested at 800V/160A in 77K.

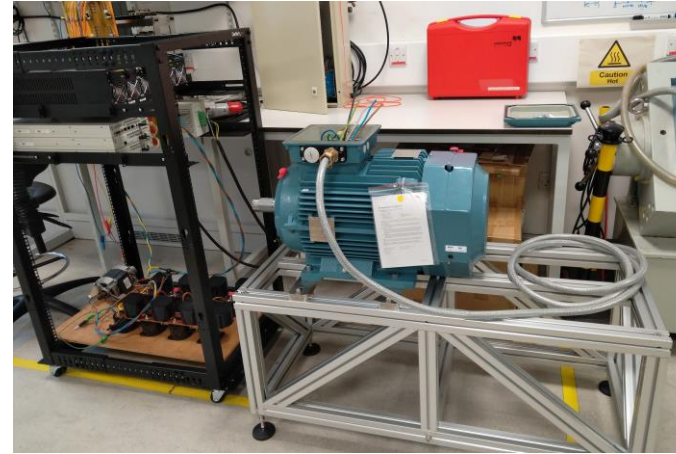
A half-bridge three-level inverter is tested up to 700V- and 600V-input voltage at room and cryogenic temperature, respectively: 20Ω resistive load, 10 kHz switching frequency.



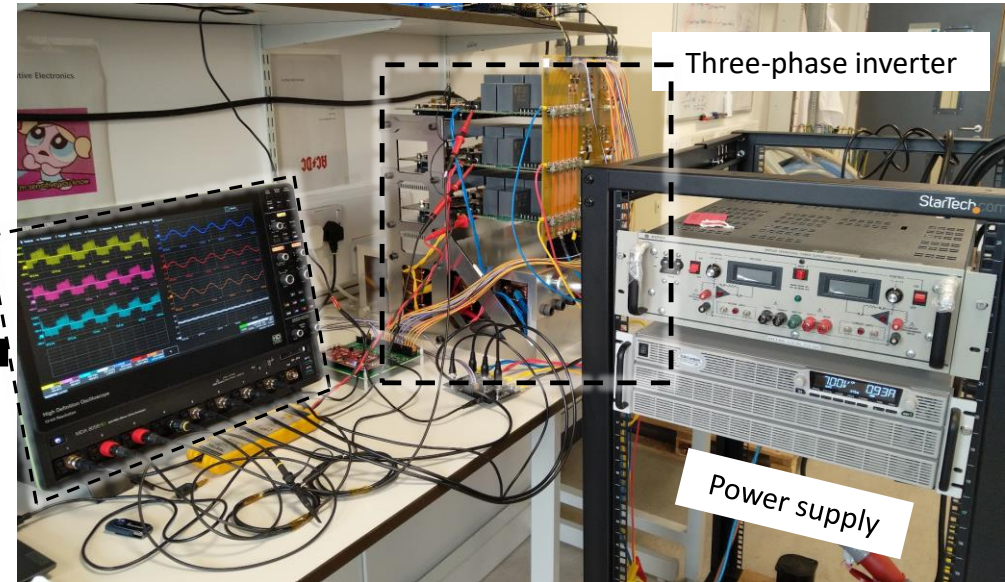
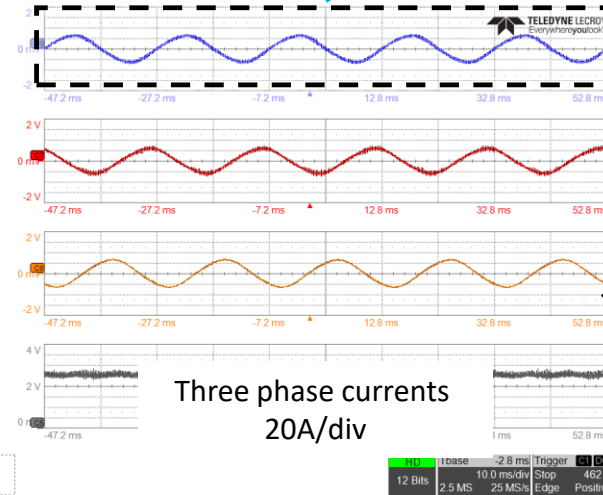
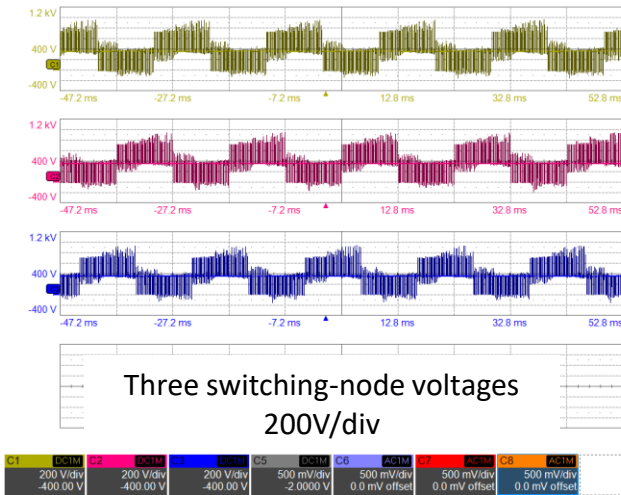
Cryogenic inverter: test progress



Spectrum of Phase-A current
THD 3.6%
(Target THD 4%)



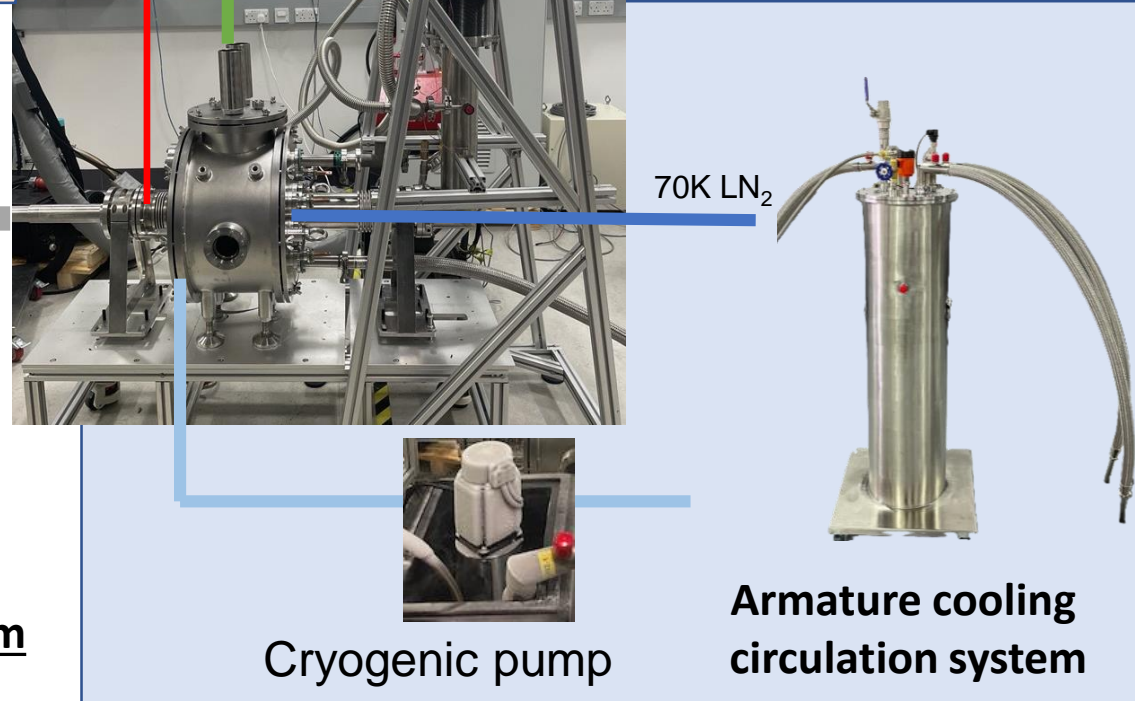
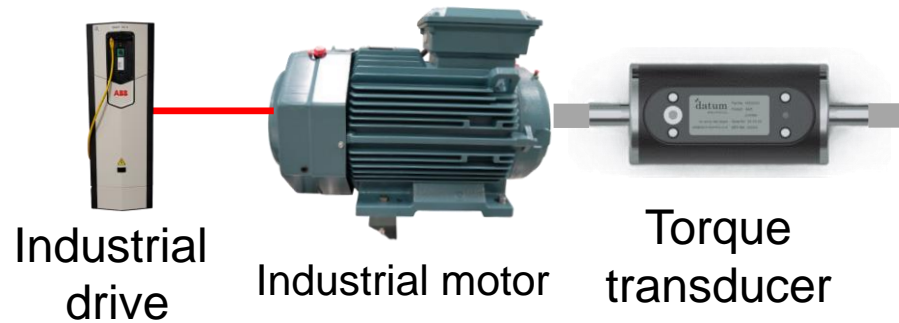
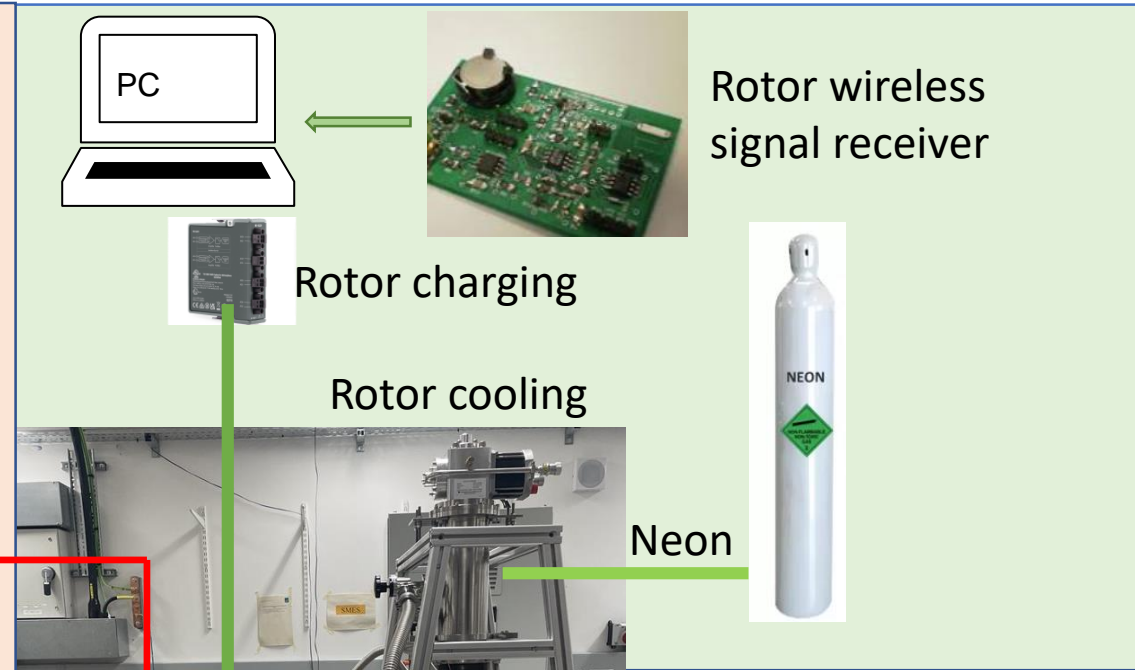
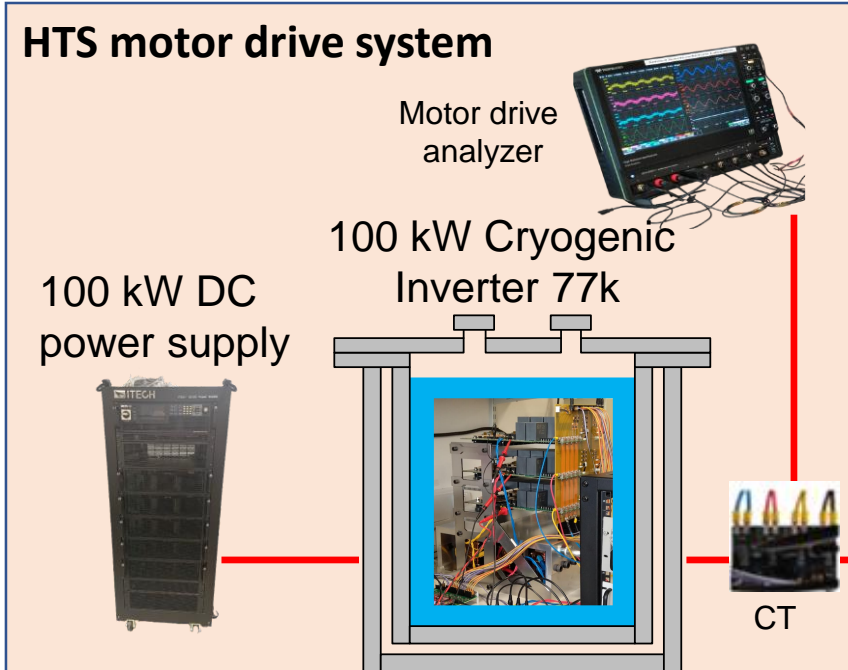
Test with an induction motor before connecting to HTS motor



RT three-phase inverter test:

@ 700V input voltage and 25A-peak phase current, equivalent to operation at 18kW

- 1) A R&D platform for exploring novel technologies
- 2) Easy access and diagnoses
- 3) Proof-of-concept for a fully HTS motor



100 kW Cryogenic Propulsion Unit Platform

Thank you for listening Questions?

We are looking for visiting researchers and PhD students to work on the following topics:

1. Superconducting aviation motor design
2. Condition monitoring and fault prevention



Lab info

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