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This presentation was given at EFATS 2022, August 30-31, 2022.

200 kW cryogenic propulsion unit development progress

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University of Strathclyde Glasgow

Applied Superconductivity Laboratory

- Launched in 2019
- Two research labs around 200 m^2
- Two Professors, Three RAs and ten PhD students

1. Cryogenic propulsion
2. HTS fusion
3. HTS for power applications

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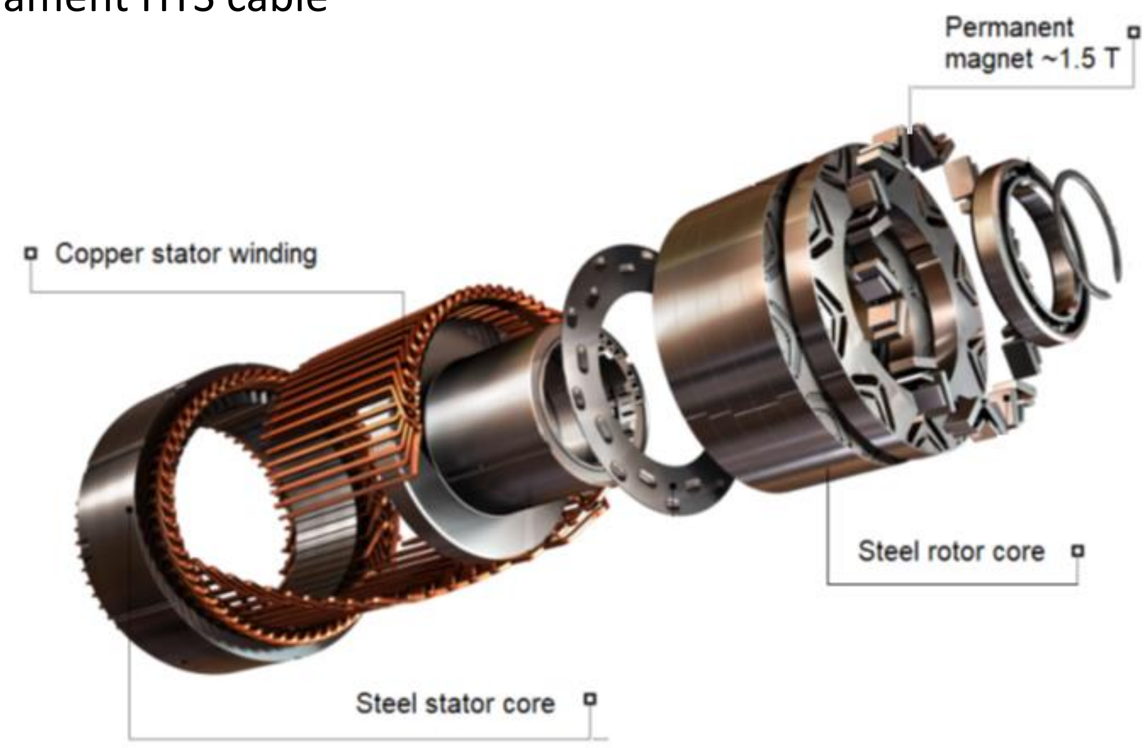
How to develop an ideal HTS machine with high performance?
>= 15 kW/kg, >= 96%

AC-capable HTS stator winding

- Multi-filament HTS cable

Brushless HTS rotor

- Large trapped field HTS magnet
- Persistent operation of HTS coils



* GE drawing

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AC-capable stator winding development

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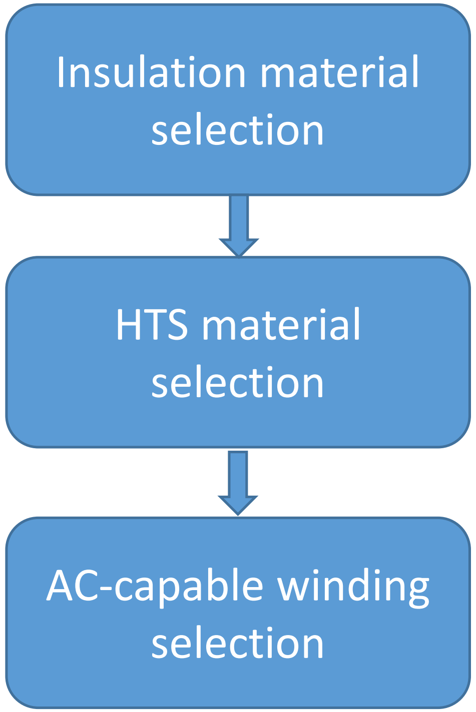

1. Ic degradation test
2. Breakdown voltage test
3. Power/thermal cycling

1. Thermal cycling
2. Ic test
3. Tc test

1. Ic test
2. Transport AC loss test
3. Total AC loss test

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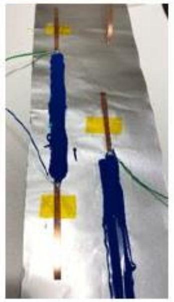
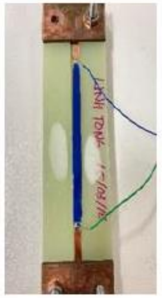
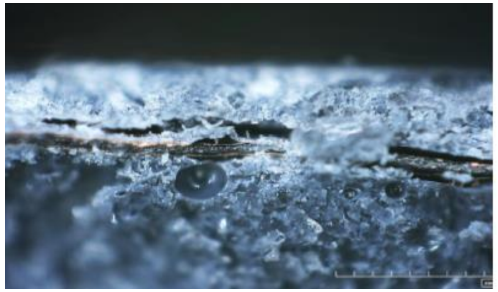
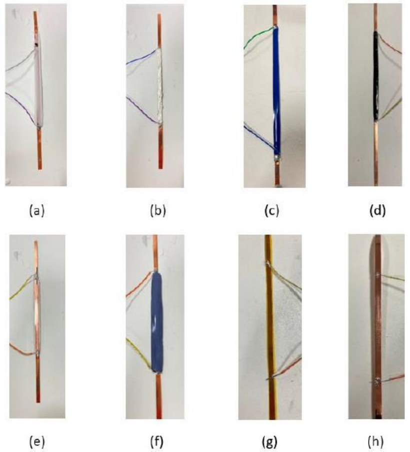
AC-capable armature winding development

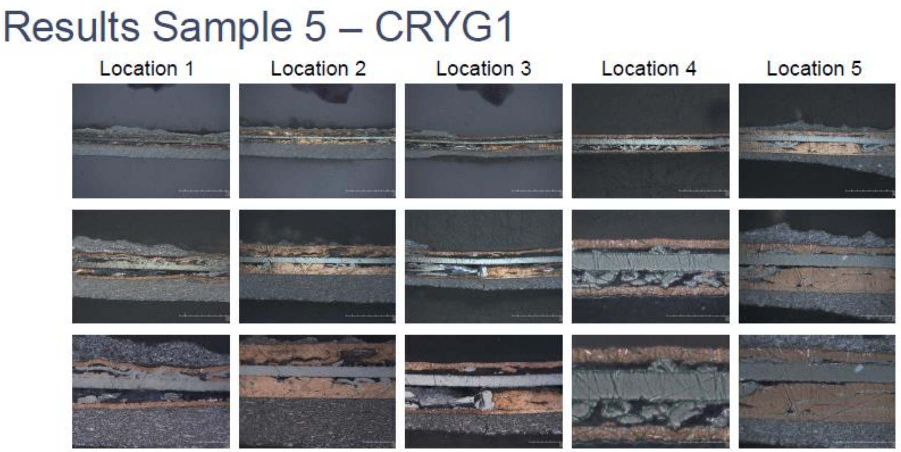
- Insulation material selection:

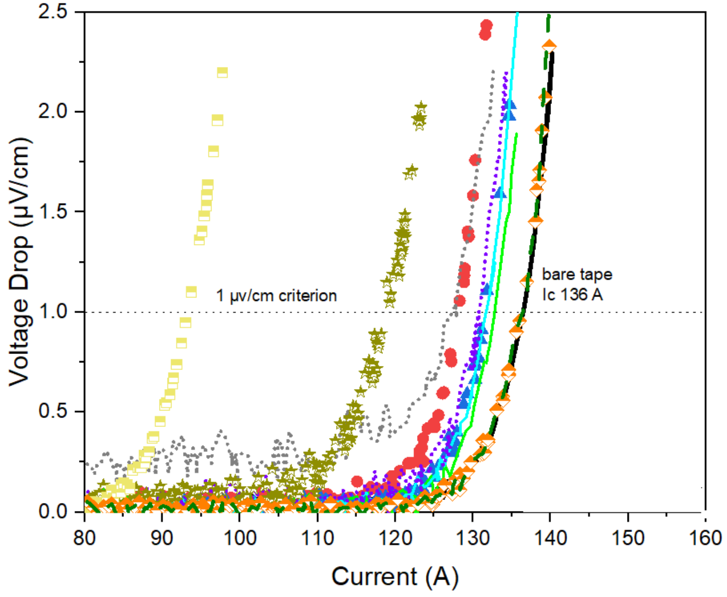
Power cycling, thermal cycling, optical microscopy inspection, Ic test









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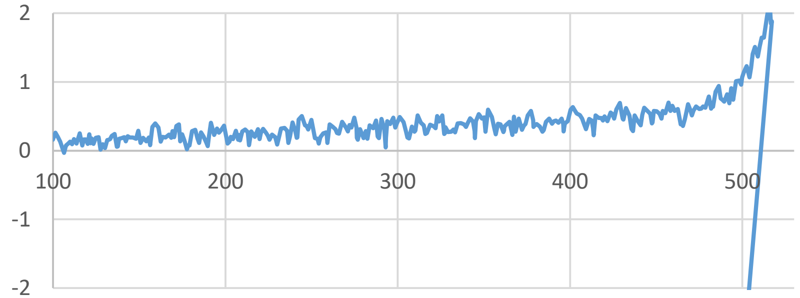
AC-capable armature winding development

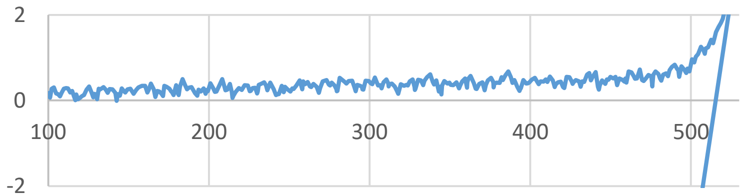
- HTS material selection:

thermal cycling -> Ic test

I-V curve after 20 thermal cycling

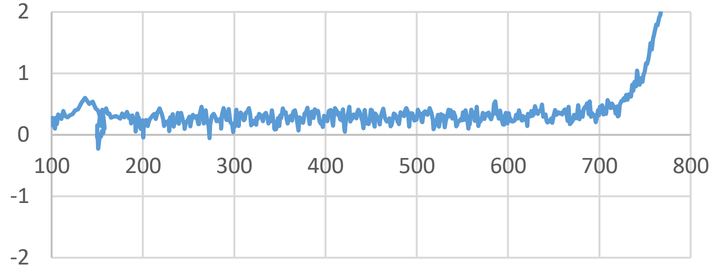


I-V curve after 100 thermal cycling

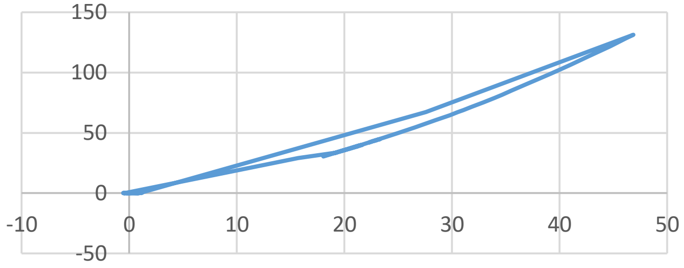


Supplier 1

I-V curve after 20 thermal cycling



I-V curve after 100 thermal cycling



Supplier 2

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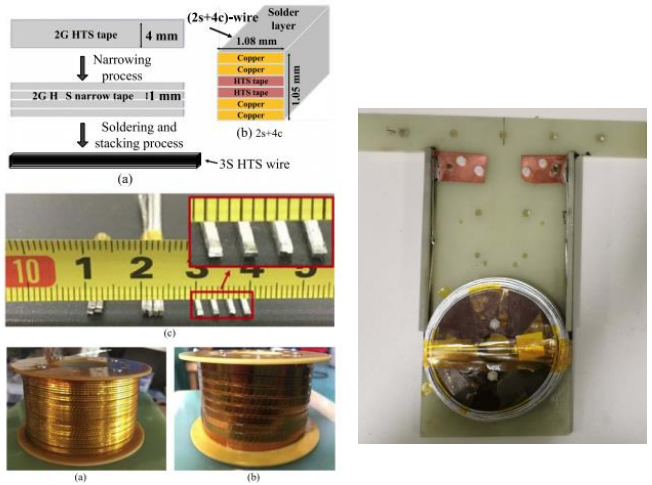
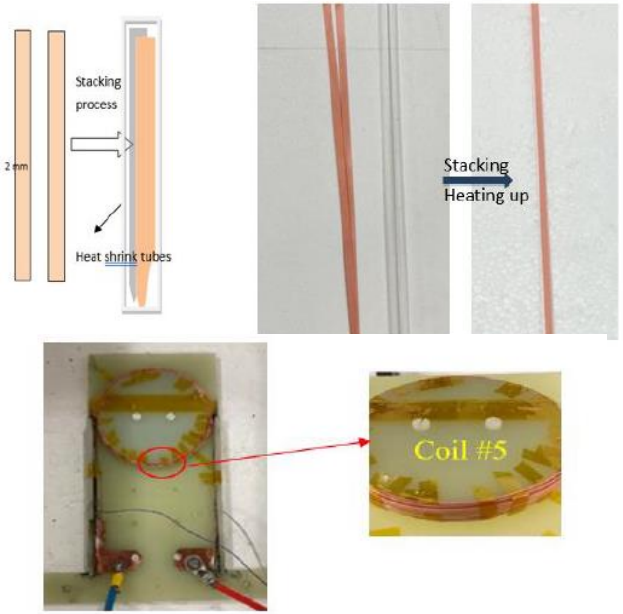
AC-capable armature winding development

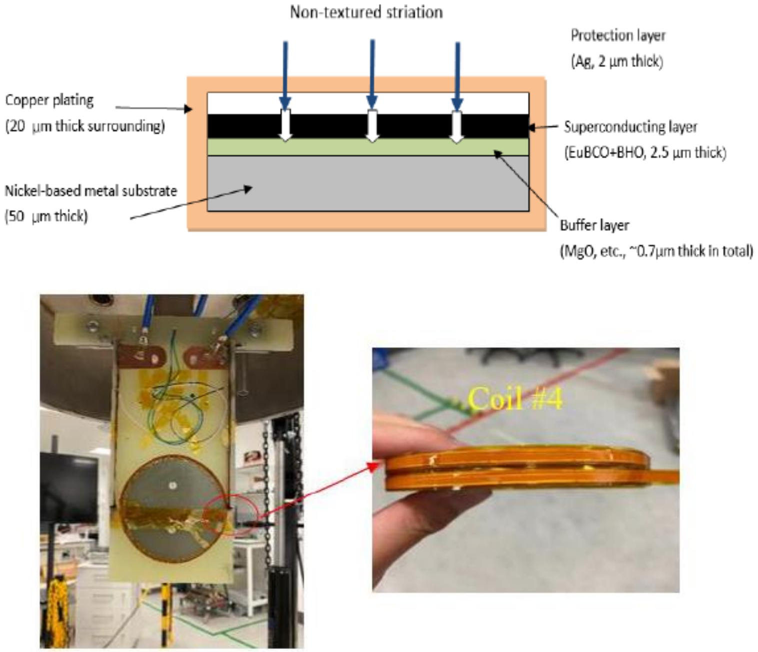
- Multi-filament HTS cable to minimize AC losses [1]
  1. soldering-stacking 1mm HTS cable [2]
  2. Insulated-stacking 2mm and 1mm HTS cables
  3. Striated 4mm cable



1mm*4 soldering HTS cable



2mm*2 non-soldering HTS cable



Striated 4mm cable* (Fujikura)

[1] Manuscript in collaboration with Airbus ASCEND under review for IEEE TAS

[2] Mingyang Wang et al 2019 Supercond. Sci. Technol. 32 01LT01

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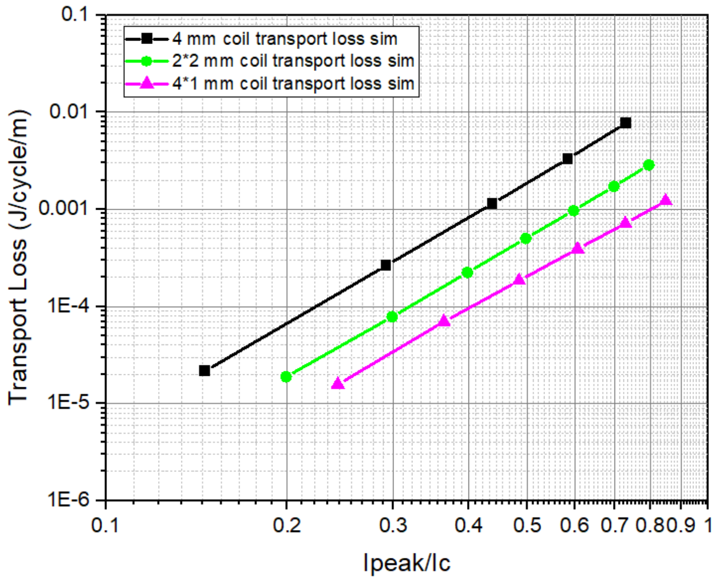
AC-capable armature winding development

- Transport AC loss via electrical method

Results (comparing to a 4mm standard coil: coil 1):

1. Striation (1mm) reduces transport loss by 42%
2. Soldering-stacked (1mm) reduces transport loss by 80%
3. Insulated-stacked (2mm) reduces transport loss by 78%
4. Insulated-stacked (1mm) reduces transport loss by more than 90%



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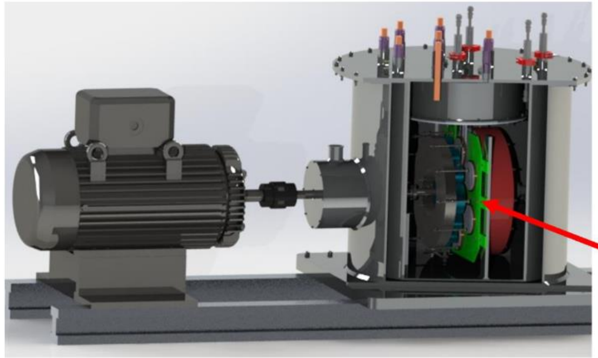
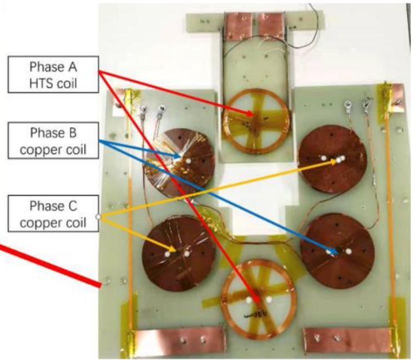
AC-capable armature winding development

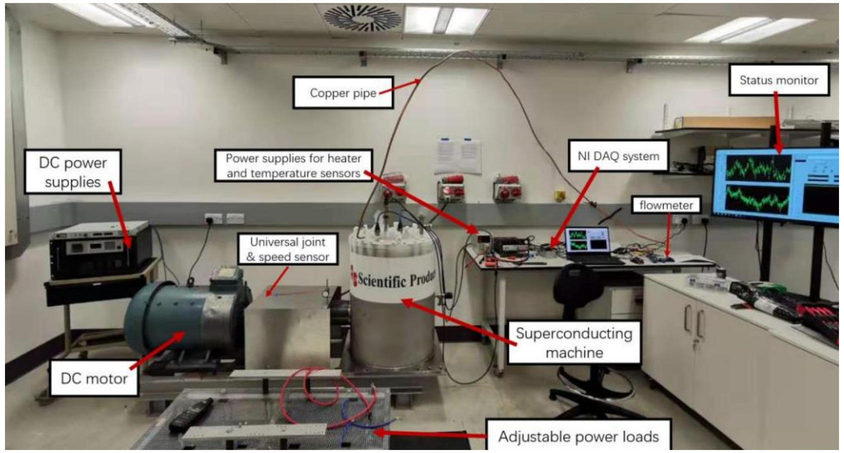
- Total AC loss via calorimetric method at 77 K

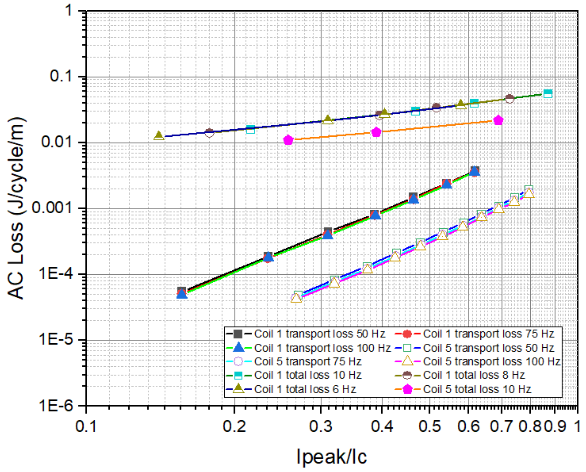
Results (comparing to a 4mm standard coil: coil 1):

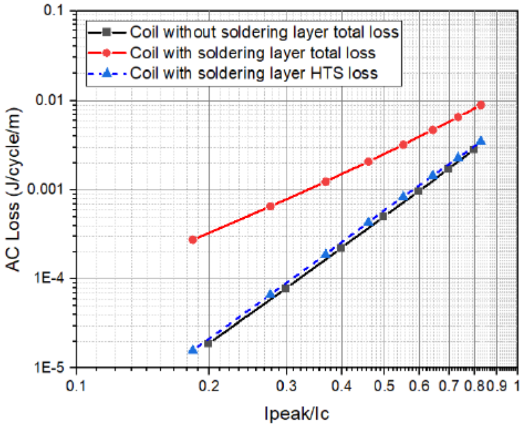
1. Striation (1mm) reduces total AC loss by 28%.
2. Soldered- stacking (1mm) reduces total AC loss by 26%.
3. 2mm*2 multi-filament coil (coil 5) reduces total AC loss by 68%.
4. 1mm*4 multi-filament coil is expected to perform better but damaged during testing

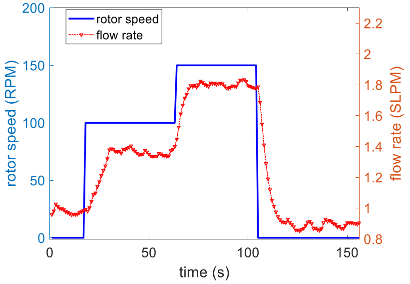


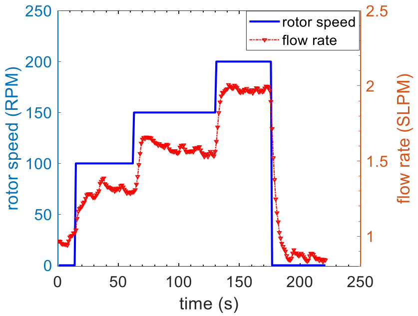












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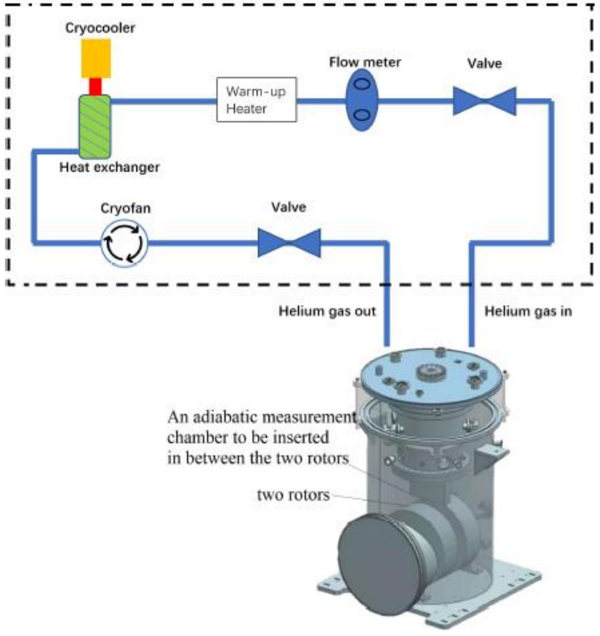
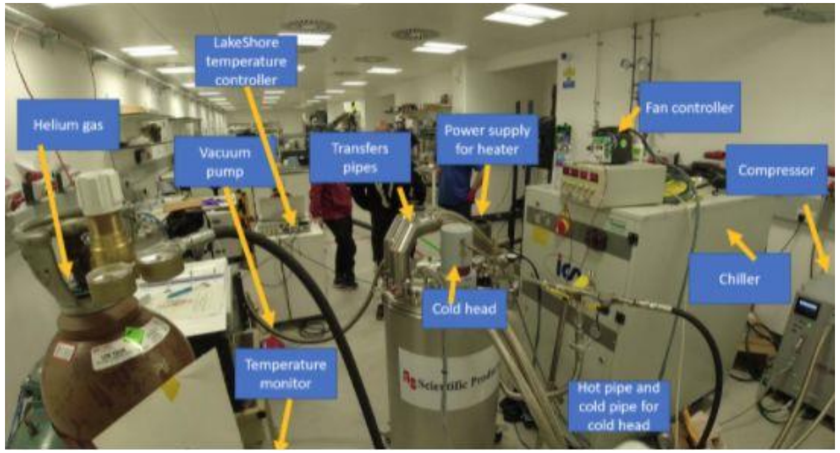
AC-capable armature winding development

- Total AC loss via calorimetric method at 20-77 K (on-going)





Application heat load	Cold head temperature	Heat exchanger temperature	Application temperature	Helium mass flow	Volumetric flow	Fan head	Fan heat load	Total heat load	Fan pressure generated
Q_{app} (W)	T_{CH} (K)	T_{HX} (K)	T_{app} (K)	m_{He} (gm/s)	V_{He} (m^3/hr)	H_{fan} (m)	Q_{fan} (W)	Q_{tot} (W)	P_{fan} (mbar)
0	15.96	17.84	18.14	16.14	2.126	27.52	13.68	28.18	73.77
20	18.42	21.16	21.80	13.09	2.087	28.81	12.31	47.80	63.80
40	20.87	24.35	25.42	11.22	2.078	29.07	11.30	66.80	55.41
60	23.29	27.42	29.01	9.90	2.075	29.17	10.56	86.06	49.12
80	25.67	30.34	32.55	8.86	2.060	29.65	10.03	105.53	45.01
100	28.06	33.33	36.28	7.93	2.028	30.64	9.61	125.11	42.29

Table 4

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Brushless HTS rotor

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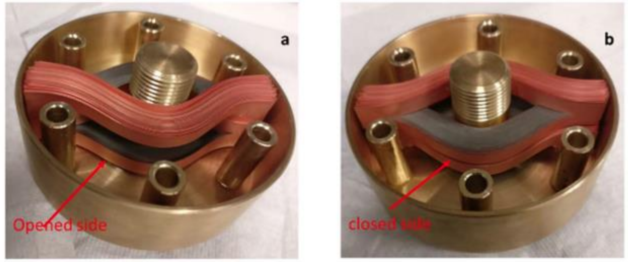
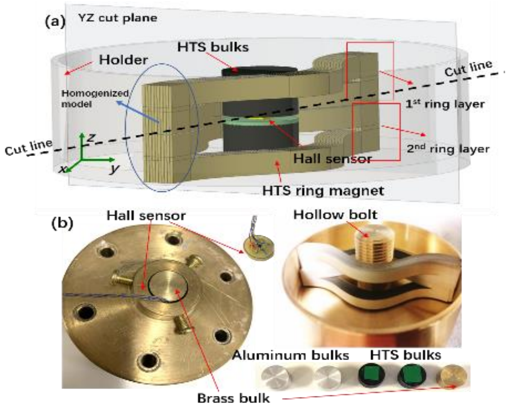
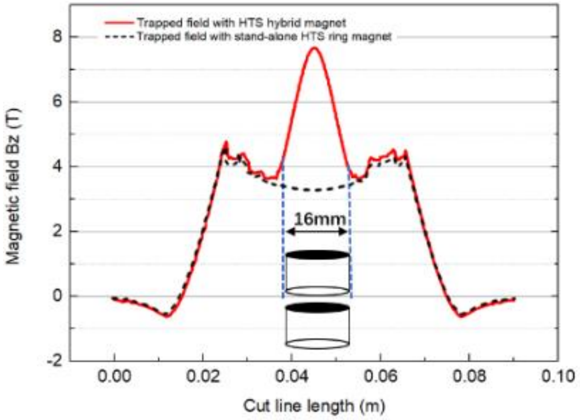
- Large HTS bulks subject to damage easily
- Large HTS ring has a low HTS filling ratio
- A new hybrid HTS trapped field magnet *

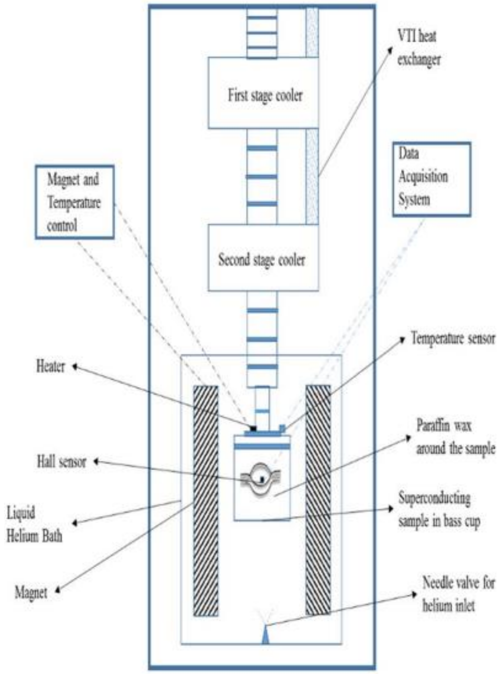


4.6 T peak field at 95mm diameter center [1]





7.35 T peak field at 95mm diameter center*



* Manuscript under review for SUST

[1] Muhammad Zulfiqar Ali et al 2020 Supercond. Sci. Technol. 33 04LT01

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Brushless HTS rotor

- A new hybrid HTS trapped field magnet *

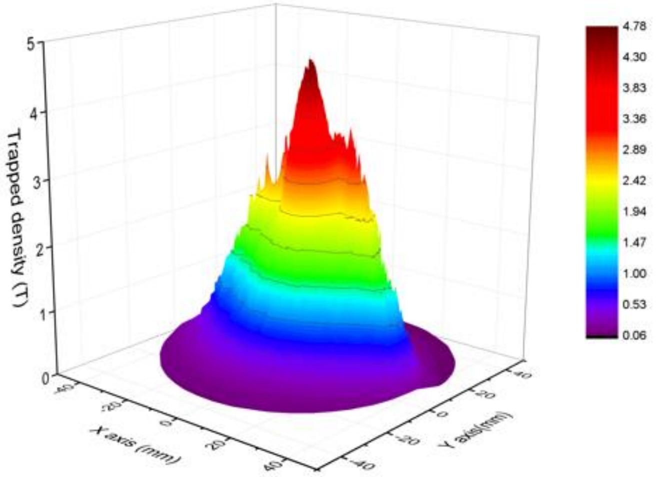
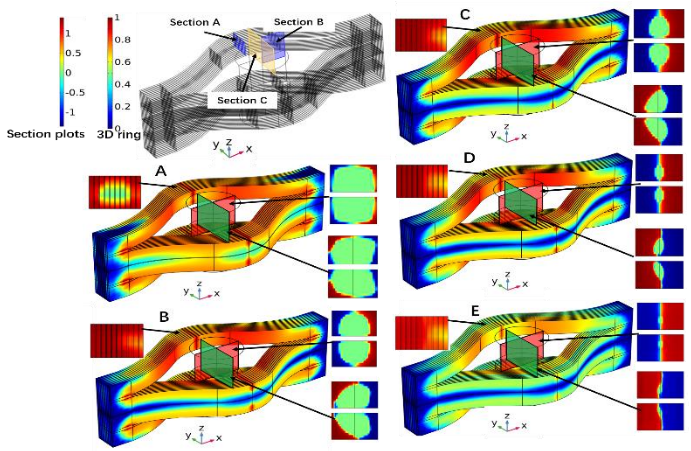
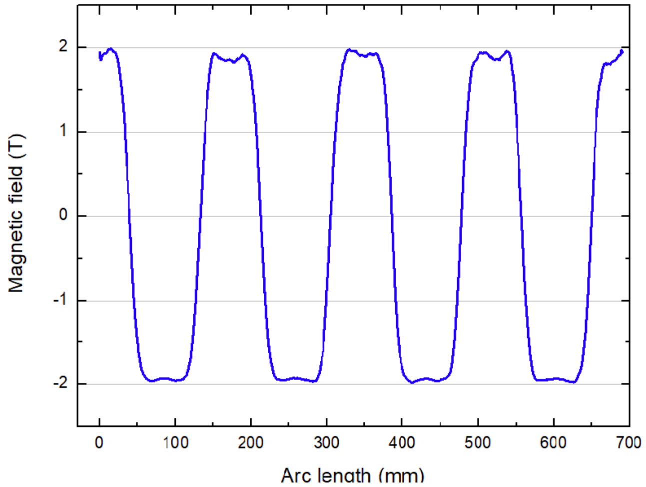


Fig.4 Field distribution at 2 mm above the surface of the HTS hybrid magnet





2 T peak at motor armature mean diameter

* Manuscript under review for SUST

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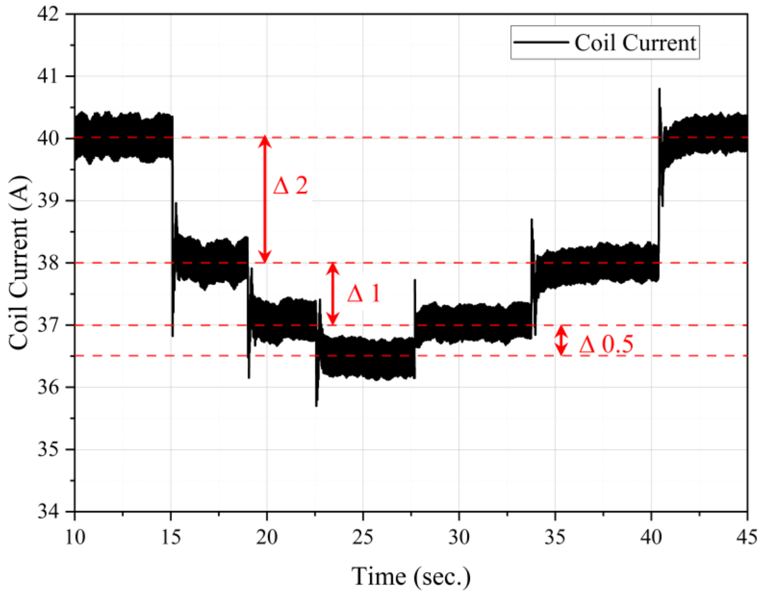
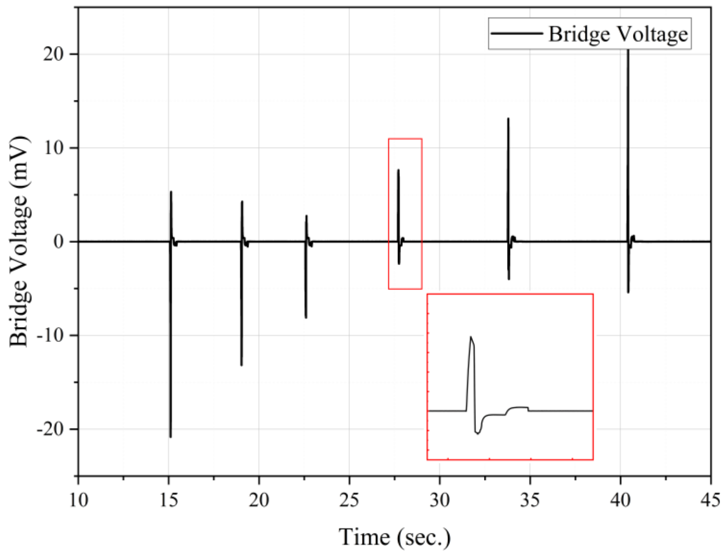
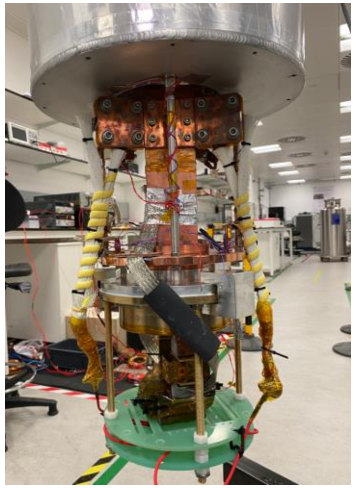
Brushless HTS rotor

Brushless control for persistent currents in joint-less HTS coils at 77 K

- No thermal leakage from current leads
- Minimized charging losses (only in ramping up and rotor field modulation)







20 K setup (on-going)

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UK ATI Zero Emission Sustainable Transportation 2022-2024:

University of Strathclyde Glasgow

Objective for WP2.2:

To develop a cryogenic propulsion motor and its drive system

- Power density and efficiency step change for cryogenic/superconducting technologies >=15kW/kg
- Demonstrate voltage reduction below 800 V dc

Definition	Value	unit
Magnetic loading peak	2-3	Tesla
Electrical loading	100	kA/m
Rated speed	1500	rpm
Rated voltage stator	300	V
Temperature rotor	30-40	K
Temperature stator	65-77	K
Power density	>=15	KW/kg

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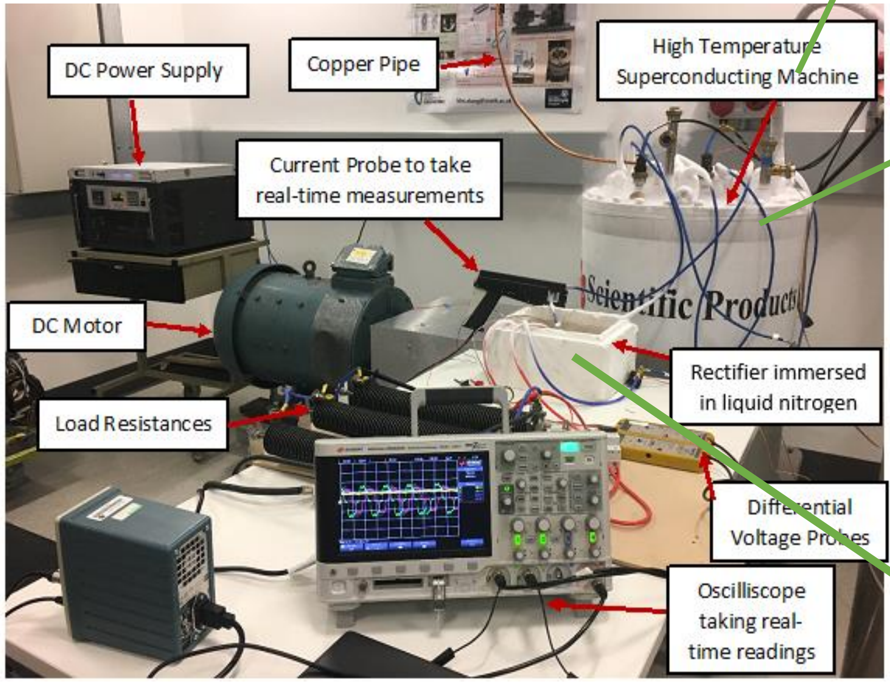
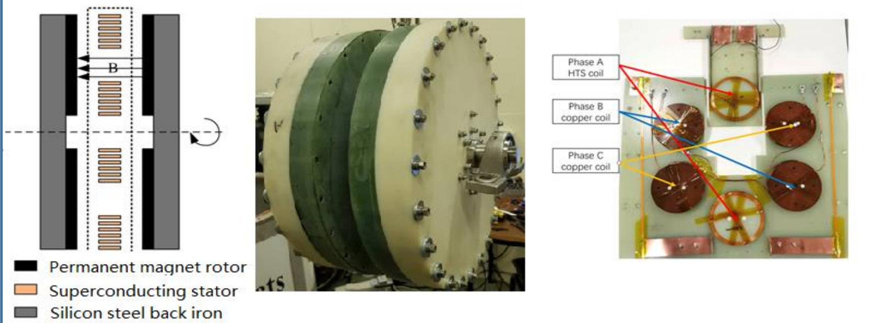
Previous 10 kW partially axial-flux superconducting motor:

between 2017-2022:

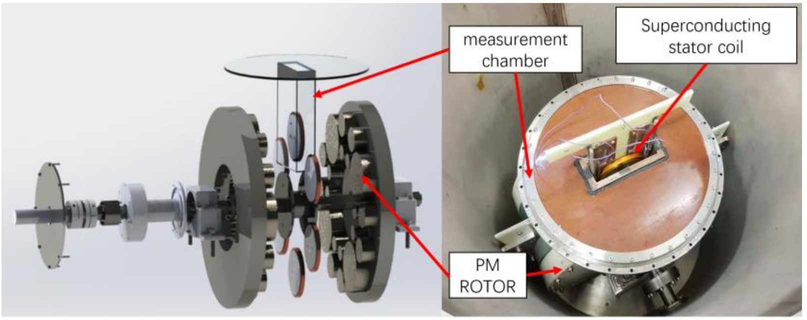
Steady tests for AC loss calculation

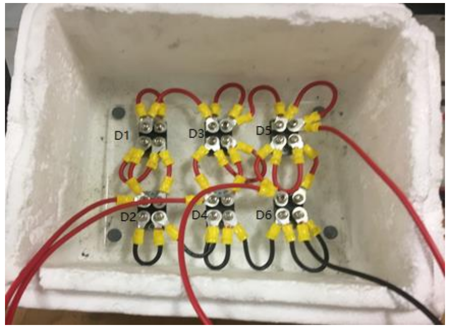
Transient tests with a cryogenic rectifier

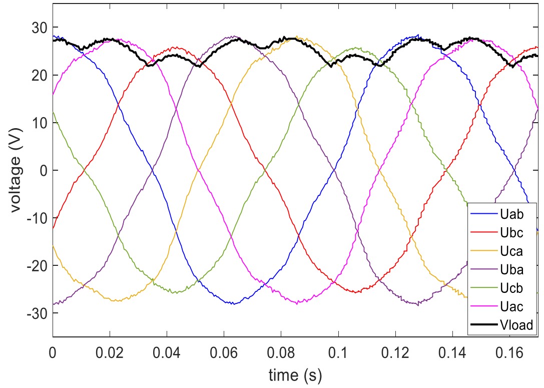


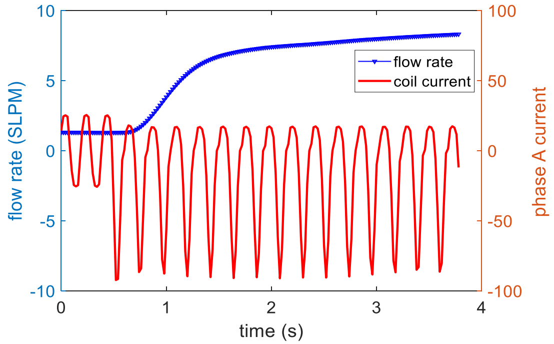


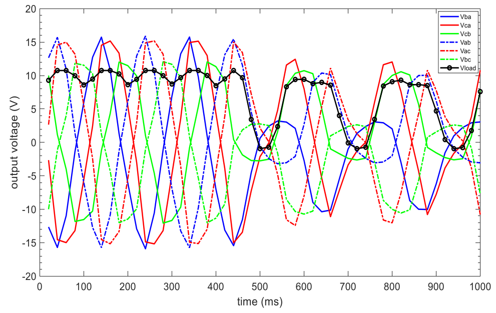
(a) cross section view
(b) two rotor discs
(c) stator disc











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New 200 kW cryogenic powertrain features:

1. Axial-flux fully HTS motor
2. Brushless operation
3. Two 100 kW cryogenic invertors
4. Neon thermosiphon rotational cooling
5. Helium gas circulation cooling