IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 50, October 2021.
Invited presentation J4Or1A-01 given at CEC-ICMC 2021, July 19-23, 2021, Virtual.

Proof of concept testing for a cryogenic propulsion Unit

Min Zhang (Min.zhang@strath.ac.uk)
Fangjing Weng, Tian Lan, Zhishu Qiu, Hengpei Liao, Muhammad Iftikhar, Mohammad Yazdani Asrami, Muhammad Ali, Felix Huber, Abdelrahman Elwakeel and Weijia Yuan

Applied Superconductivity Laboratory
University of Strathclyde
Glasgow, UK

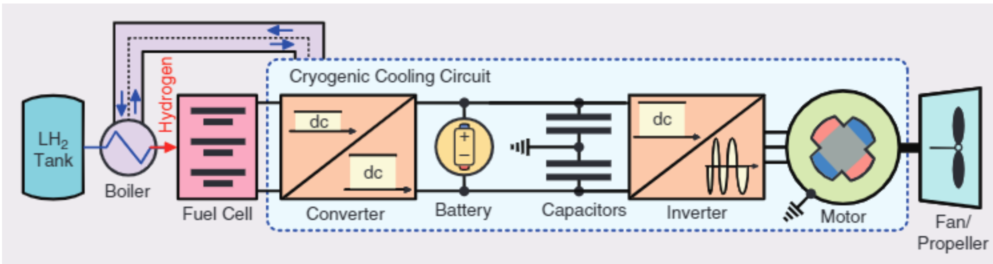
Funding acknowledgement:
1. Royal Academy of Engineering: Fully superconducting machines for next generation electric aircraft propulsion
2. *EPSRC: Developing Highly efficient HTS AC windings for fully superconducting machines*
3. *H2020: Developing novel high temperature superconductor rotor windings for electric aircraft propulsion machines*

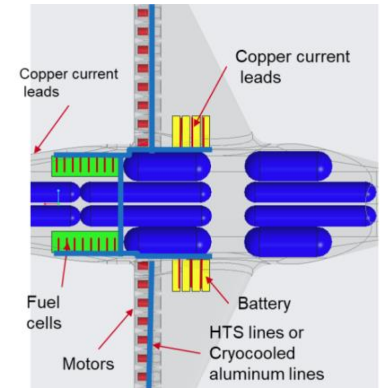
University of Strathclyde Glasgow

Introduction

- Hydrogen enables zero emission aviation:

1. Fuel cell powered electrical propulsion:

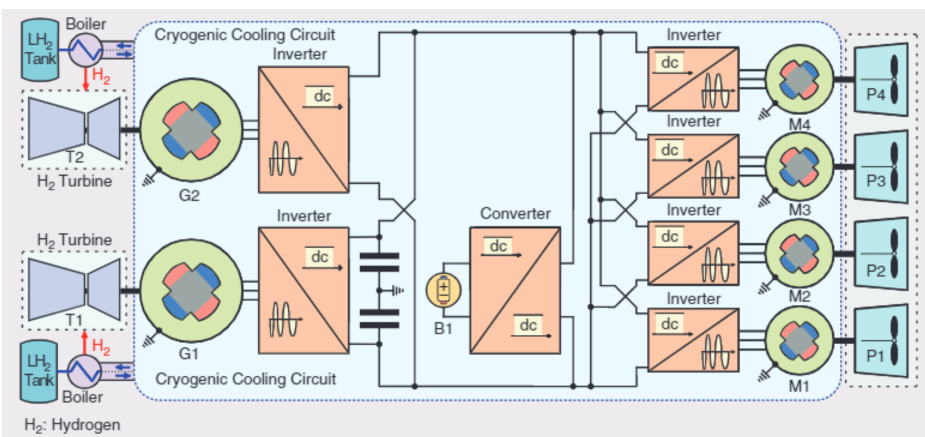




Example projects:

- Center for High Efficiency Electric Aircraft (CHEETA)
- GKN H2GEAR: a liquid hydrogen propulsion system

2. LH2+gas turbine cryogenic propulsion



- Cryogen onboard
- Electrical propulsion units are required

Example projects:

- Siemens/Rolls Royce: eAircraft unit

Figures from:
IEEE Electrification Magazine / MARCH 2021
CHEETA project

Introduction

- How to achieve high power density and high efficiency?
  - Use liquid hydrogen to cool down conventional conductors to increase power density
  - Use superconductor to increase both power density and efficiency

	$Cu_{0.15}Al_{0.85}$ Cuponal^{TM} @ 294K	Al > 99.999% Hyperconductor @ 20K	YBaCuO or MgB_2 Superconductor @ 20-65K
Weight	9,355 kg (heavy!)	411 kg (light)	357 kg (light)
Waste Heat	155 kW (hot!)	28.5 kW (hot)	3.7 kW (cool!)
Cost	medium	high	high
Complexity	low	medium	medium
TRL Level	9	4	4, aircraft 9, CERN
Protection Risks	high	high	medium, (FCL intrinsic)

Talk title: Design of a 20 MW Drivetrain Microgrid for Electric Aircraft Propulsion Powered by Liquid H_2 Fuel Cells
Author: T. Haugan, timothy.haugan@us.af.mil

Performance metrics of electrical conductors for aerospace cryogenic motors, generators, and transmission cables

M.D. Sumption[a,*], J. Murphy[b,c], M. Susner[b], T. Haugan[b]

[a] CSMM, MSE, The Ohio State University, Columbus, OH 43210, USA
[b] Aerospace Systems Directorate of the Air Force Research Laboratory, Wright-Patterson AFB, 45433, USA
[c] University of Dayton Research Institute, Dayton, OH 45469-0073, USA

* Both superconductors and normal-state cryogenic conductors can increase power density in a case when liquid cryogen is "free", but **only superconductors can lead to total system power density increases** when heat cannot be rejected to the fuel.

Hydrogen consumption per 250 kW for a specific fuel cell: 4.8 g/s @ 60°C/4 bar

→

All heat generated in the propulsion unit rejected to H2 fuel: >= **98.6% propulsion system efficiency**

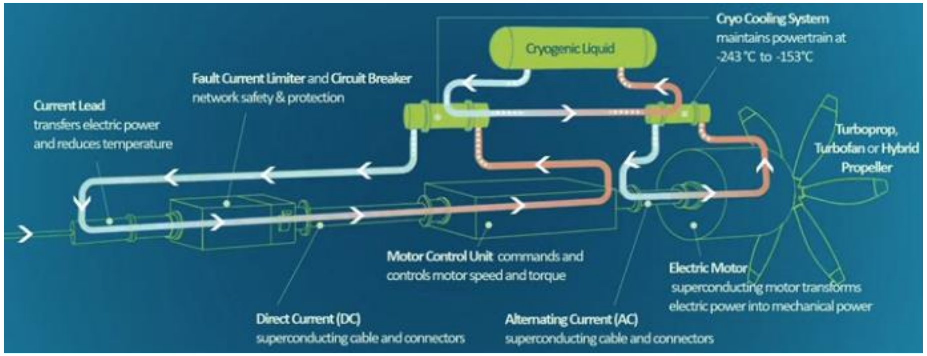
If propulsion system efficiency is not high enough -> extra liquid hydrogen for cooling

Introduction

- High propulsion efficiency -> **use superconductors**
  - ✓ Minimizing heat rejected to LH2 fuel
  - ✓ Increase the overall system power density

Example projects:

- Airbus ASCEND program to explore liquid hydrogen and superconductivity:



- H2020 IMOTHEP: INVESTIGATION AND MATURATION OF TECHNOLOGIES FOR HYBRID ELECTRIC PROPULSION

  Work package 5.5: superconductivity system for SMR-RAD design

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A cryogenic propulsion study (2014-2021):

Proof of concept stage 1:
Axial-flux HTS machine with permanent magnet rotors and HTS stator

- **77K, 300 rpm**
- **Connection to a cryogenic rectifier**
- **AC loss measurement**
- **Transient tests**

Proof of concept stage 2:
20 K 1500 rpm (testing on-going)

Demonstrator stage:
200 kW fully HTS axial-flux demonstrator

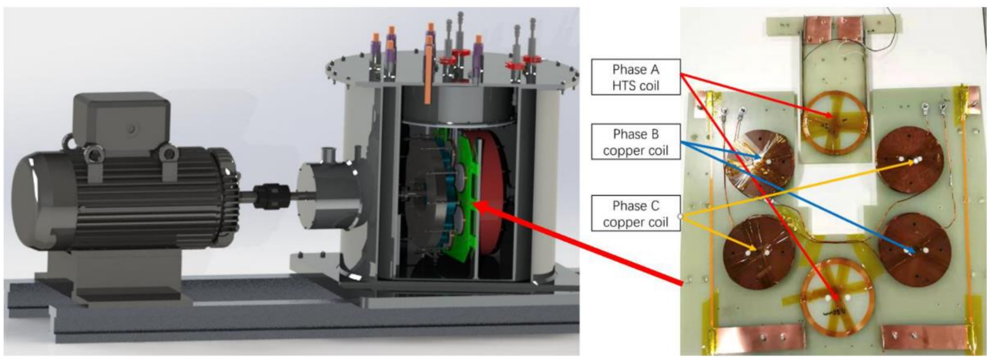
1. How much heat will be rejected into fuel?
2. What will happen in a fault scenario?
3. What is the theoretical maximum power density and efficiency?

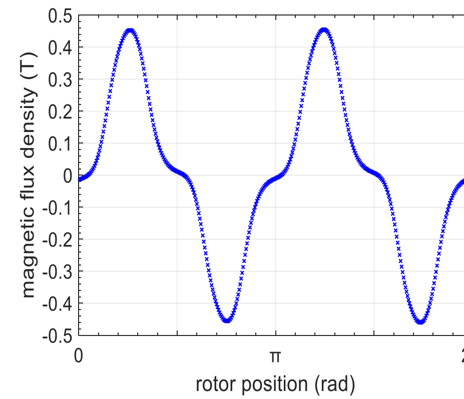
1. How much heat will be rejected into fuel?

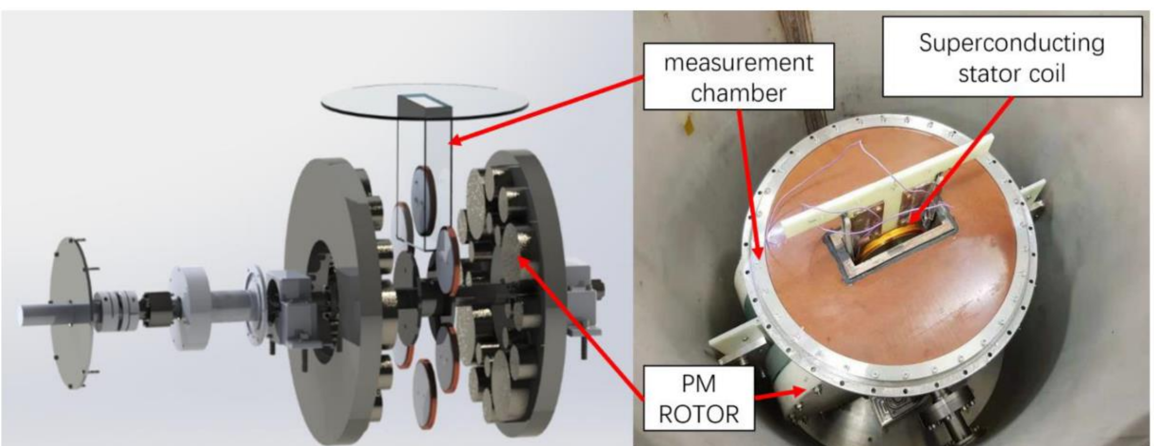
Proof-of-concept stage 1:

How to measure the losses of superconducting winding in machines:
An axial flux machine with superconducting armature windings:

- **0.45 *T*** in the air gap
- 2-pole-pair
- 77 K







- With only £45 k seed funding back in 2015, we cannot afford six HTS windings…
- The system met all initial design targets and works perfectly for three years now.

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1. How much heat will be rejected into fuel?

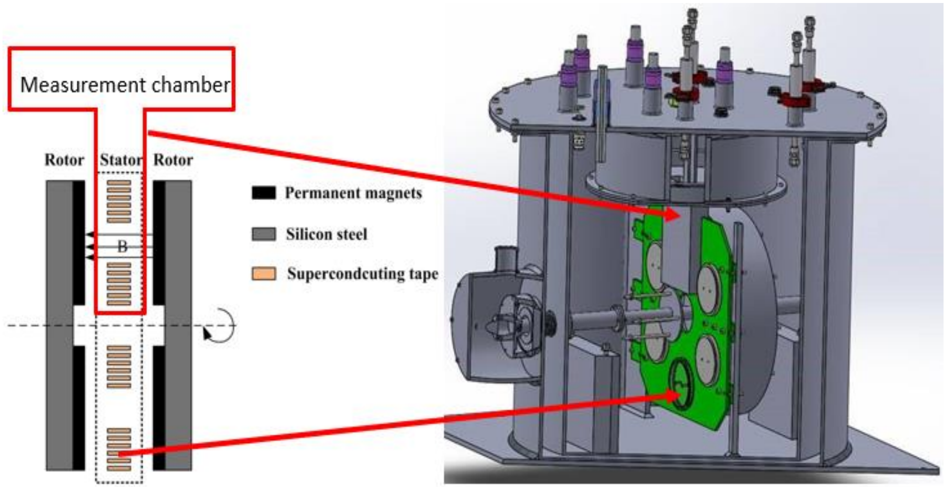
Proof-of-concept stage 1:

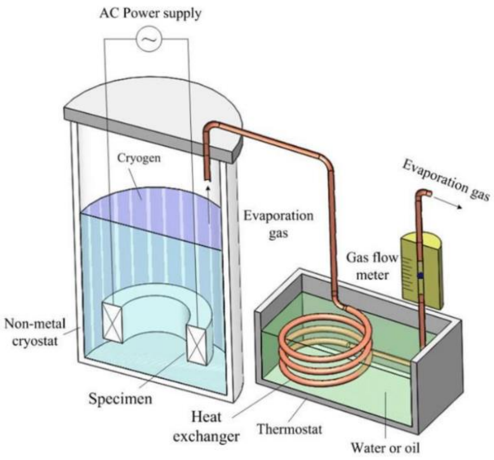
- To measure heat to be rejected into fuel:

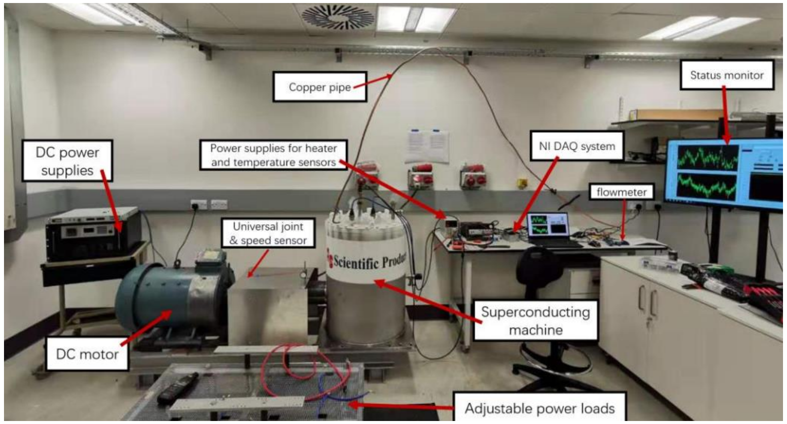
The latent heat of vaporisation of liquid nitrogen is 199 kJ/kg
Measuring the flow rate of nitrogen gas, then calculating Joule heat in the cryostat

$$Q_{ac} = \frac{F \times C_k}{f}$$

F is the flow rate
C_k is the flow rate constant
f is the electrical frequency







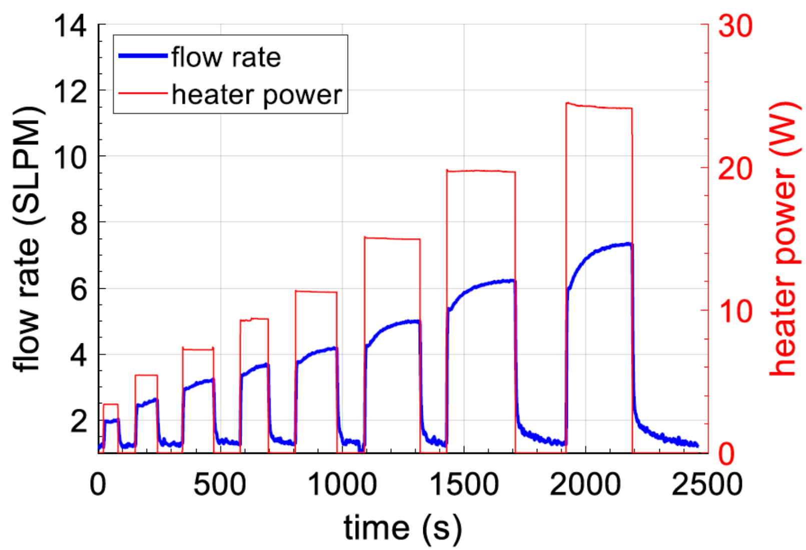
1. How much heat will be rejected into fuel?

Proof-of-concept stage 1:

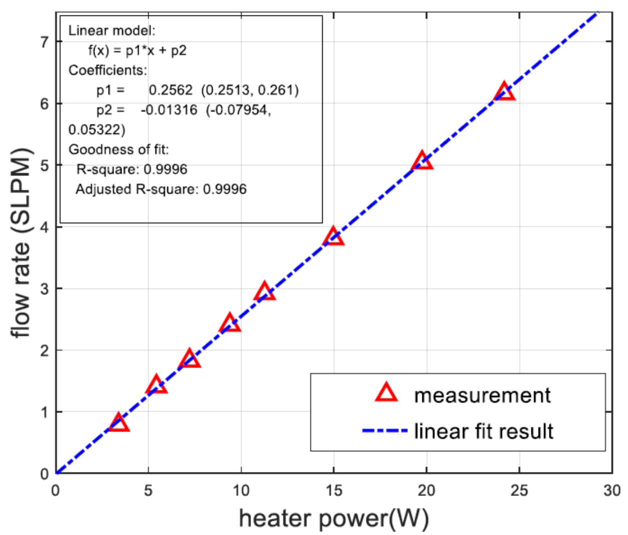
- To measure heat to be rejected into fuel *:

System calibration:
Background heat calibration, rotational calibration, terminal calibration

Flow rate constant: 0.256 SLPM/W
Accordant with theoretical value with **2.4% error**. No gas leakage



(a) Data of flow rate and heater power



(b) Flow rate versus heater power

* Fangjing Weng et al 2020 Supercond. Sci. Technol. **33** 104002: Fully superconducting machine for electric aircraft propulsion: study of AC loss for HTS stator

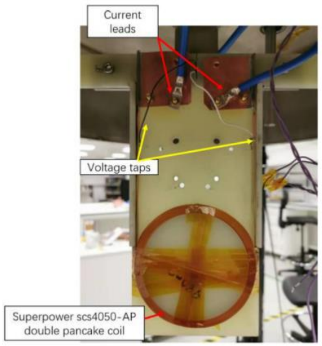
1. How much heat will be rejected into fuel?

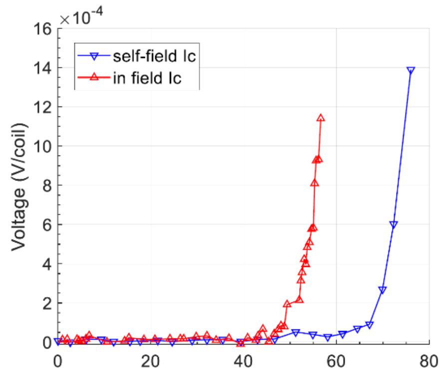
Proof-of-concept stage 1 (2014-2019):

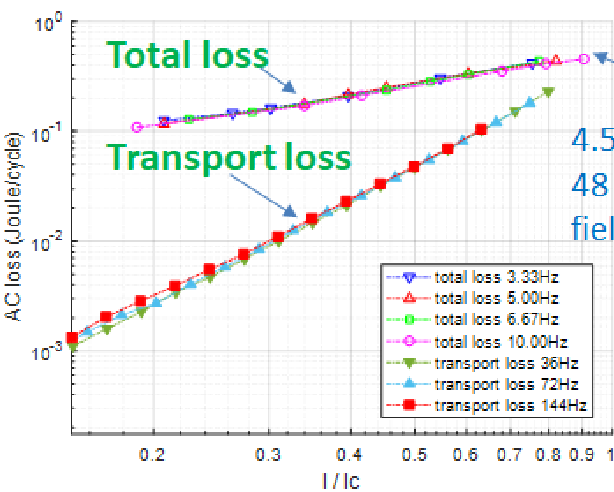
- To measure heat to be rejected into fuel:

Parameters	value
Tape type	Superpower SCS4050-AP
Tape Ic	140A
Coil Ic (self-field)	72A
Coil inner diameter	95mm
Coil outer diameter	99.8mm
Turns per layer	38
Total coil turns	76
inductance	937.4μH

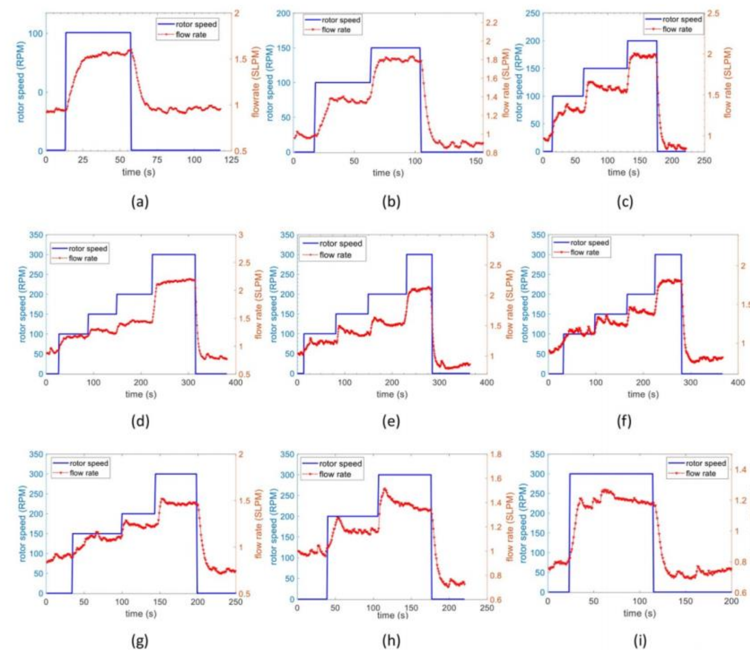
Self-field critical current: **72 A**
In-field critical current: **53 A** (at peak **0.45 T**)







4.56 W of heat with 48 A and a peak field of 0.45 T



@ 300 rpm, 77 K: 99.2%
@ 1500 rpm, 77 K: 96%

Liquid cryogen is NOT free if the propulsion system efficiency is not high enough

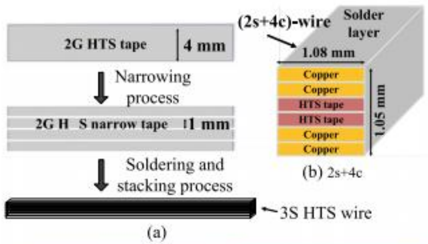
1. How much heat will be rejected into fuel?

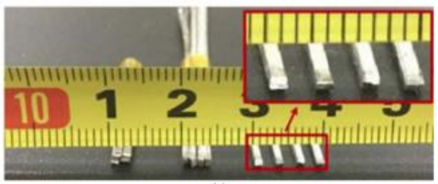
- To minimise heat to be rejected into fuel:

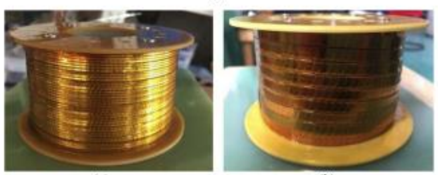
Multi-filament HTS cable*:

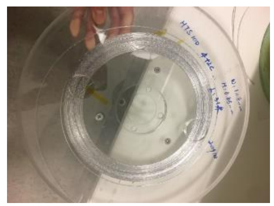
Brant equation:

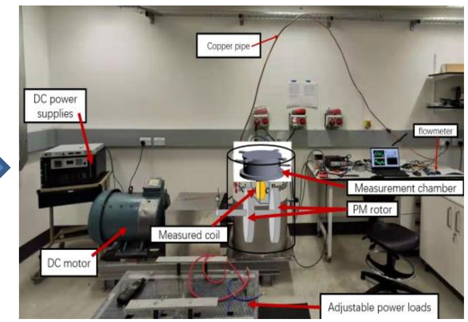
$$P_{\mathrm{mag}} = 4\pi\mu_0 w^2 f H_0 H_c \left\{ \frac{2H_c}{H_0} \ln\left[\cosh\left(\frac{H_0}{H_c}\right)\right] - \tanh\left(\frac{H_0}{H_c}\right) \right\}$$

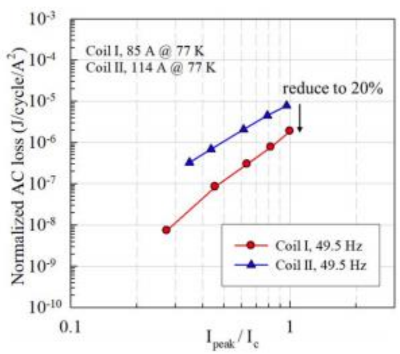


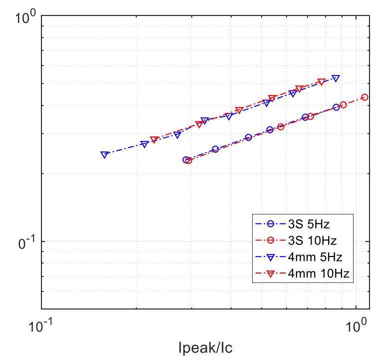

(c)


(a) (b)









1mm wide multi-filament HTS cable:

- 40% and 80% reduction in transport AC losses achieved
- 26% reduction in total AC losses (depending on soldering)

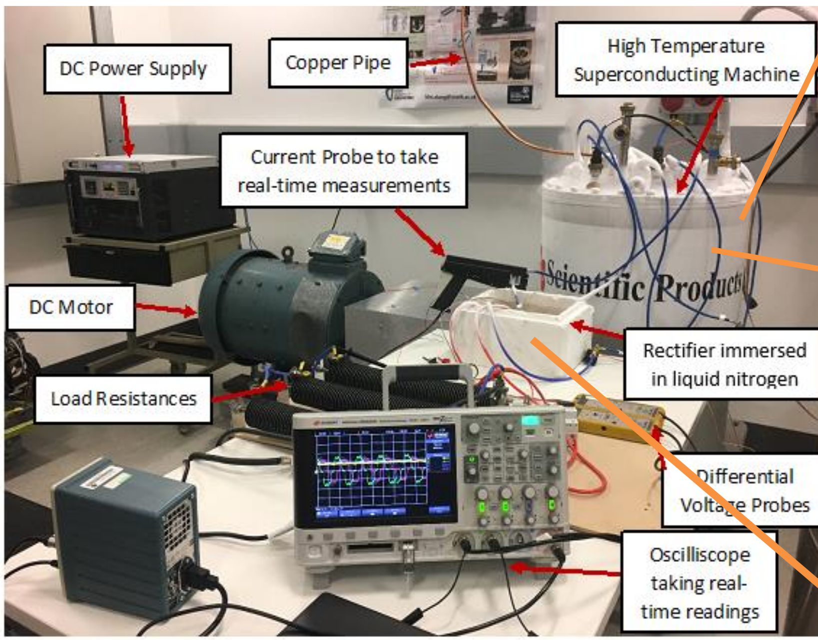
We can optimize superconducting machines windings to minimize heat rejected into fuel

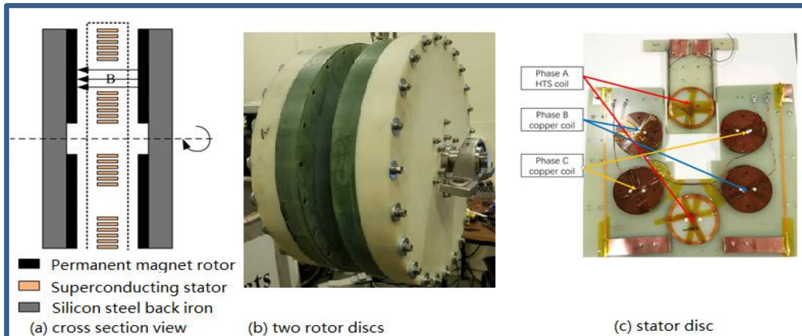
* Mingyang Wang *et al* 2019 *Supercond. Sci. Technol.* **32** 01LT01

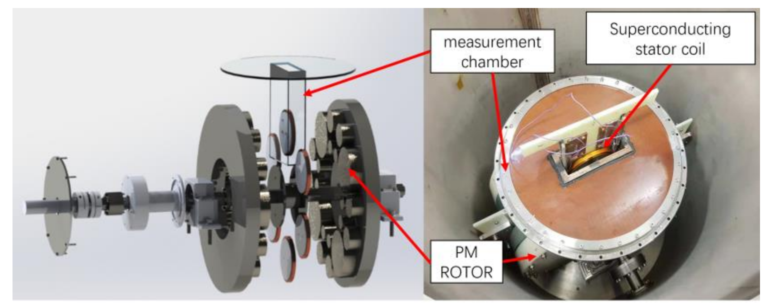
2. What will happen in a fault scenario?

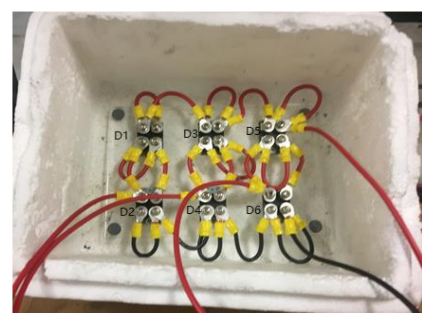
Proof-of-concept stage 1:

Superconducting machine + cryogenic rectifier
77 K, 300 rpm









We tested the cryogenic propulsion unit in a generation mode

2. What will happen in a fault scenario?

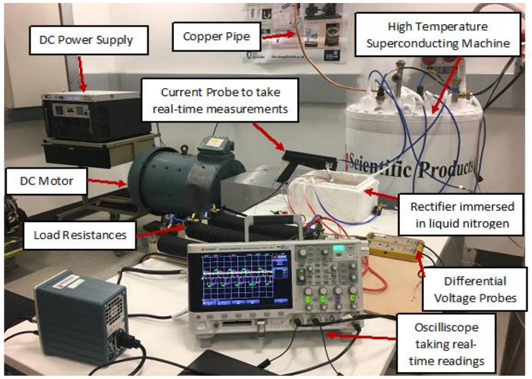
Proof-of-concept stage 1*:

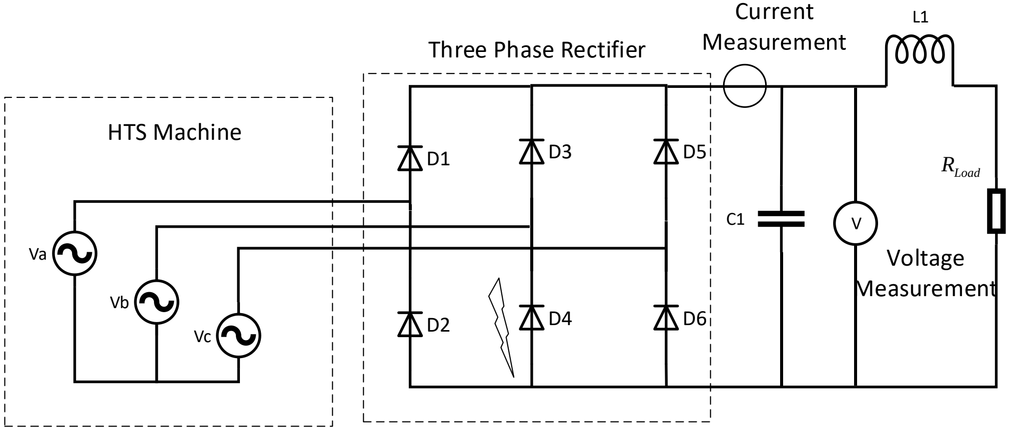
Superconducting machine + cryogenic rectifier

77 K, 300 rpm

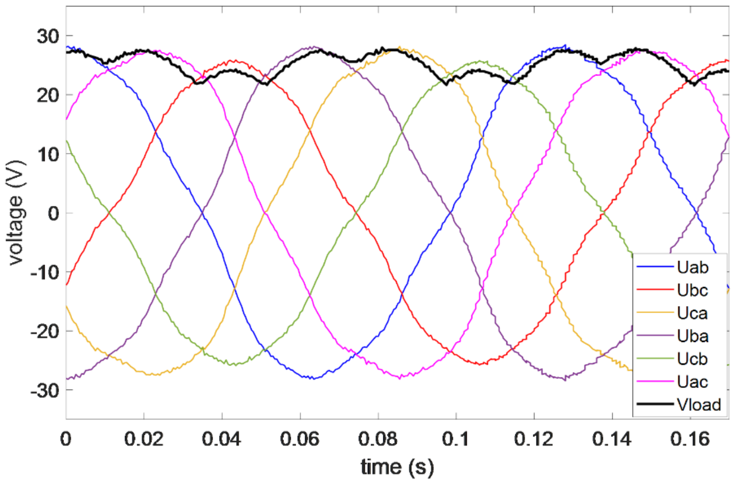
Short circuiting in D4:

When Vb> Va, short circuit current flows from phase b to phase a; when Vb>Vc, short circuit current flows from phase b to phase c.

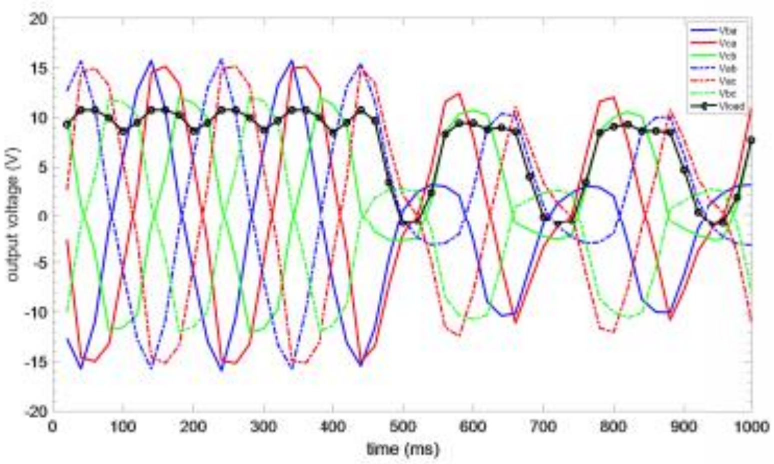




Steady status:

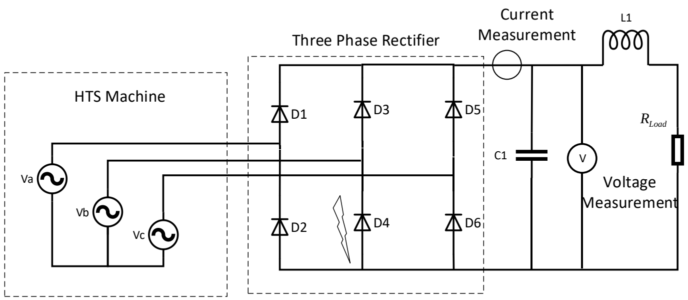


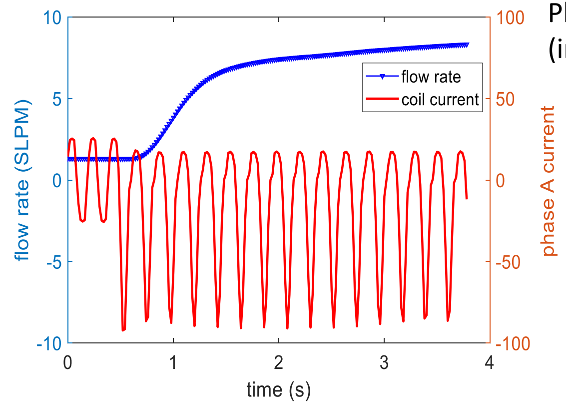
Transient status:



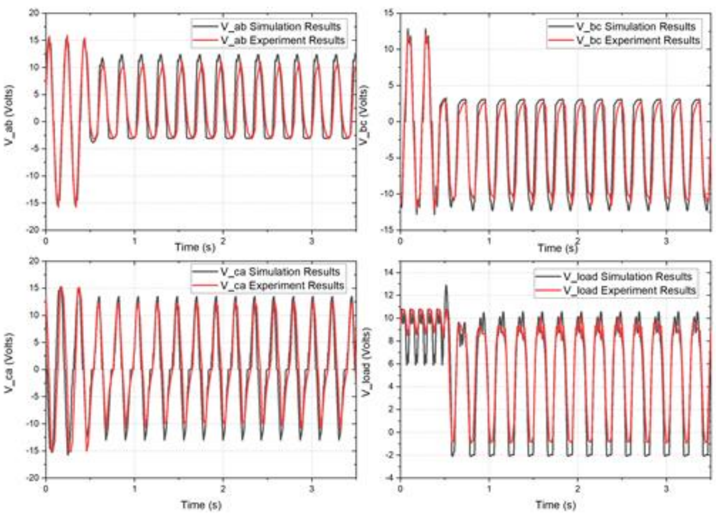
*F. Weng et al.IEEE Access: Transient Test and AC Loss Study of a Cryogenic Propulsion Unit for All Electric Aircraft

2. What will happen in a fault scenario?





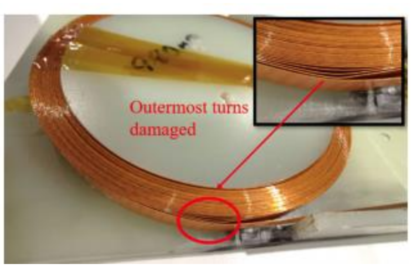
Phase a current 25A to >80 A (in-field Ic <55 A)



During fault, the HTS coil quenched and its resistance increased 30 times.

R_{load}	Measured resistance for the load resistance bank	0.33 Ω
$R_{HTScoil}$	Measured resistance for the HTS coil joints	2 μΩ
R_{quench}	Equivalent resistance after the HTS coil quenches	60 μΩ

- The quenched HTS coil acted as a fault current limiter itself, limiting the fault level.
- No electrical/thermal damage of the coils.
- One coil suffered from a few turns' mechanical damage due to lack of impregnation.



- HTS propulsion units can be fault resilient: self-protecting using quench resistance
- It is vital to provide reliable insulation and impregnation for the winding to prevent mechanical damage during fault.

3. What is the theoretical maximum power density and efficiency?

- How to model a HTS modeling accurately and efficiently?

High aspect ratio, highly non-linear material, time consuming

T-A formulation for large-scale HTS modelling*

- Treat the 1 um thickness of 2G HTS with zero thickness
- More than 100 times faster than existing HTS models

T-formulation

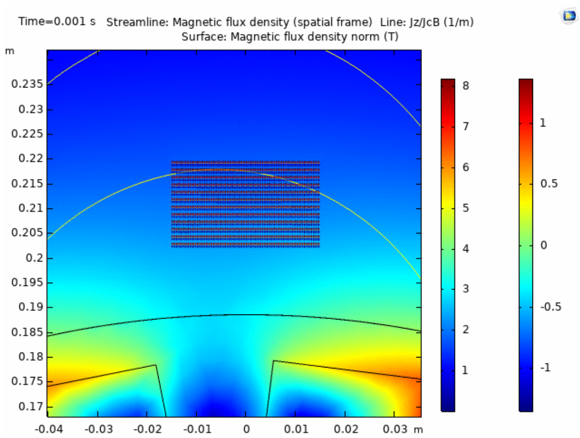
$$\mathbf{E}(\mathbf{J}) = E_0 \left(\frac{|\mathbf{J}|}{J_c(\mathbf{B}, T_h)} \right)^n \frac{\mathbf{J}}{J_c(\mathbf{B}, T_h)}$$

$$\mathbf{J} = \nabla \times (T\mathbf{n})$$

$$\nabla \times \boldsymbol{E} = \frac{\partial B}{\partial t}$$

A-formulation

$$\nabla \times \nabla \times \boldsymbol{A} = \boldsymbol{\mu}_0 \boldsymbol{J}$$

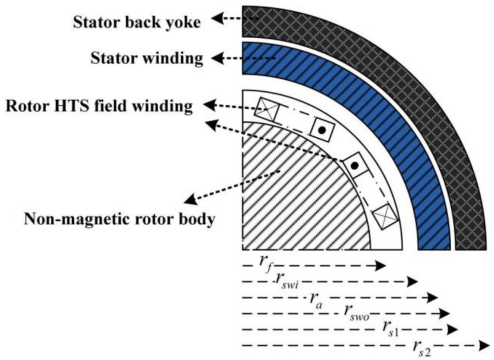


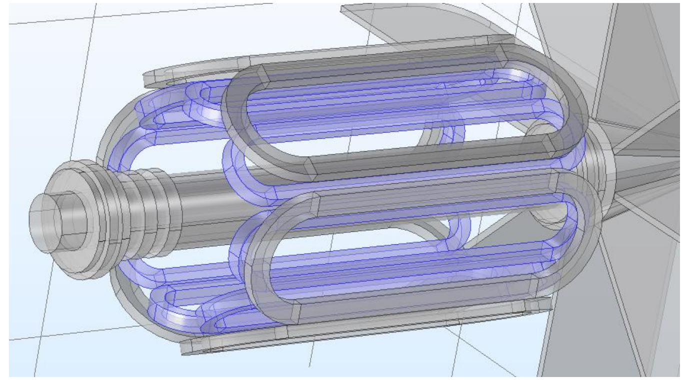
* Huiming Zhang, Min Zhang, Weijia Yuan, 2017 Supercond. Sci. Technol. 30 024005;

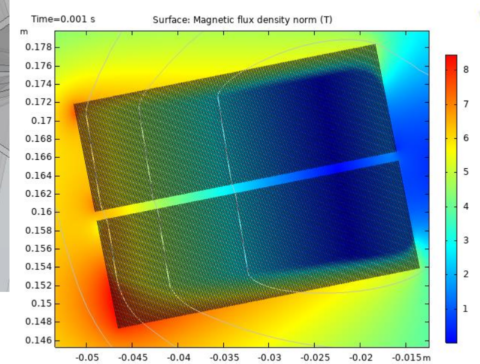
* T-A models free for downloading from the International HTS Modeling workgroup website

3. What is the theoretical maximum power density and efficiency?

A 2.67 MW baseline fully HTS machine design:

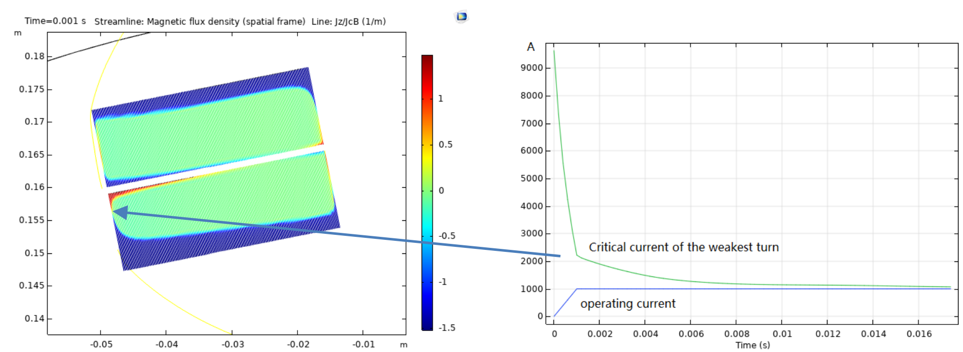






- Stator and rotor: concentrated racetrack coils with 2G HTS
- 8-6 design to maximise winding factor

YBCO winding	Design 1	Design 2	Design 3
Power	2.67 MW	2.67 MW	2.67 MW
Operational temperature	25/65 K	25/65 K	25/65 K
Stator HTS width	1 mm	0.5 mm	0.25 mm
Stator efficiency	95.9%	98.8 %	99.5%



The up limit of this machine is 54 kW/kg (Power/ HTS mass), with room for improving

Conclusion for proof-of concept study

University of Strathclyde Glasgow

1. How much heat will be rejected into fuel?

- Liquid cryogen is NOT free if the propulsion system efficiency <=98.6%
- 96% HTS efficiency achieved for our demonstrator at 77 K
- 95.9% HTS efficiency achieved using existing technology for the benchmark motor at 25 K
- 99.5% armature efficiency can be achieved if 0.25 mm multi-filament HTS becomes available

2. What will happen in a fault scenario?

- HTS winding can be self-protecting: during quench, the resistance value increased by 30 times to limit the fault current.
- Impregnation is essential to prevent mechanical damage

3. What is the theoretical maximum power density and efficiency?

- 54 kW/kg (Power/ HTS mass) is the up limit for the benchmark motor, with room for improving
- 99.5% armature efficiency can be achieved for the benchmark motor at 25 K

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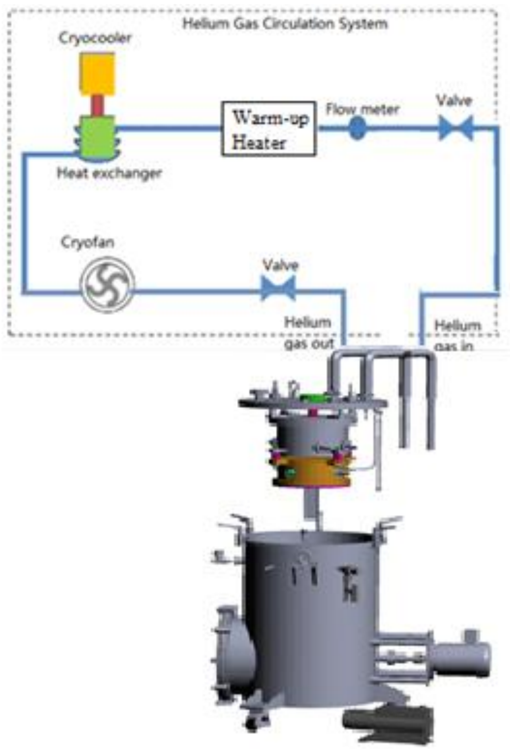
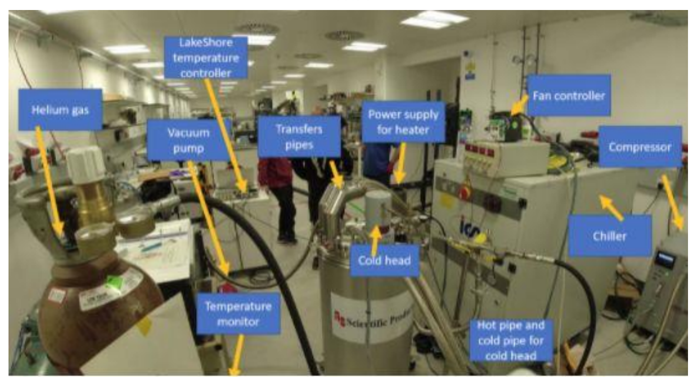
Proof-of-concept stage 2 (2020-now)

- 77 K -> 20 K: enabling MgB2, Bi2212 measurements
- 300 rpm -> 1500 rpm: 10 Hz -> 50 Hz



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} (m³/hr)	H_{fan} (m)	Q_{fan} (W)	Q_{tot} (W)	p_{fan} (mbar)
0	15.19	16.76	17.64	4.88	2.019	30.93	7.94	23.43	26.40
20	17.78	20.31	22.35	3.94	1.994	31.68	7.42	42.92	22.10
40	20.33	23.65	27.19	3.34	1.977	32.20	7.07	62.57	19.21
60	22.83	26.84	32.26	2.88	1.938	33.31	6.83	82.33	17.48
80	25.26	29.87	37.59	2.52	1.889	34.67	6.65	102.15	16.32
100	27.67	32.87	43.04	2.29	1.891	34.64	6.48	121.98	14.81

Table 3



- Using pressurized helium circulation cooling to represent hydrogen cooling environment
- Calorimetrically measure AC losses in a rotational magnetic field

Strathclyde Applied Superconductivity Laboratory

A Laboratory built to deliver

- Curiosity driven research
- Long term planning
- Great team work

Min.zhang@strath.ac.uk