Progress on a 100 kW fully HTS propulsion motor 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

ASC 2024 1LOr2A-01

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- Topology
- HTS Rotor
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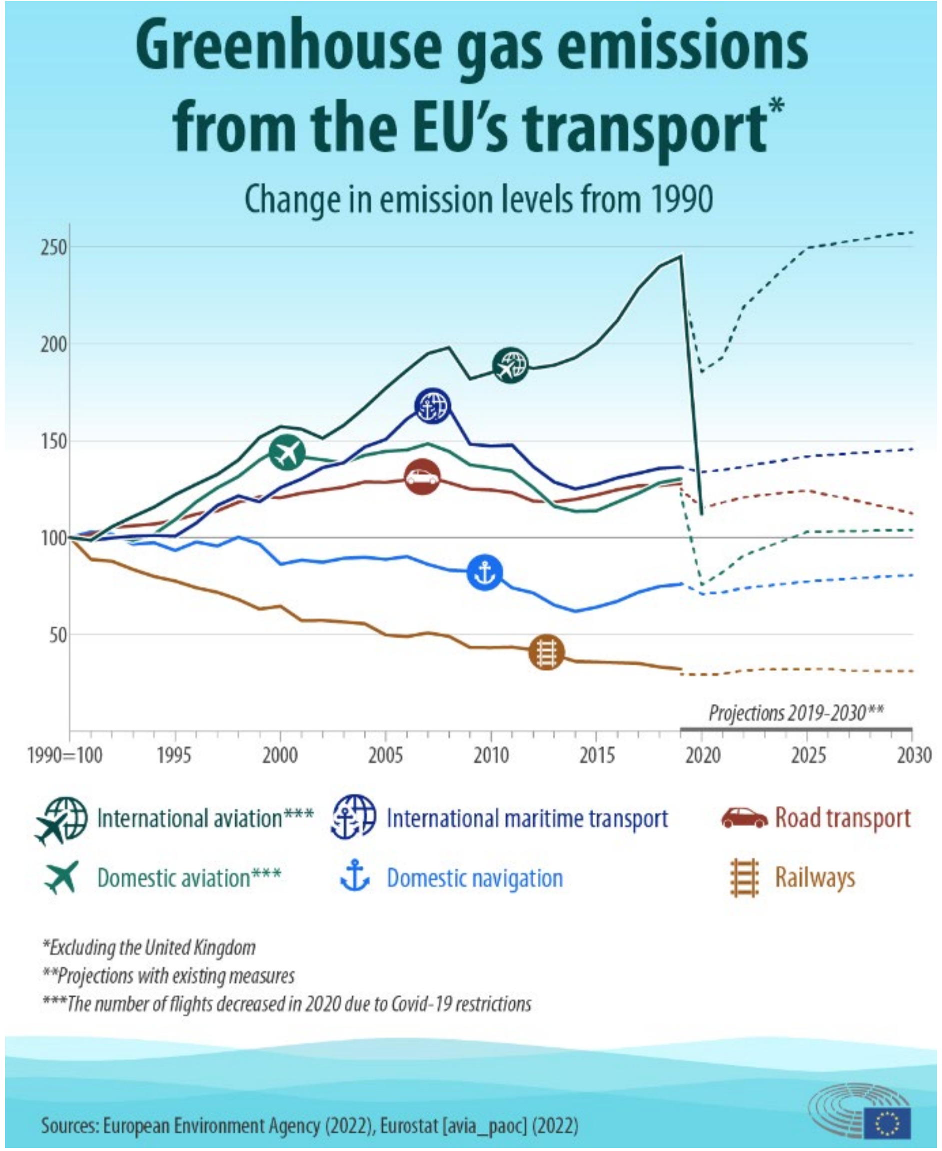
- Cooling system

Introduction

Introduction

Electrification in aviation helps to achieve net-zero targets



- The global **aviation** industry has agreed to try to achieve net-zero emissions by 2050
- One promising way for reducing emission is via electrification
- Conventional electrical motors are too heavy for aviation
- Improving conductor current density leads to lighter and more powerful electrical motors

Introduction

Improving conductor current density is desirable but with penalty

GKN Aerospace Launches H2FlyGHT: Pioneering £44M Project for 2 MW Cryogenic Hydrogen-Electric Propulsion

23 May 2024

Innovation

Airbus takes superconductivity research for hydrogen-powered aircraft a step further

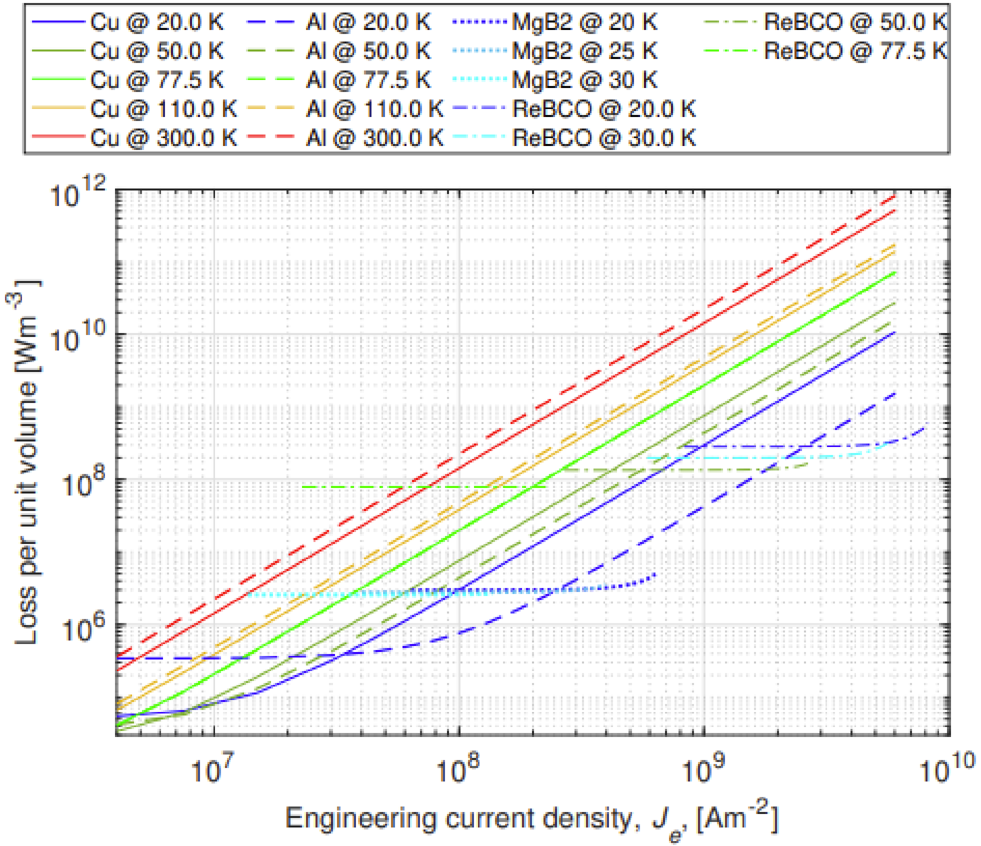
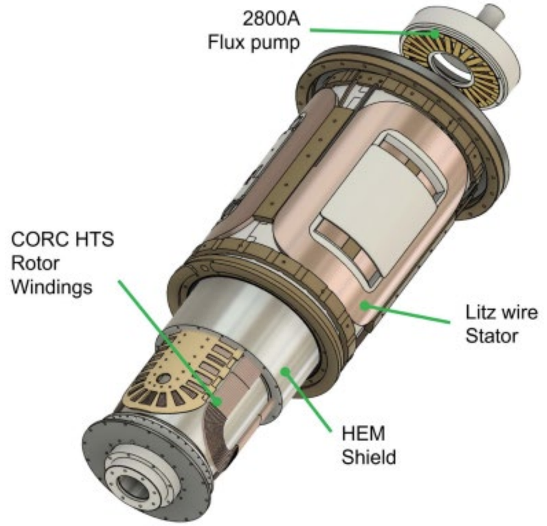


Fig. 2: Loss per unit length of conductor when the conductors, at different temperatures, are carrying 150 Hz transport ac of different amplitudes (amplitudes converted to engineering current densities). The conductors are simultaneously being subject to 150 Hz alternating external magnetic field of amplitude 0.4 T.



100 kW Robinson Institute

250 kW GREEN and Safran

* Calculation in "Analytical ac loss comparison between ReBCO, MgB2, copper and aluminum Litz wires for cryogenic electrical machines", to be published in IEEE TAS

Introduction

Improving conductor current density is desirable but with penalty

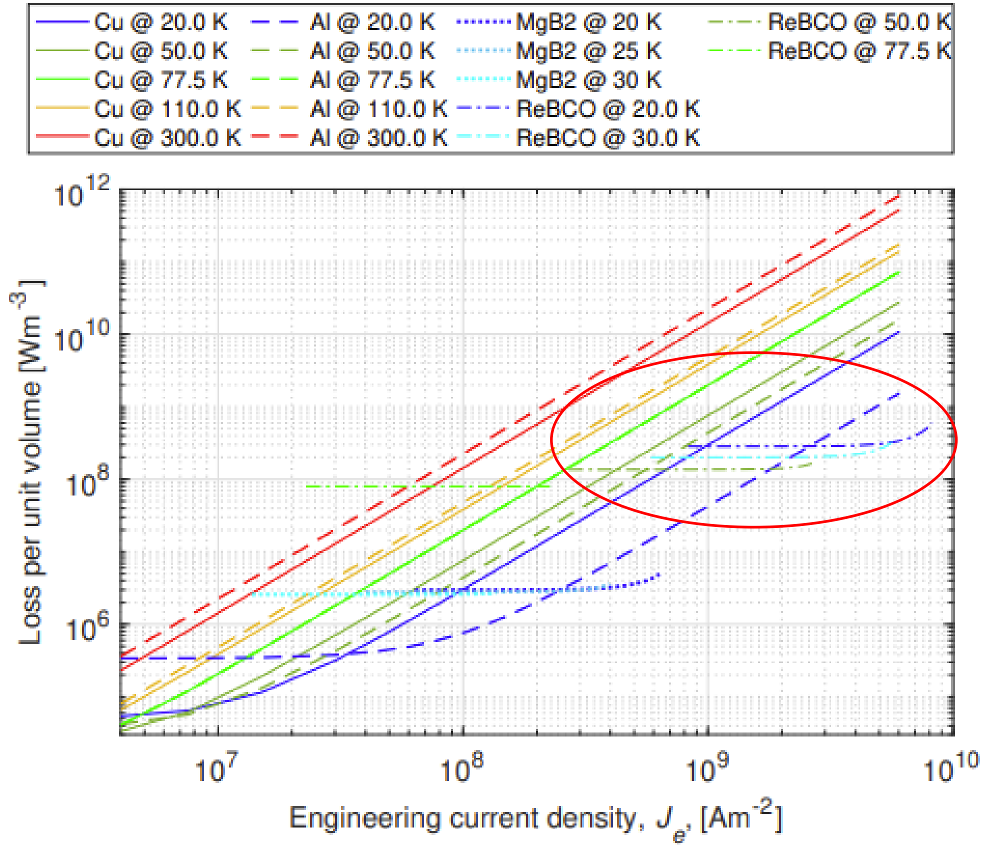


Fig. 2: Loss per unit length of conductor when the conductors, at different temperatures, are carrying 150 Hz transport ac of different amplitudes (amplitudes converted to engineering current densities). The conductors are simultaneously being subject to 150 Hz alternating external magnetic field of amplitude 0.4 T.

- Improving current density by providing cooling
- Cooling penalty must be considered by estimating losses

ReBCO is interesting to us:

DC rotor: zero losses with high magnetic loading
AC stator: @50 K, lower losses above 5e8 Am^{-2}

Introduction

Exploring the potential of HTS in aviation motor

Major challenges we are facing:

1. Rotor: how to provide very large DC for rotational HTS coils
2. Stator: how to design multi-filament HTS AC coils with minimized AC losses
3. Different temperature requirements for rotor and stator

Main targets we want to achieve:

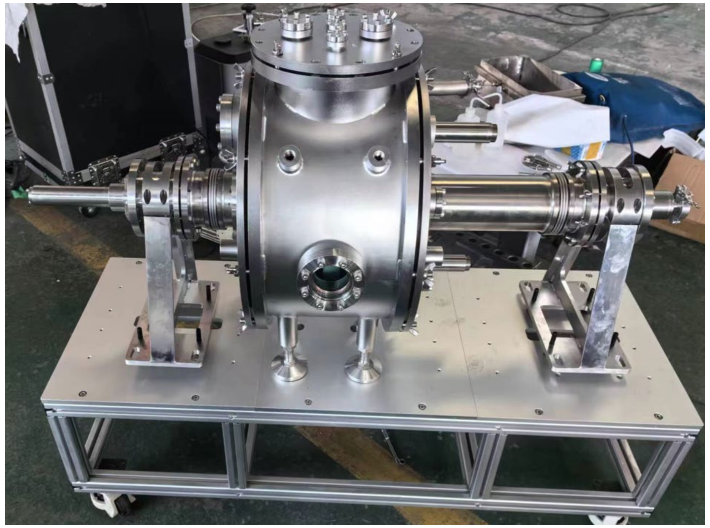
- Use a single type of superconductor to replace copper
- Use a simple topology
- Remove iron if possible
- >=15 kW/kg power density

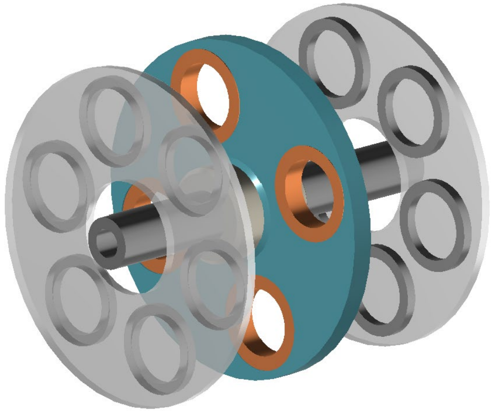
100 kW motor design

<u>Brushless axial-flux fully superconducting motor</u>

Key novelties:

- HTS DC windings for brushless rotor
- HTS coupling AC windings for stator



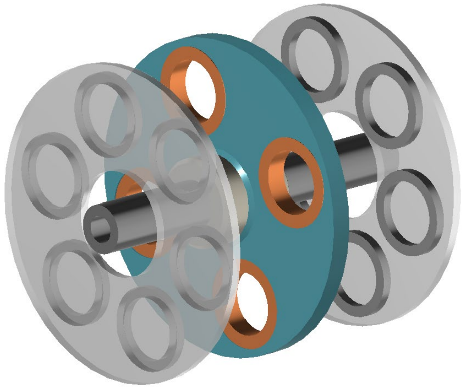


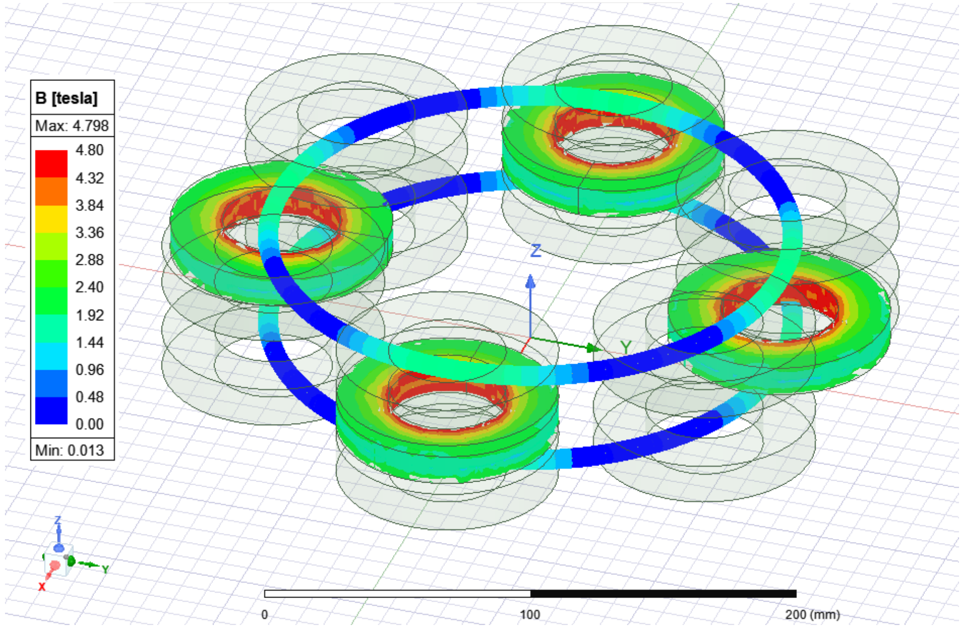
- Two HTS stators
- One HTS rotor
- Double pancake coils

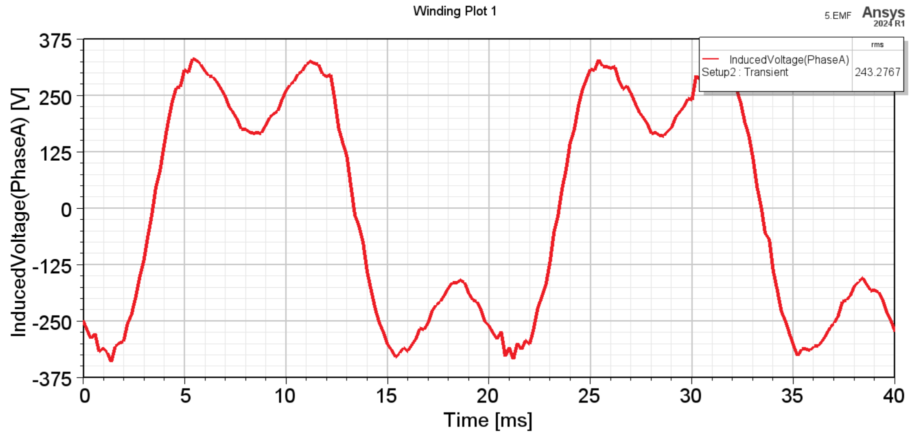
Achievable value	Testing value	Unit	Description
200	100	kW	output power
1500	1500	rpm	rated speed
2	2		pole pair number
250	160	Apk	peak current apply to one stator
3	3		phase number
2	1.4	T	magnetic loading
300	300	Vrms	phase voltage rms

100 kW motor design

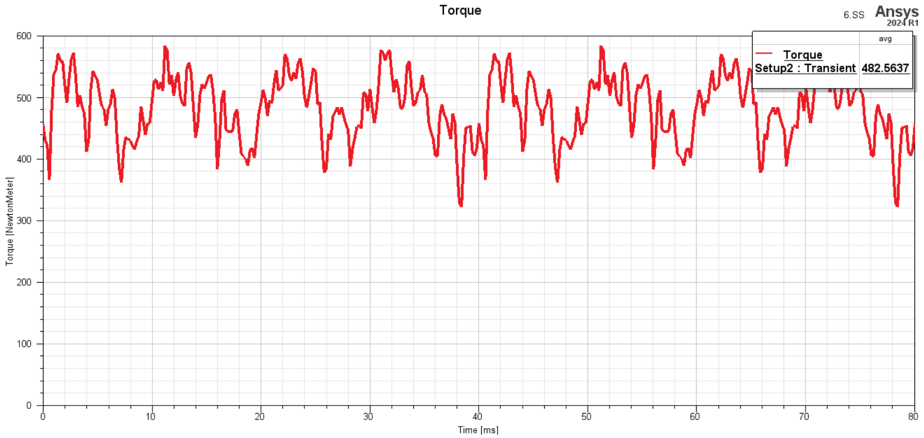
3D FEM simulation to confirm motor performance:







Induced voltage in phase A



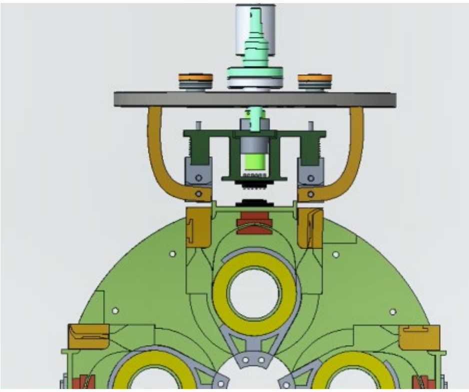
Motor torque

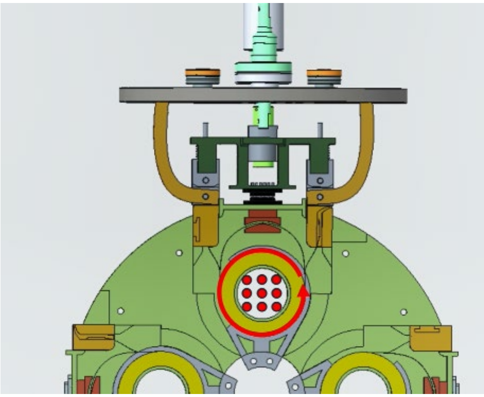
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

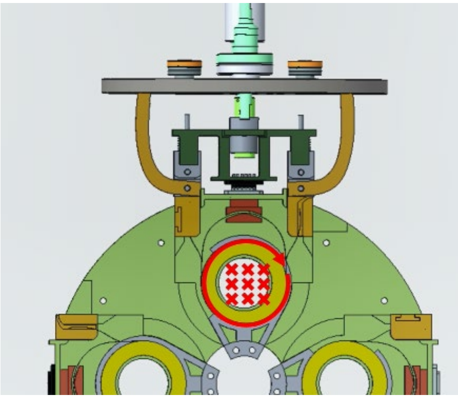
HTS rotor

HTS brushless rotor

Rotor challenge: how to provide very large DC for rotational HTS coils







Key requirements:

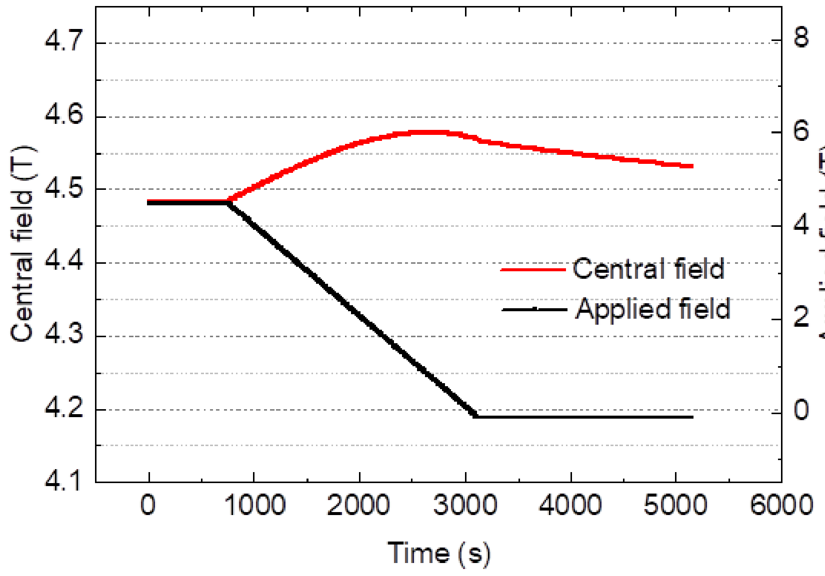
1. Higher magnetic field than PM with an air-cored design.
2. slow magnetic field decay rate

Solution:

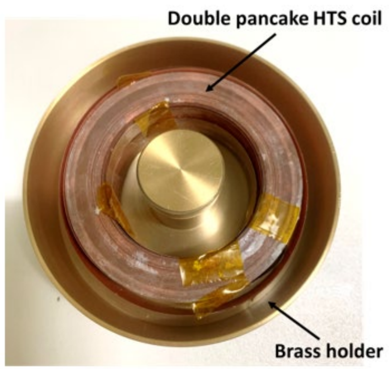
Closed-loop HTS coils + removeable charger

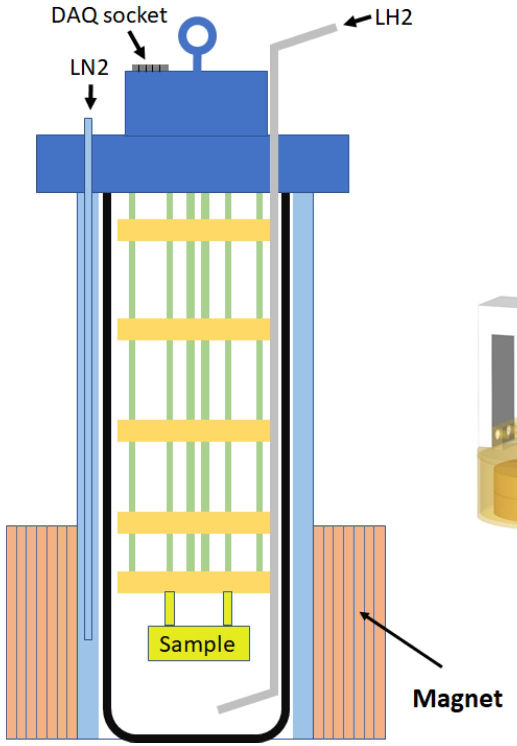
HTS brushless rotor

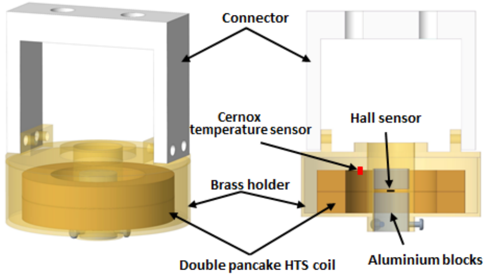
Previous feasibility study at 4 K*:



Field cooling trapped field @ 4K	Residual trapped field after 3 hours	Decay rate	Equivalent resistance at 4k
4.58 T	4.4 T	3.9%	2 nΩ

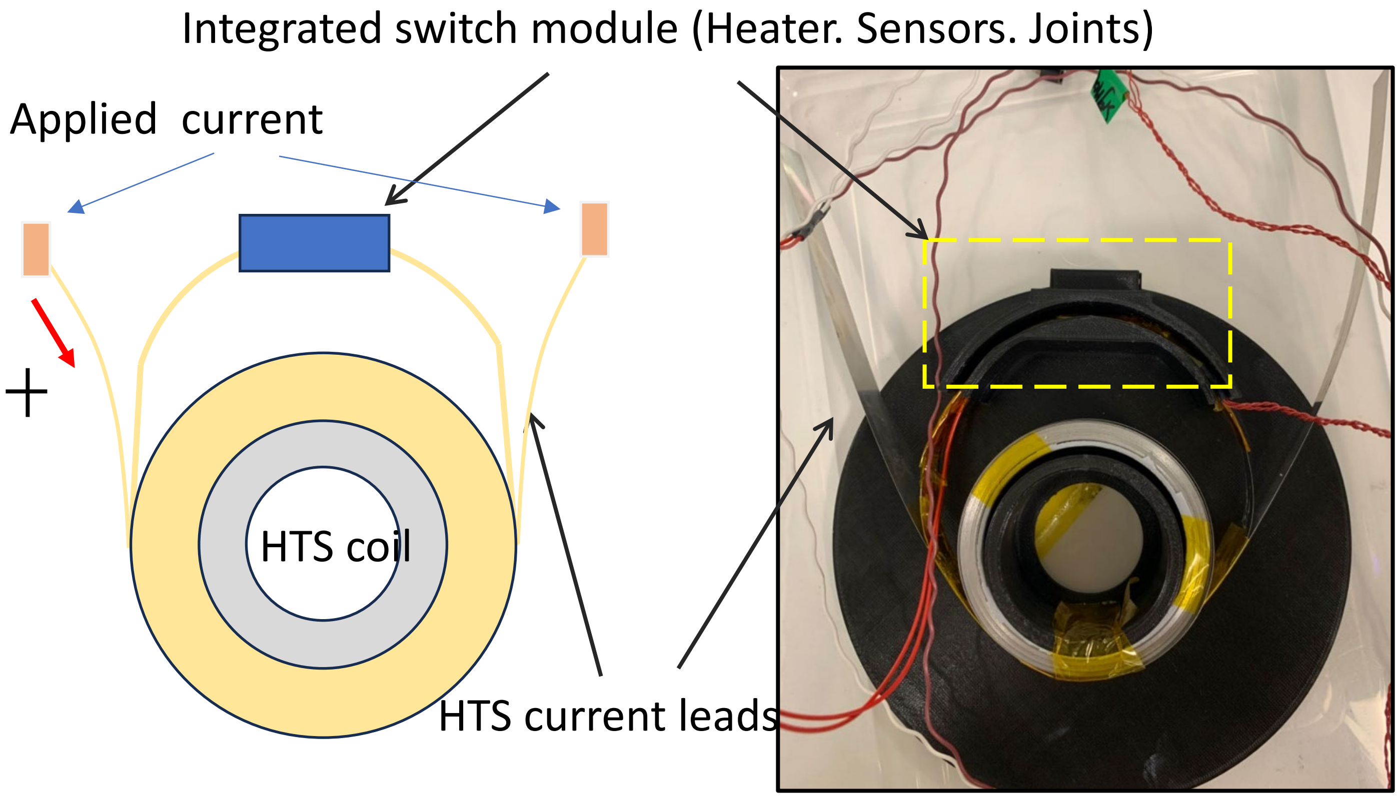


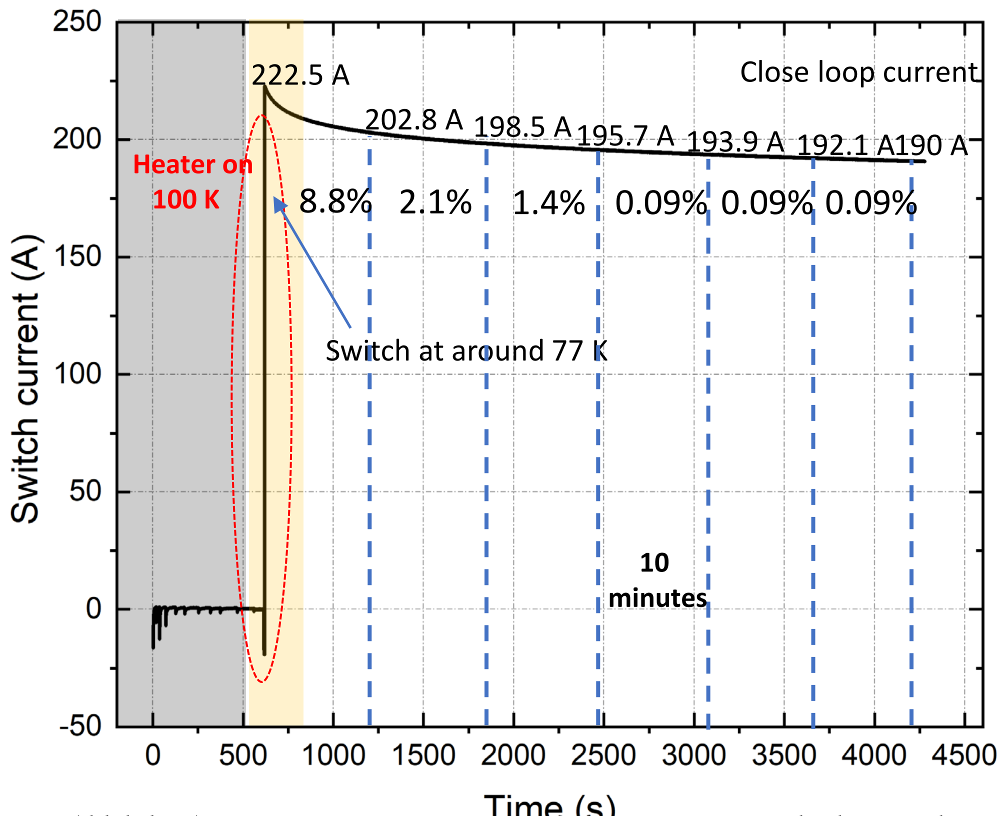




* Test was supported by LNCMI-CNRS, a member of the European Magnetic Field Laboratory (EMFL)

HTS brushless rotor: charging

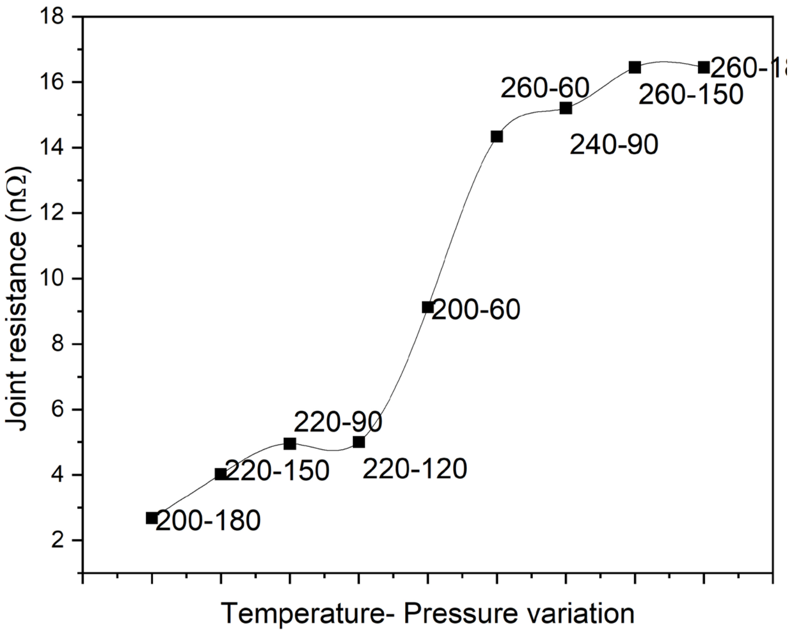


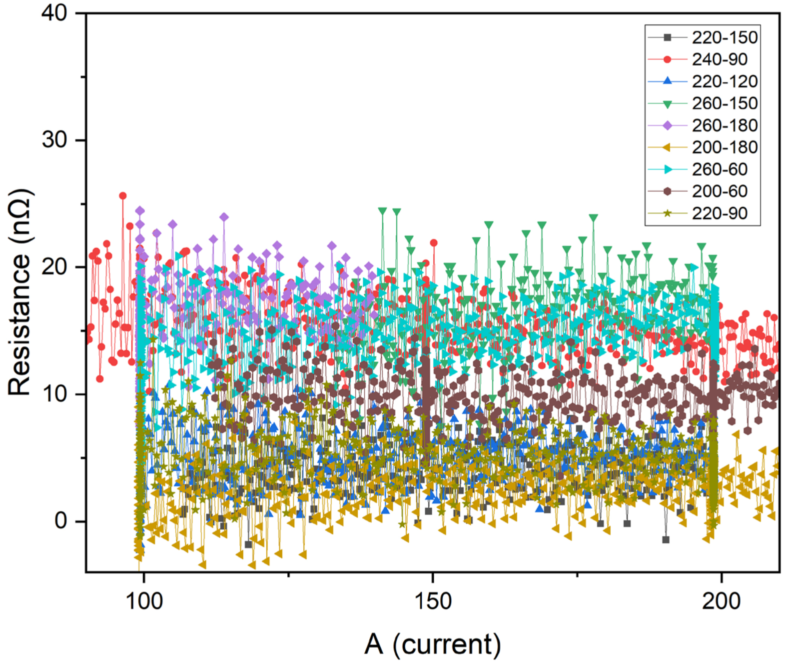


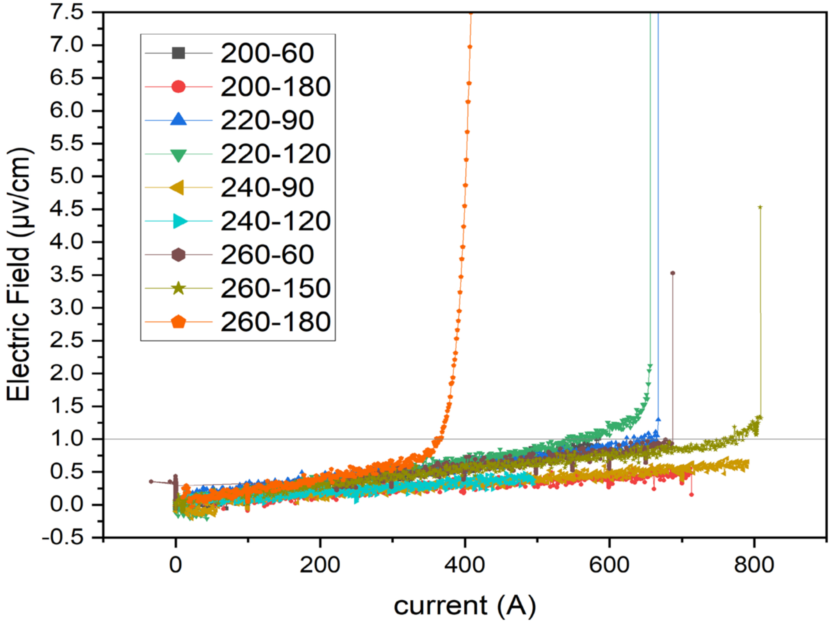
HTS brushless rotor：low resistive joints

Low-resistive soldering joints：

- Temperature 200-260K
- Weight 60-180 kg
- Tested temperature-pressure variations

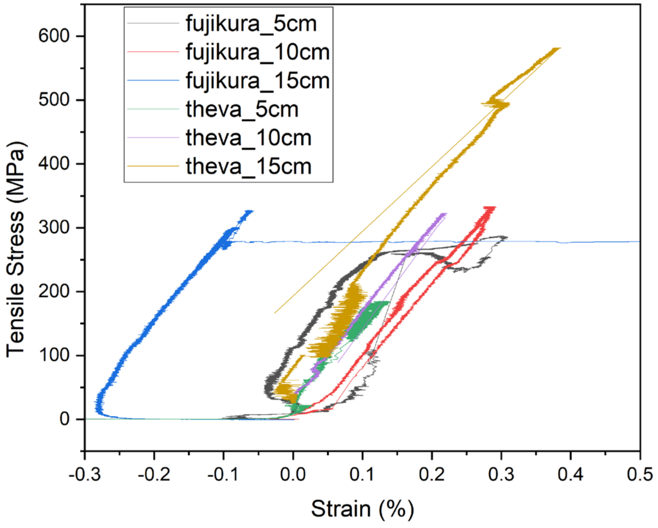


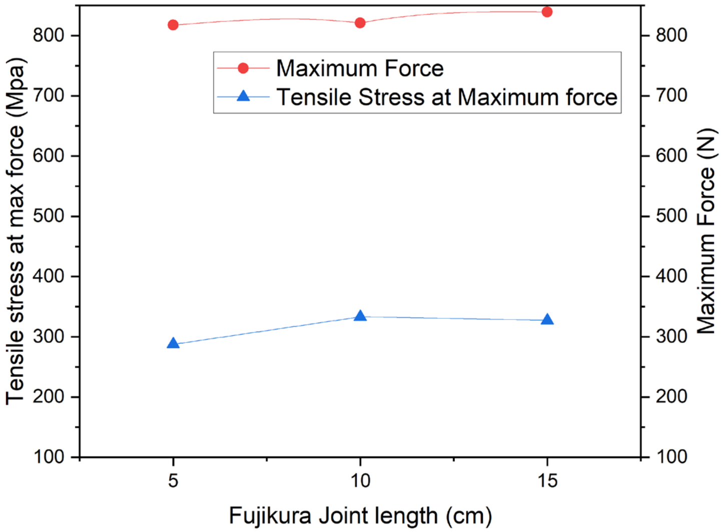


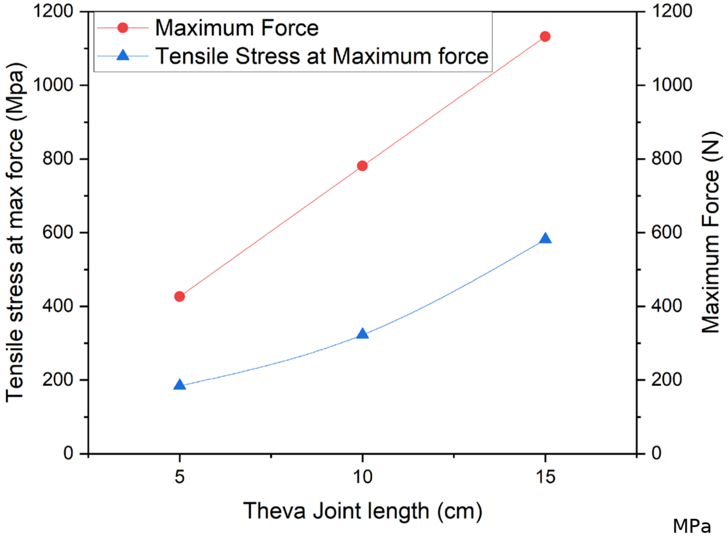


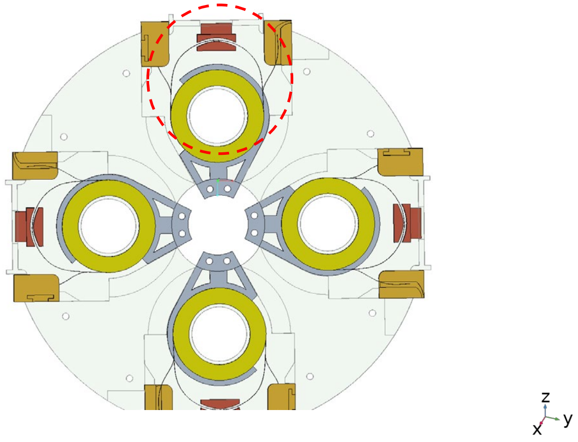
HTS brushless rotor：low resistive joints

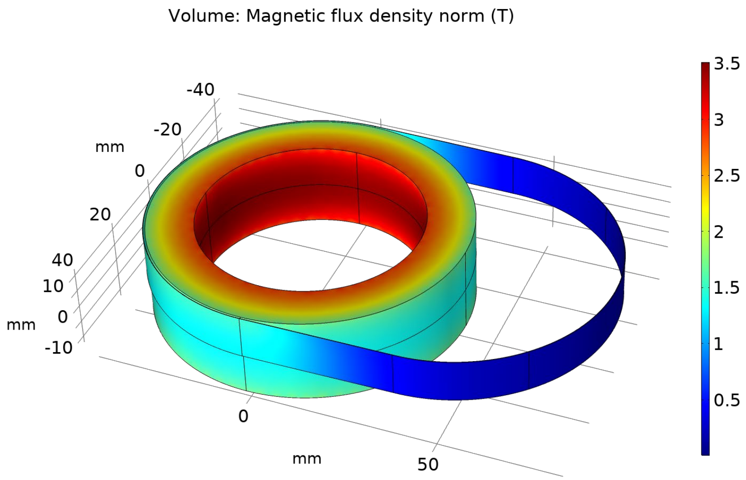
- Mechanical strength of HTS joints at room temperature*

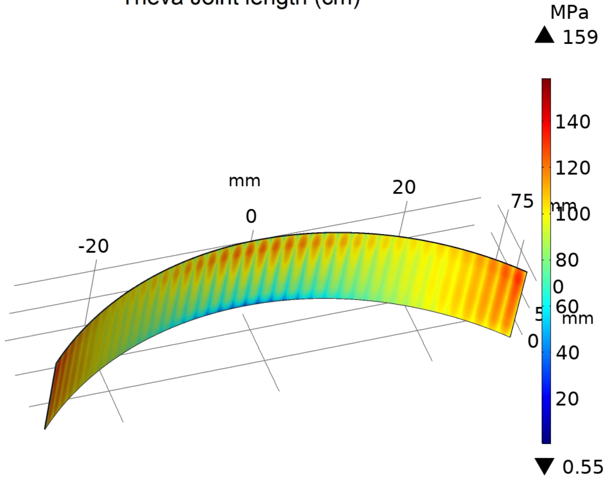








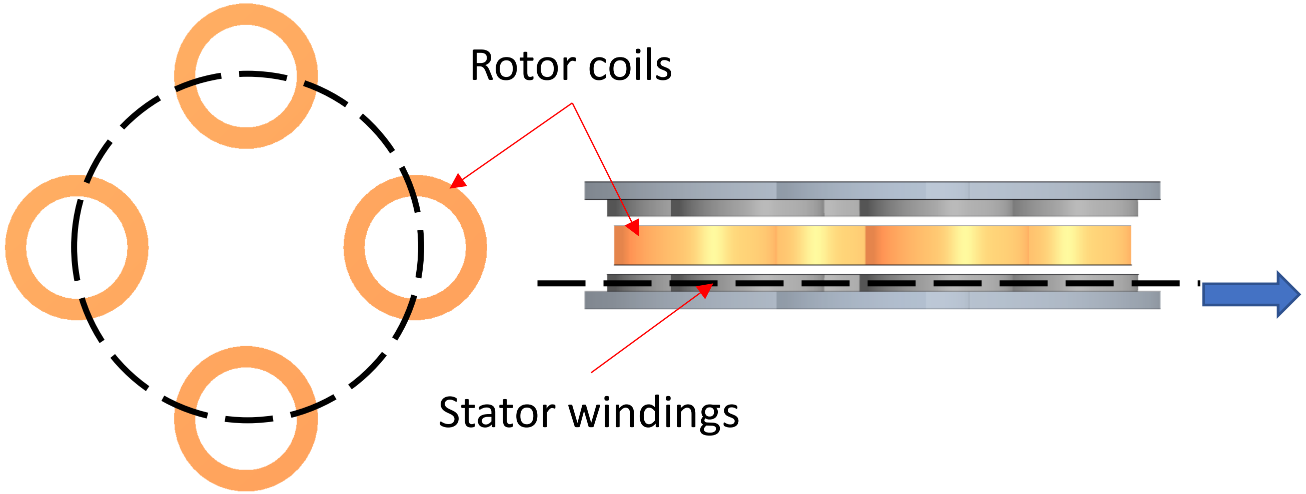


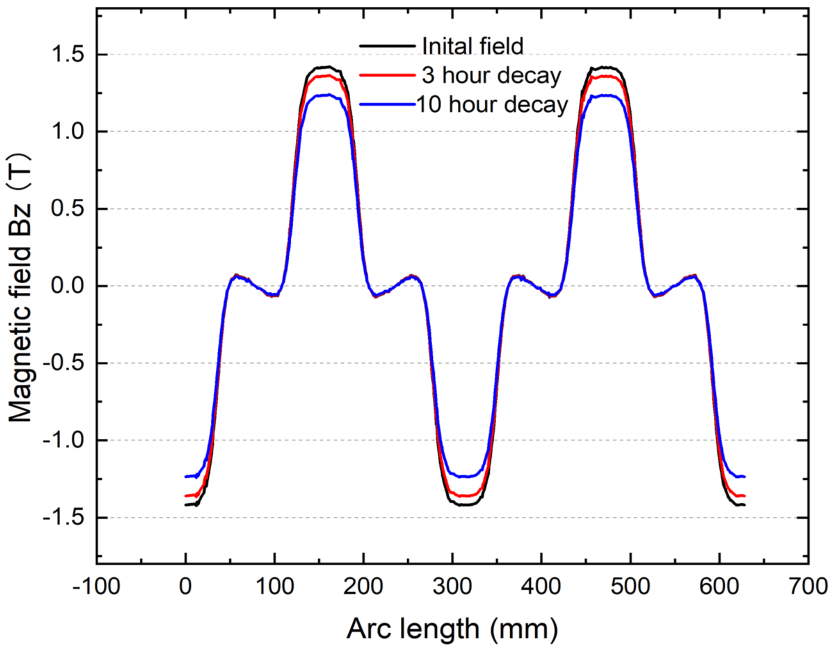


The highest von Mises stress is 187 Mpa, lower than the yield strength of joints tested

* Test was supported by Strathclyde Advanced Material Research Laboratory

HTS brushless rotor: decaying





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%

- Decay rate is acceptable for a 3 hour flight

HTS Stator

HTS coupled stator

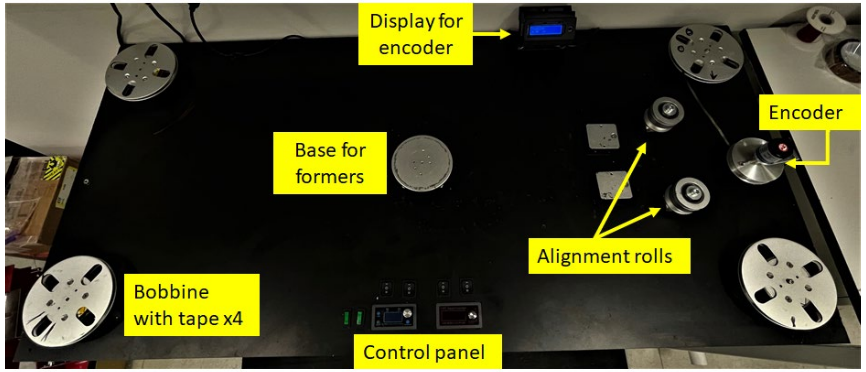
Challenge:

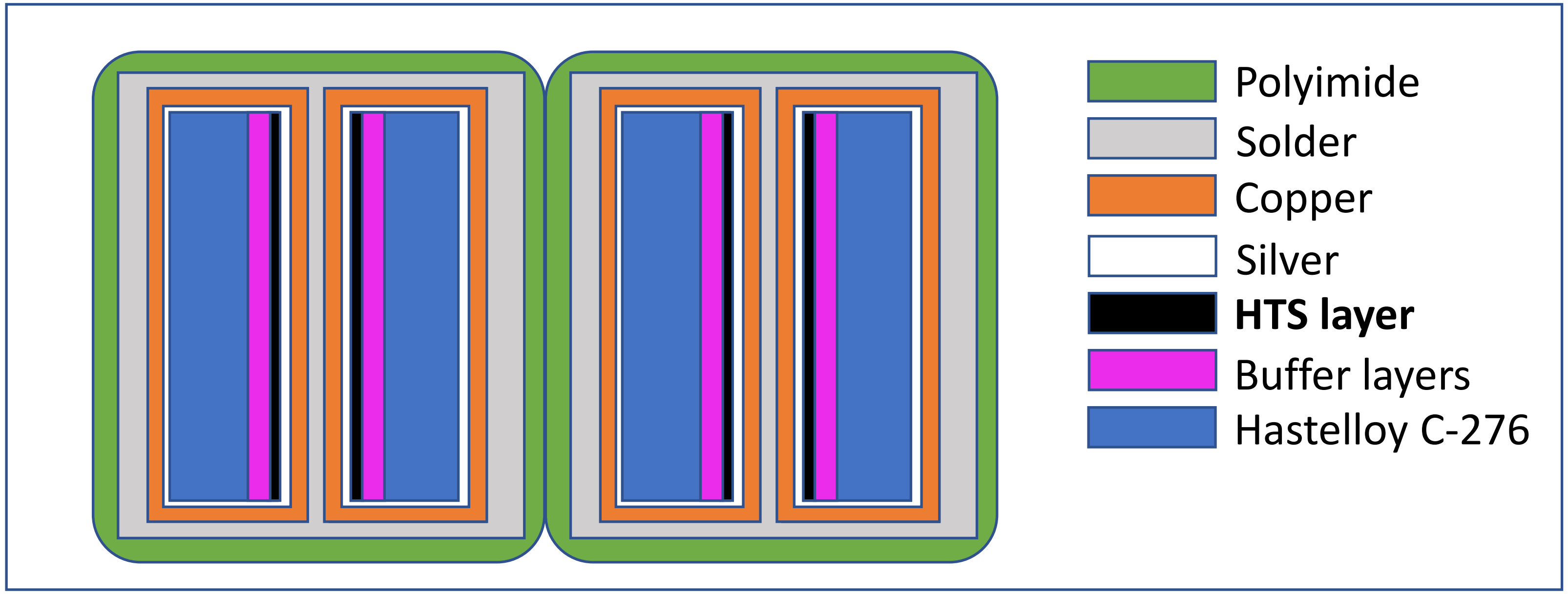
- Use narrow HTS to reduce AC loss
- Peak current is 160 A at 1.4 T

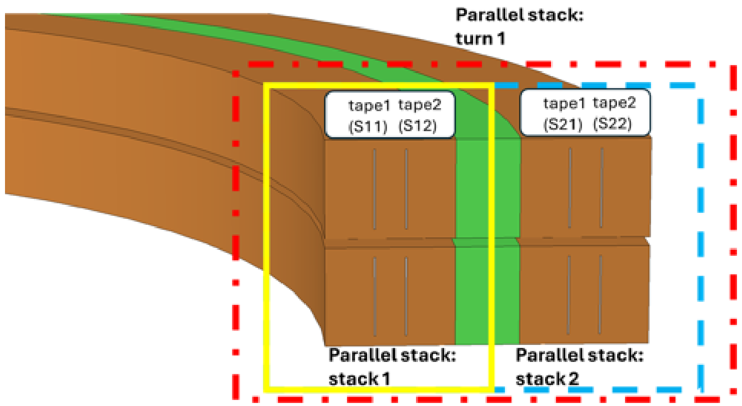
Solution: a HTS coupled winding

- Four 4mm HTS in parallel connection
- Operational temperature at 65 K to increase Ic
- Six HTS double pancake coils per stator
- Fully insulated and impregnated

Value	Unit	Description
4	mm	tape width
65	K	working temperature
250	A	self field coil Ic @ 77K
160	A	Peak current @ 1.4T

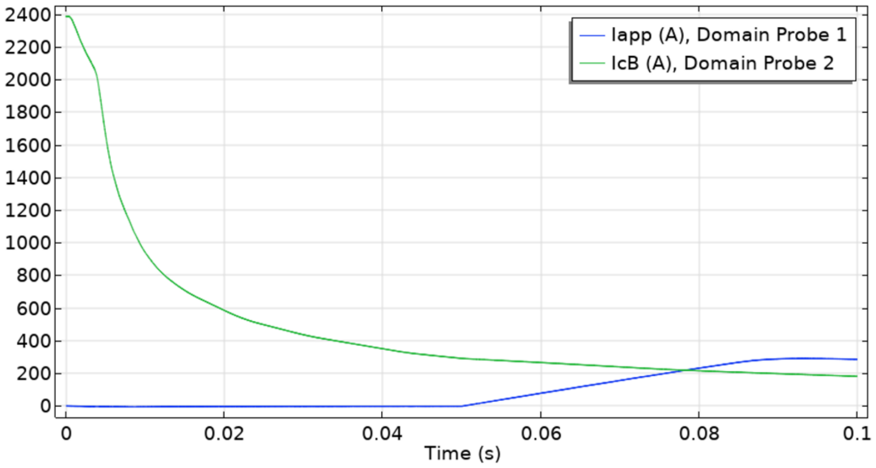




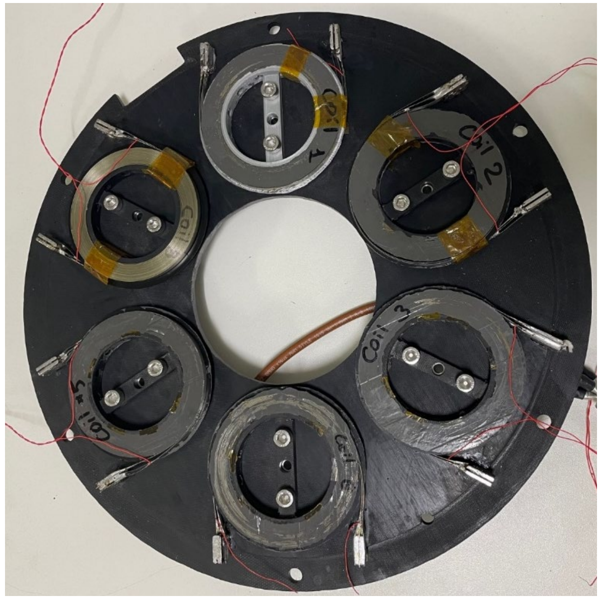


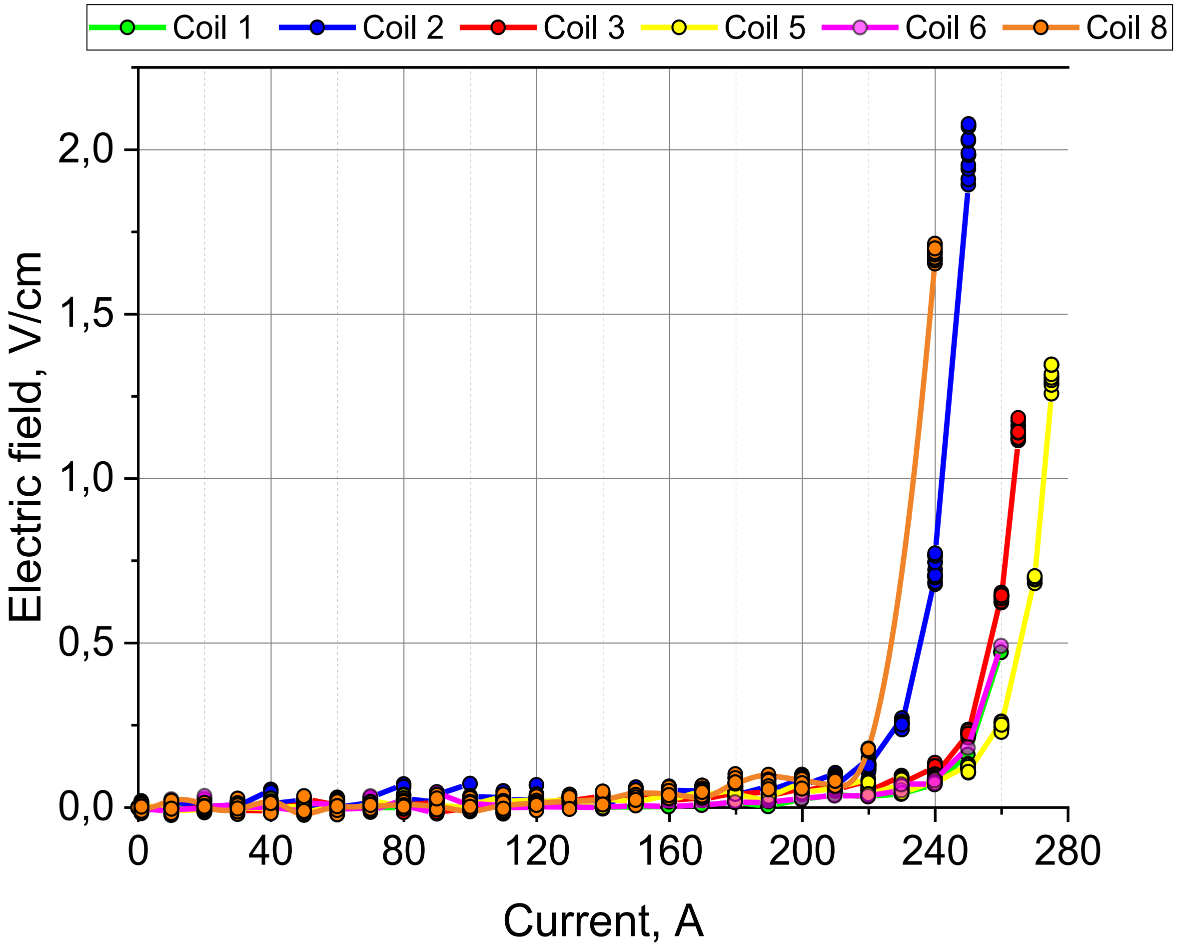
*AC loss measurement of the coupled coils in presentation 1LOr1D-02

HTS coupled stator



Calculated IcB is 220 A @ 77 K self-field.
Measurements for six coils are consistent with simulation:

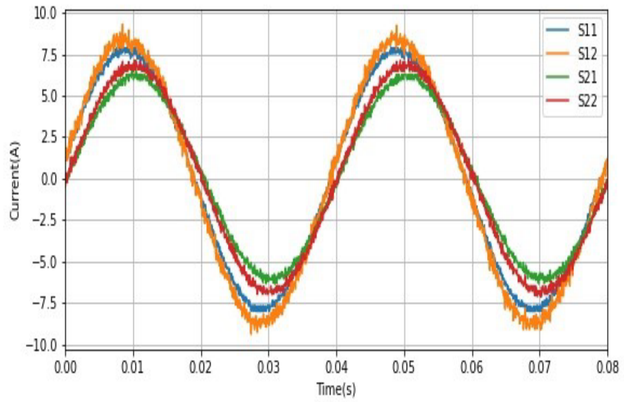


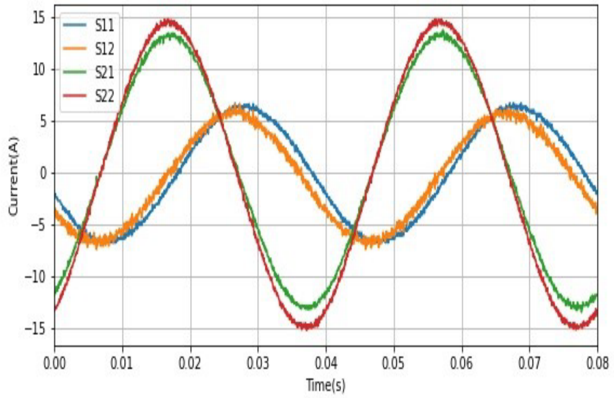


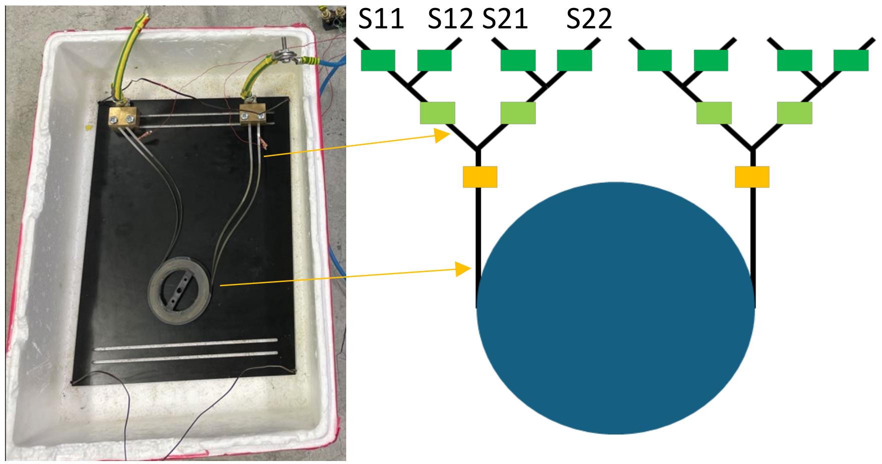
HTS coupled stator

This coil experiences two types of coupling:

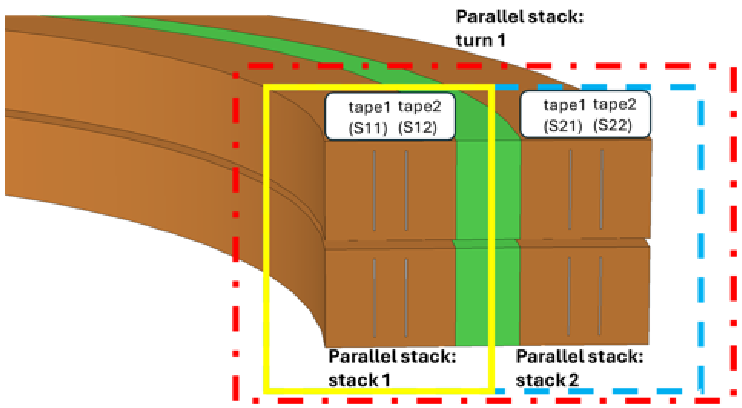
- Coupling via current leads between two stacks. This can be removed by inductance balance as shown below*:







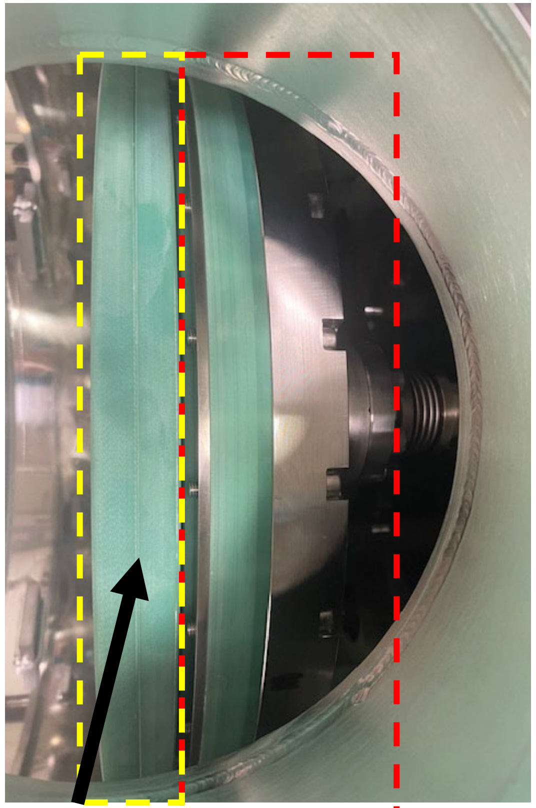
- Coupling within one stack via the soldering layer. This is impossible to model in 2D for the transverse current flowing
- AC loss consists of HTS losses, coupling loss in the stack, coupling losses between two stacks (without inductance balance) and soldering losses.



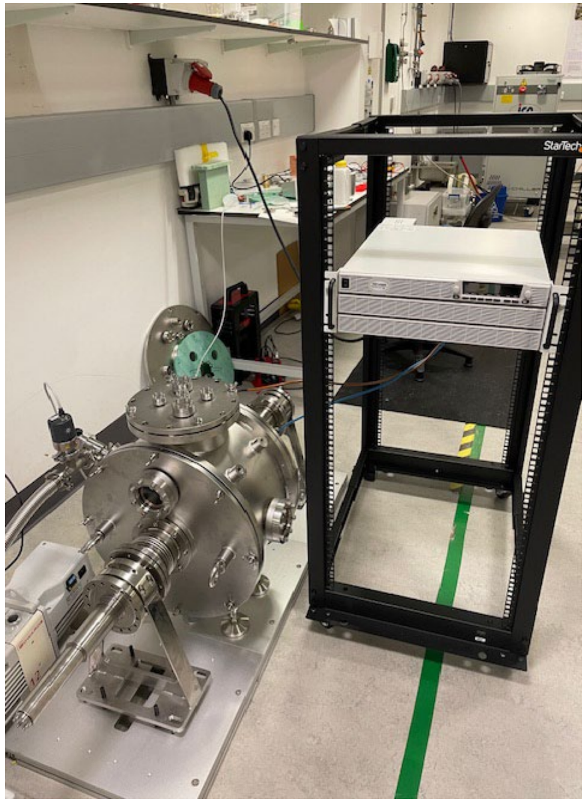
HTS coupled stator

Tests that were carried out so far:

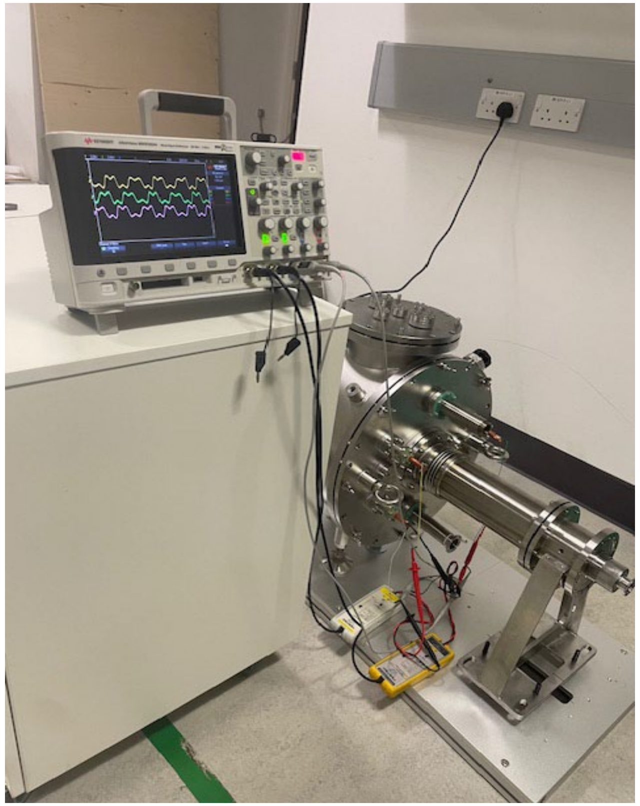
- A four-pole PM rotor assembled next to the stator for testing purpose
- 800 V voltage breakdown test passed
- Open circuit voltage matches simulation



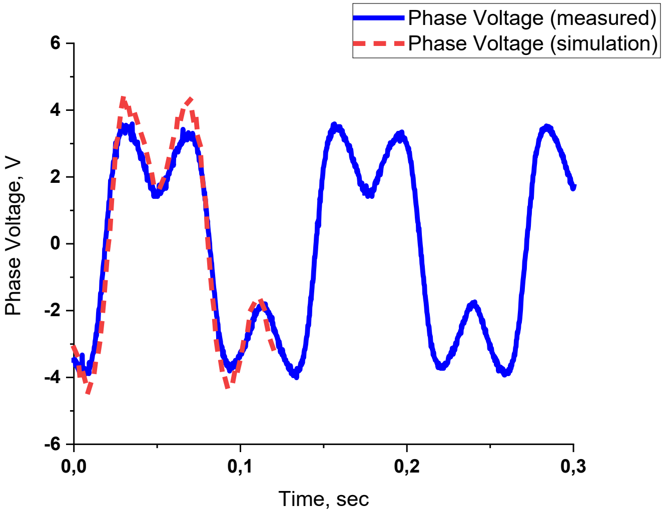
PM Rotor **Stator**



800V breakdown test was passed

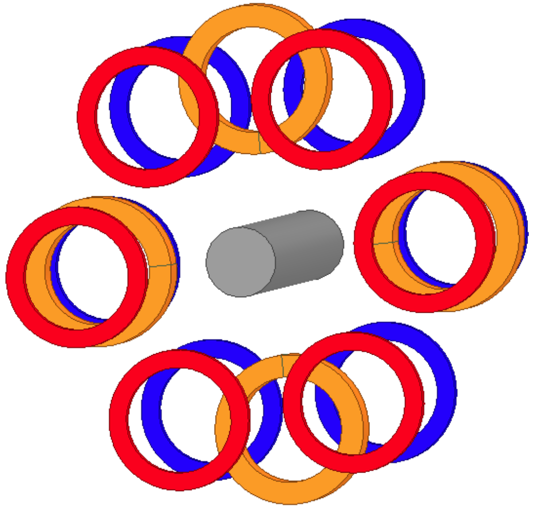


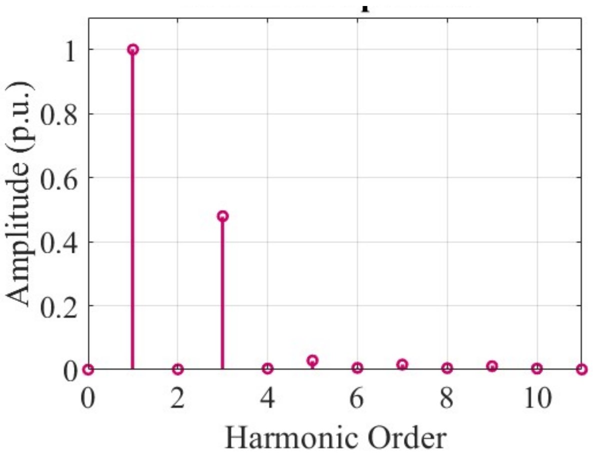
Test in generator mode (rotating rotor, no load)



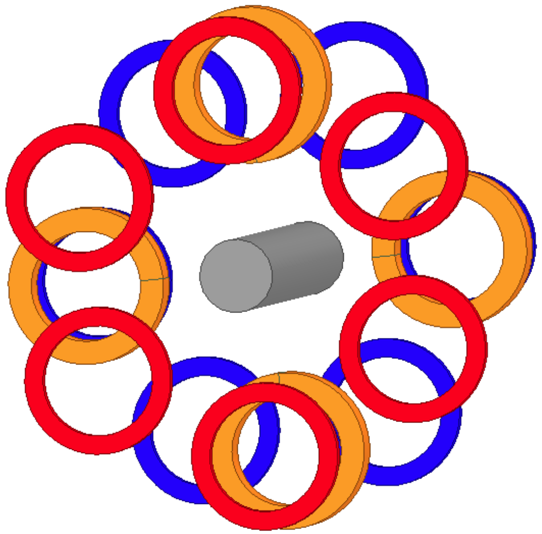
Measurement vs simulation (250rpm)

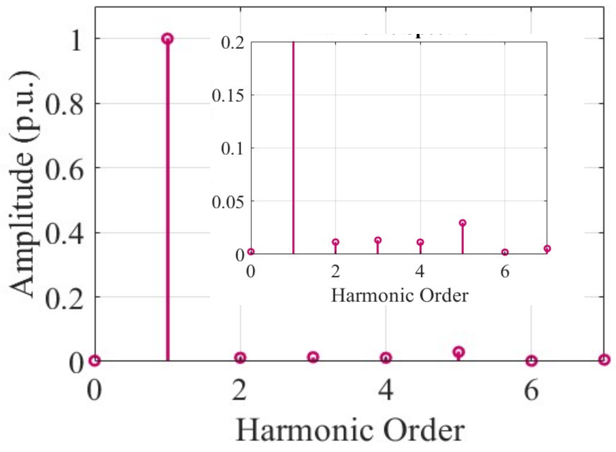
HTS stator: the relative position of the second stator



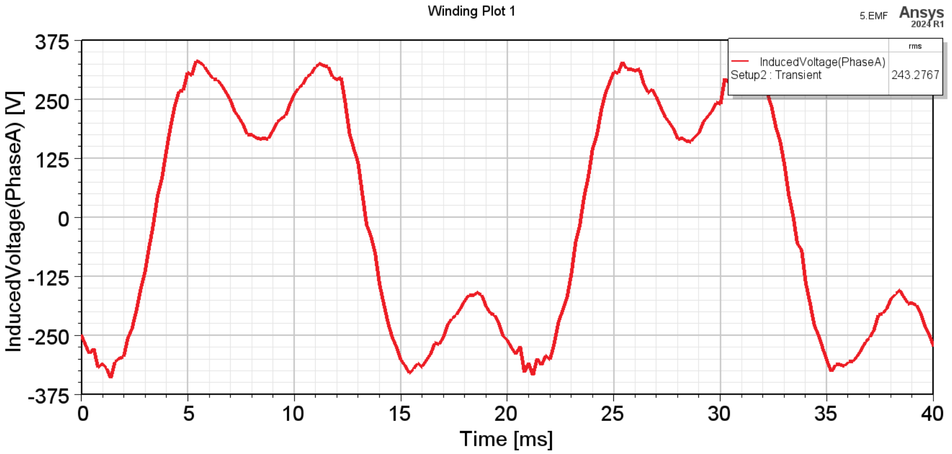


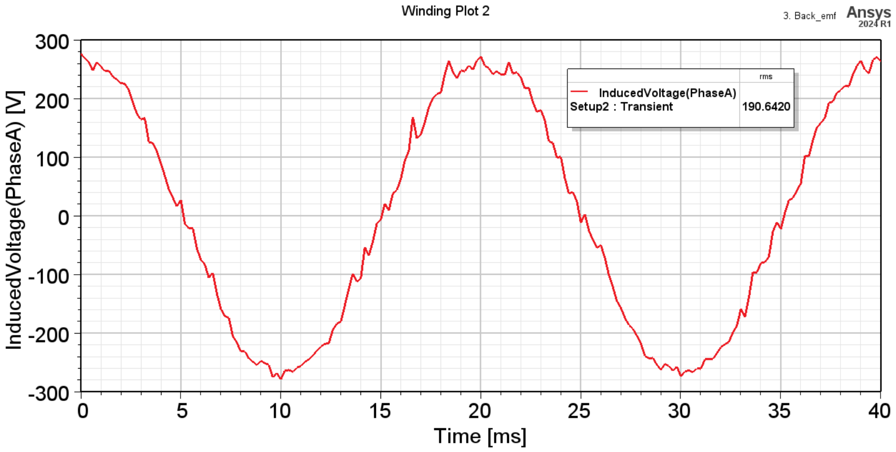
Face-face stators





30 deg shift for the second stator

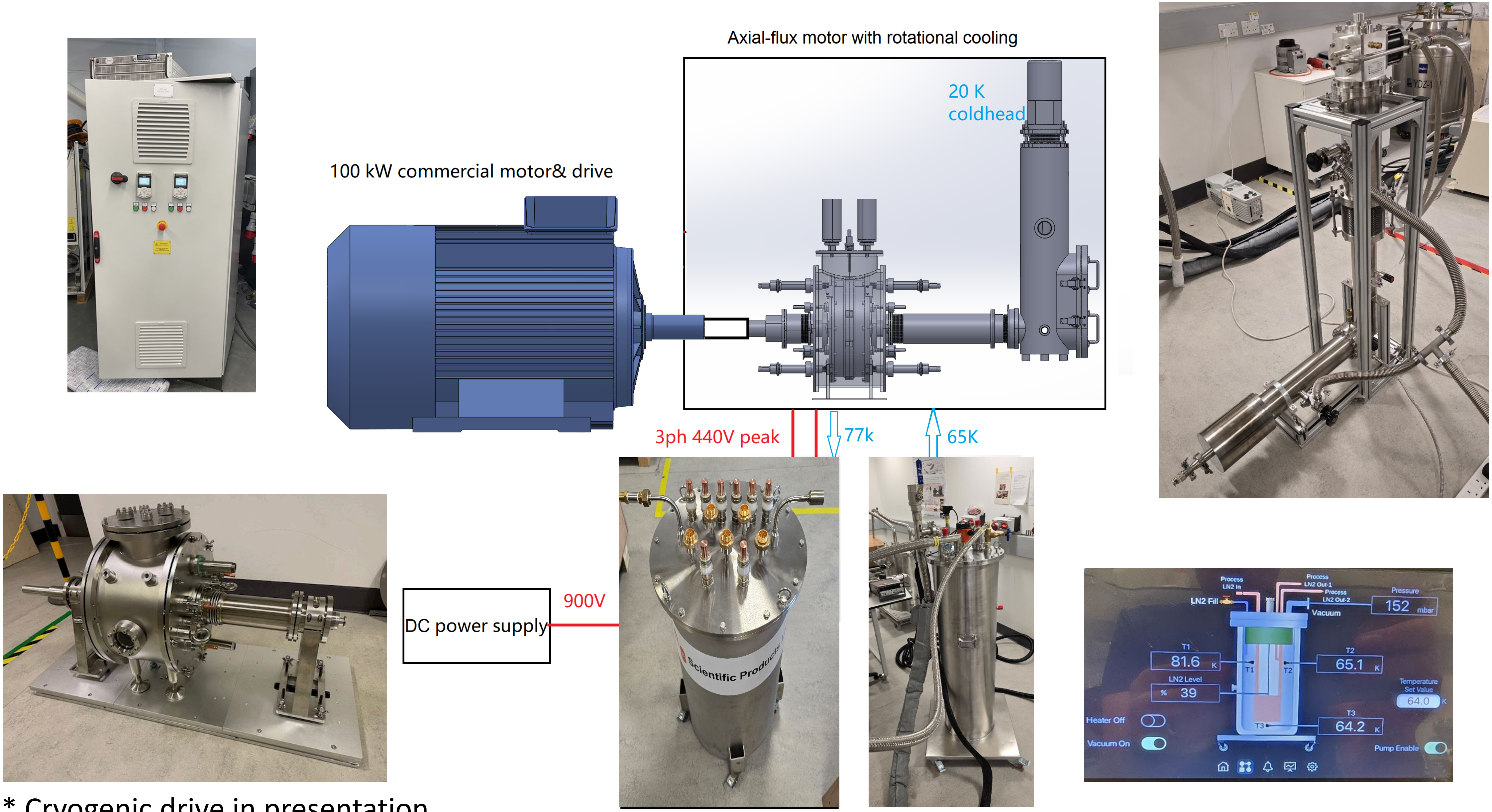




- Much less third harmonics
- But only 60% of the torque

Cooling

Motor cooling



* Cryogenic drive in presentation

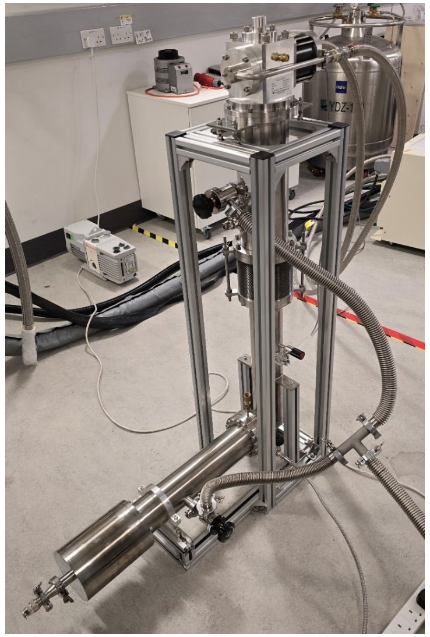
Cryogenic drive with SFCL

Subcooled LN2

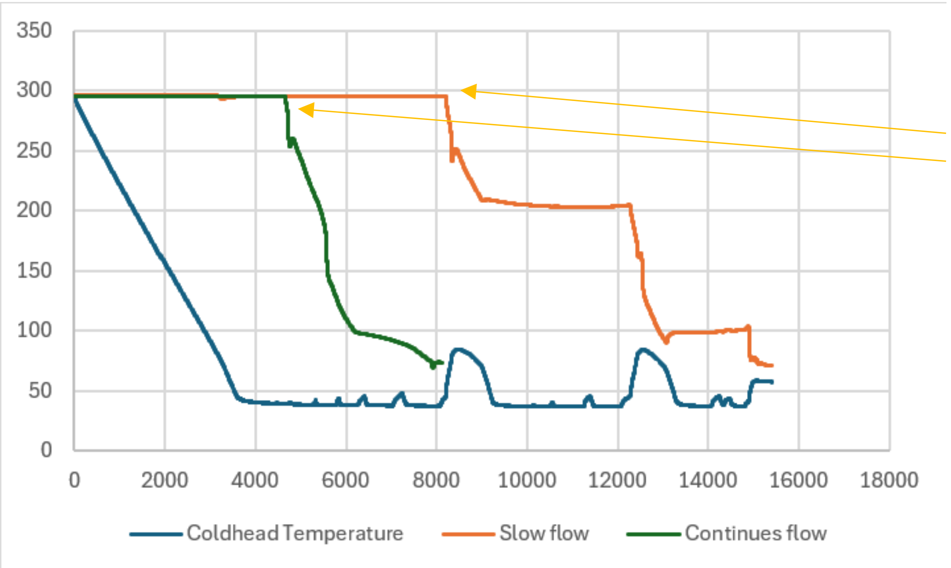
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Motor cooling

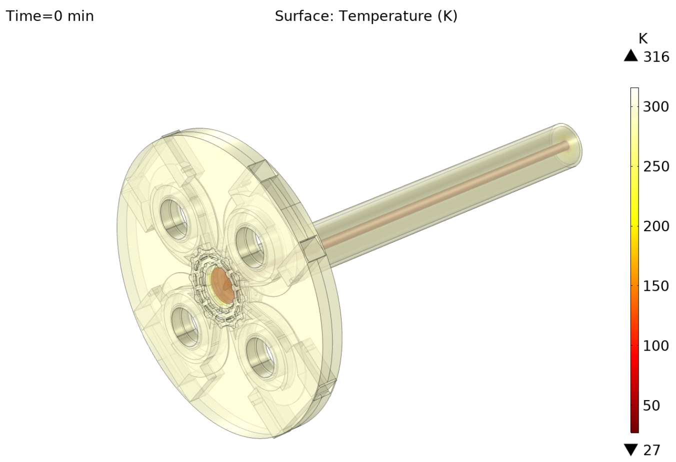
Thermosiphon rotational cooling



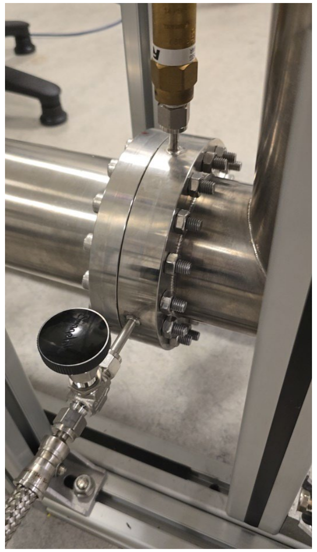
Coldhead cooling power: 50 W @ 20K



Experiment results with N2



Thermosiphon happened here:
Liquid nitrogen formed, leading to a rapid cooling for the rotor terminal.



We plan to test neon as next step
Boiling point of Neon: 27.1K

Conclusion

We have designed and developed a 100 kW fully axial-flux HTS motor for aviation propulsion

- Designed power density is 15 kW/kg
- Novel brushless HTS rotor technology
- HTS coupled AC windings for stator
- Neon thermosiphon and sub-cooled LN2 for motor cooling

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

1. HTS simulation
2. AC loss measurement
3. HTS motor design and development

Lab info

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