Electric aircraft: solving the propulsion materials and engineering challenges

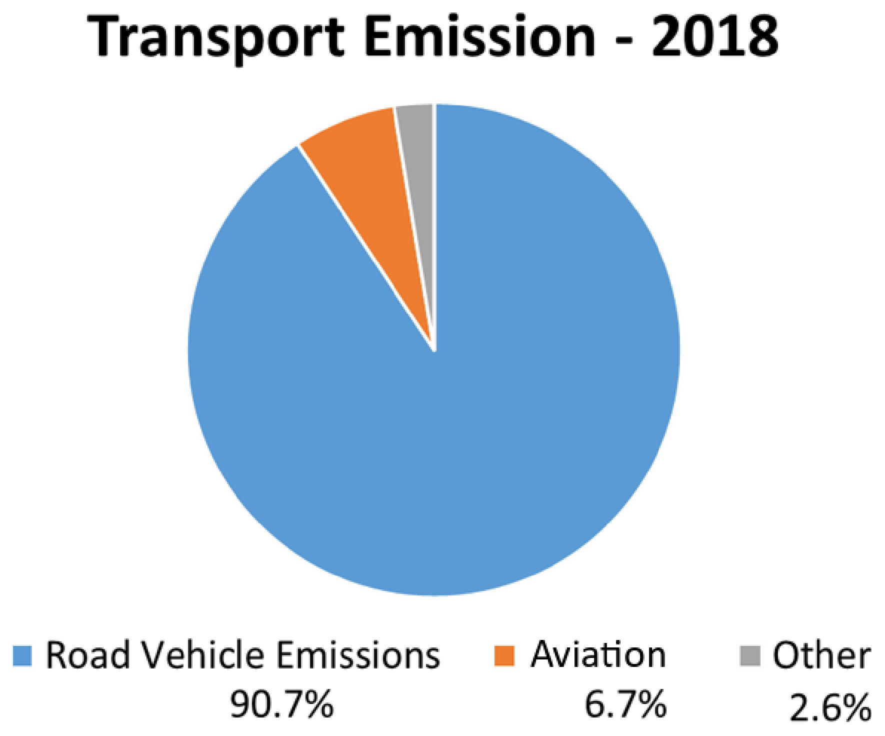
Rodney A Badcock, Naoyuki Amemiya, Alan Caughley, Michael Gschwendtner, Kent A Hamilton, Bill Heffernan, Sangkwon Jeong, Zhenan Jiang, Andrew Lapthorne, Grant Lumsden, Rachel Oliver, Sarat Singamneni, James G Storey, Duleepa J Thrimawithana, Hubertus W Weijers

14th July 2023

Acknowledgement:
We are grateful to the MBIE Advanced Energy Technology Platforms programme RTVU2004 "High power electric motors for large-scale transport" that has enabled much of this work

Are we ready to tackle the big problems?

- New Zealand is both ***blessed by our resources*** and ***cursed by our geography***!
  - We have truly sustainable, and renewable, electricity supply (>90%)
  - Transport accounts for about 20% of NZ's greenhouse gas emissions (of which 85% comes from fossil fuels)
  - Our transport routes are long and skinny
    - The only current rapid transport option is aviation
  - Our aviation routes are short-hop, barely reaching cruise altitude

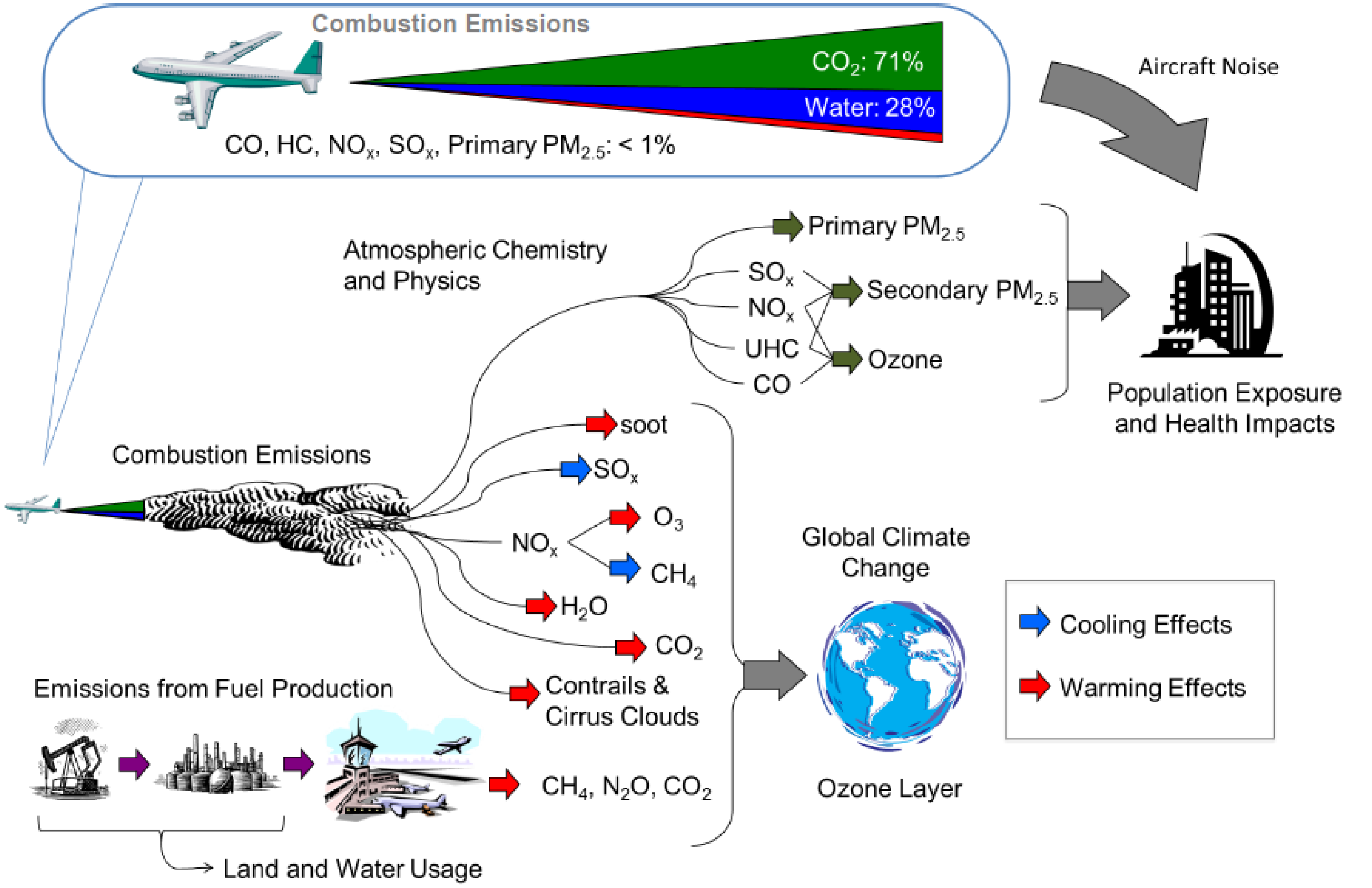


See Maille Giffin **M2Or2G-02**

- **Electric heavy transport could make an enormous impact on our fuel imports and greenhouse gas emissions**

Environmental impact of aviation

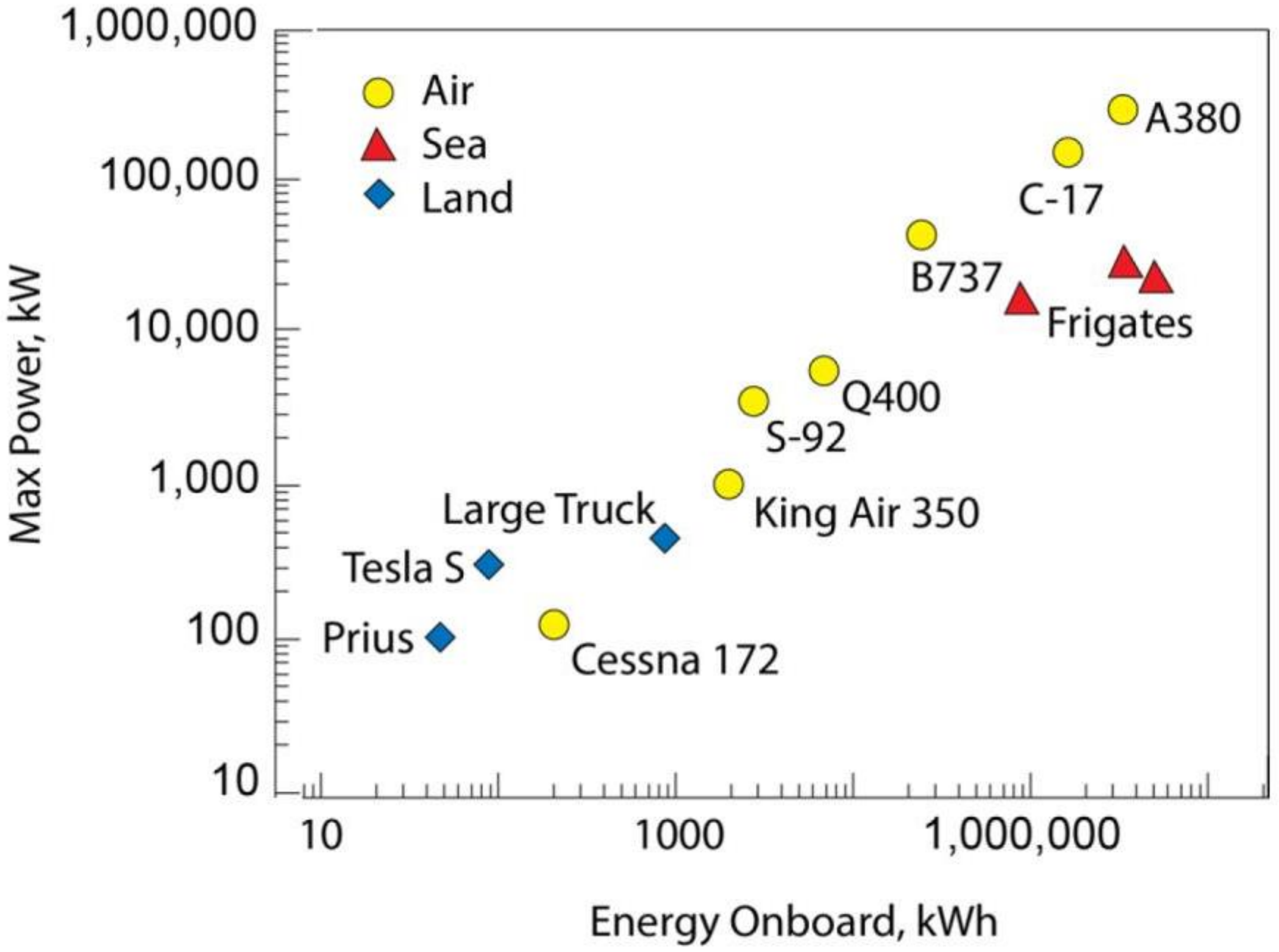
- Aviation has a growing impact on the environment
  - Not just greenhouse gases, but health and noise
- NZ requires a reduction of carbon emissions to 30% below 2005 levels by 2030



Credit: *James I. Hileman, "Some Perspectives on the Environmental Impacts of Aviation and Alternative Fuels", ARPA-E ASCEND-REEACH Kickoff, January 27, 2021, Federal Aviation Authority*

Aviation needs energy!

- Jet A1 is a great energy-dense fuel.
- Aviation requires
  - On-board storage (capacity)
  - Massive power flows to refuel quickly
- Rethink the purpose of an airport? – an **Energy Hub?**



Epstein, Alan H. "Aeropropulsion for commercial aviation in the twenty-first century and research directions needed." AIAA journal 52, no. 5 (2014): 901-911.

Will electric aviation also use hydrogen?

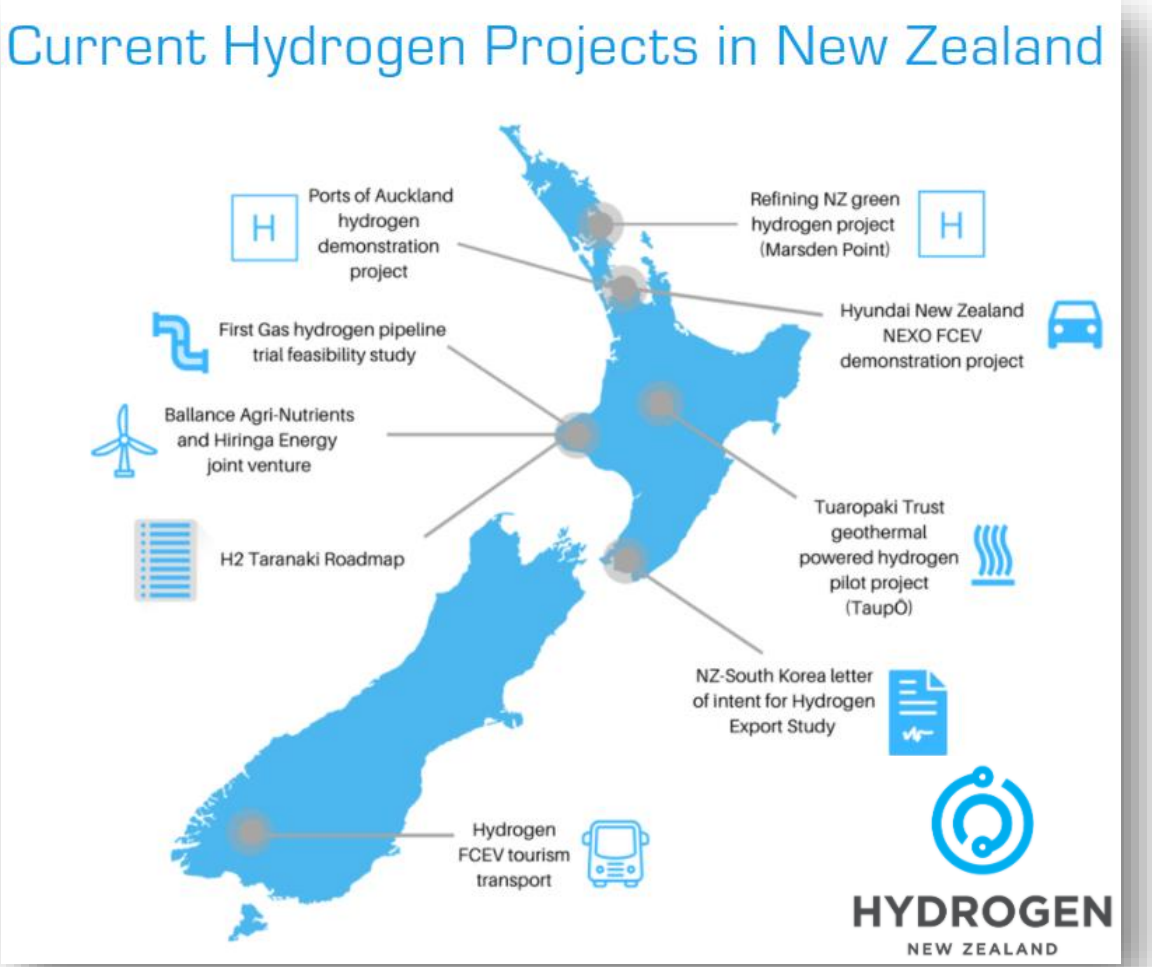

DESTINATIONS FOOD & DR

CNN travel

SAVED BY THE FUTURE

This aviation startup is soaring ahead with hydrogen-powered planes

Rebecca Cairns, CNN • Updated 24th October 2020



See Maille Giffin **M2Or2G-02**

Key technology challenges: low carbon emission aviation

- Multi-threaded initiative
  - SAF (bio-fuel, PTL, H_2)
  - Hybrid aircraft
  - All-electric aircraft
- At its heart will be:
  - **Cryogenic**
    - Fuels, conductors, electric bus, electronics
  - **Superconducting**
    - The ***ONLY*** way to meet the power/weight demand for aircraft like the A320 and larger


AIR NEW ZEALAND ON COURSE FOR FLIGHT NZ0
By Geoffrey Thomas August 04, 2022
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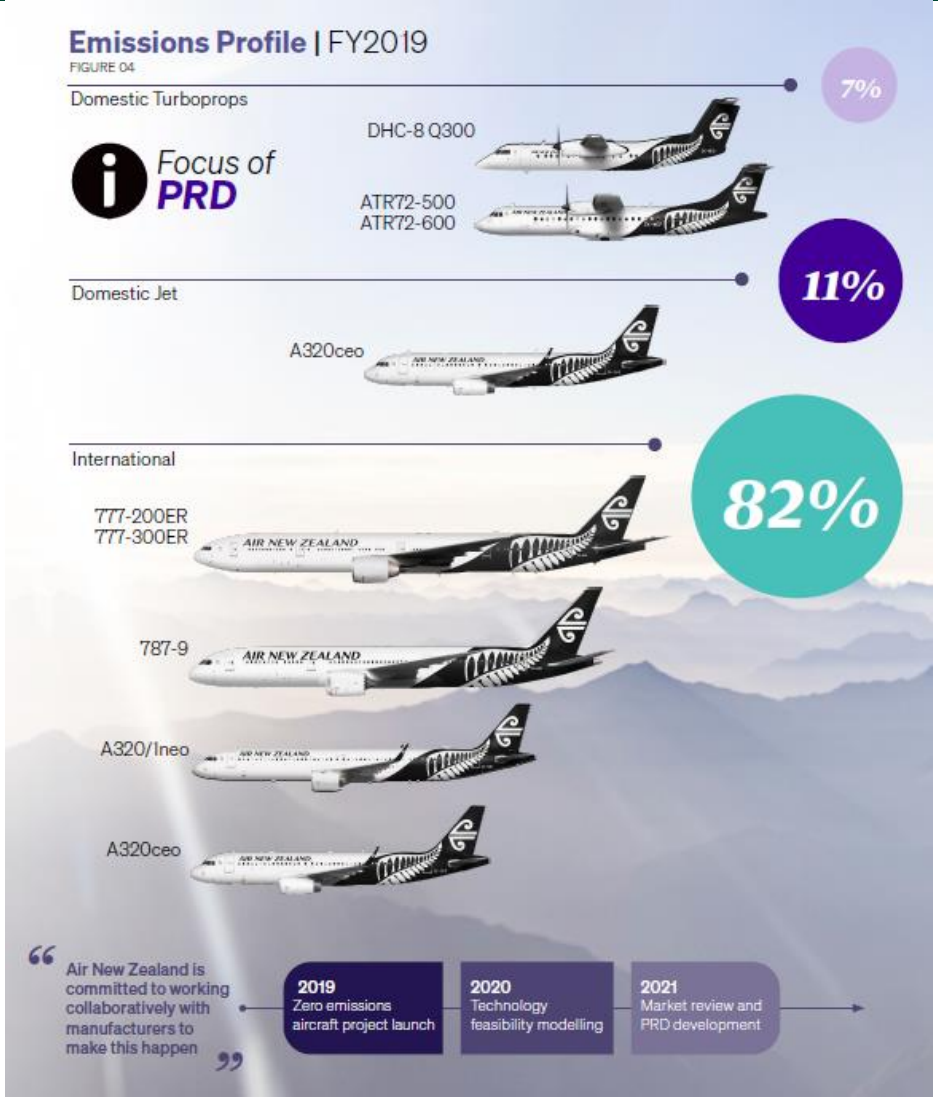
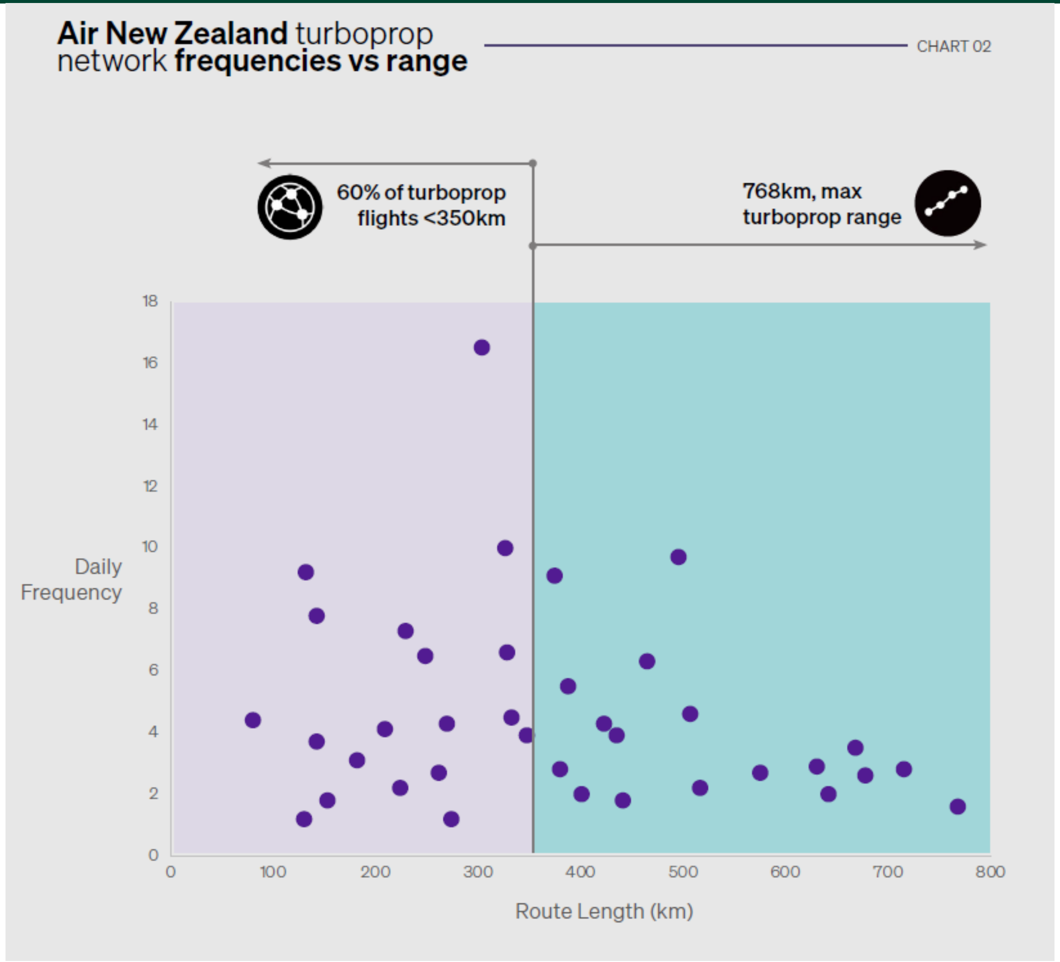
Melanie Carroll · 13:47, Nov 04 2022
Air New Zealand and Airbus to research future of hydrogen-powered aircraft in Aotearoa
AIRBUS
E-FAN X
G-WEFX

The New Zealand Aviation Fleet – getting real about implementing zero emissions





From Air New Zealand Zero Emissions Aircraft PRD
https://flightnz0.airnewzealand.co.nz/initiatives/mission-next-gen-aircraft

Driving international cutting edge - aerospace

- Can we accelerate the development of small, light, high power propulsion systems?
  - Look at whole of system – machine, cooling and power electronics
- Where will the planners, engineers, technicians and service staff come from?
  - A whole new range of technology practitioners required
- What are the primary technology gaps for HTS machines?
- What system design trade-offs need to be made?
- Use the Paihau – Robinson principles
  - Work with the best
  - Train the next generation
  - Use the application to drive the R&D

The AETP Programme – Workstream Collaboration

Advanced Energy Technology Platforms

4 Workstreams, 7 Years

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

Grant RTVU2004. Funded by New Zealand's Ministry of Business, Innovation and Employment

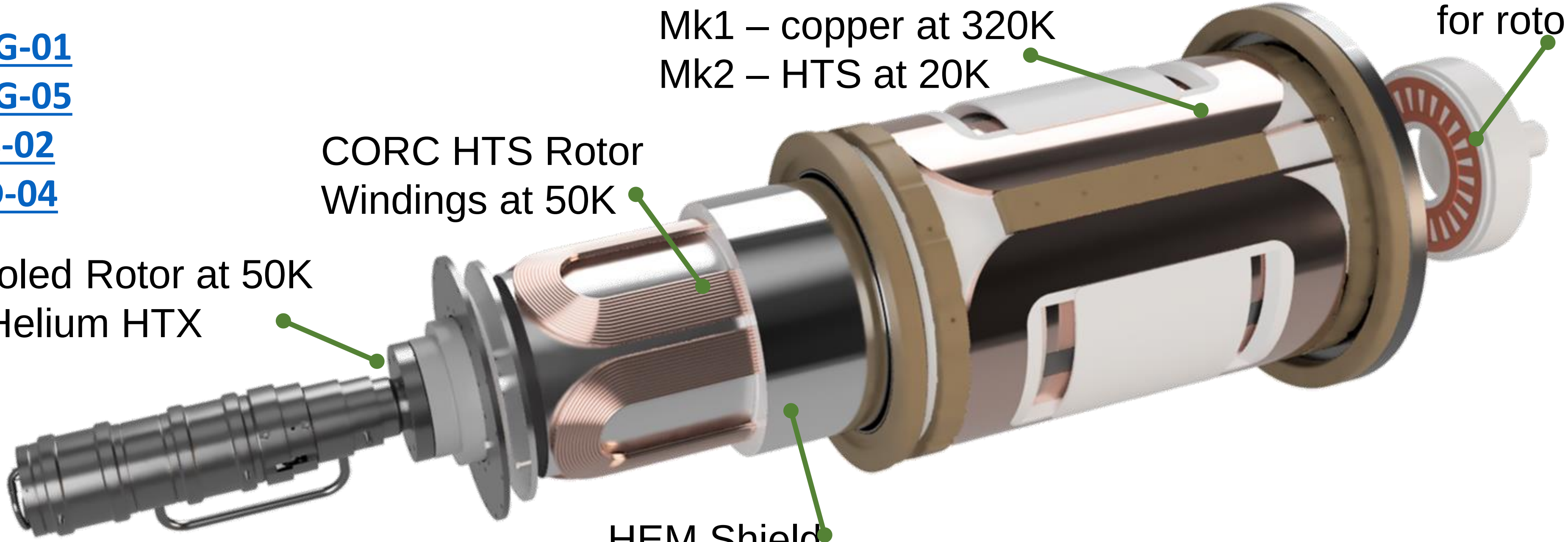
MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HIKINA WHAKATUTUKI

https://www.electrictransport.co.nz/partners/

1.1 Superconducting Machines	1.2 Cryogenic Systems	1.3 Power Electronics	Training Industry-Ready Capability
Victoria University of Wellington Te Herenga Waka; The University of Auckland; Kyoto University; Air New Zealand; KGPS	Victoria University of Wellington Te Herenga Waka; KAIST; Callaghan Innovation (New Zealand's Innovation Agency); AUT	The University of Auckland; Victoria University of Wellington Te Herenga Waka; UC University of Canterbury; University of Cambridge	Ara Institute of Canterbury; Manukau Institute of Technology; UC University of Canterbury

What do we believe is the aviation solution?

See:
M3Or2G-01
M1Or3G-05
C2Or2B-02
C3Or2D-04



- **Fully Superconducting Machines**
- **Cryogenic Cooling Systems**
  - Optimized mechanical cryocoolers
  - Additively manufactured cryo-components
  - Whole-of-system modelling
- **Lightweight Power Electronics**
  - New concepts for size and weight optimization
  - GaN-based cryogenic electronics
- **Industry-ready Training Strategies**

The AETP Programme – Workstream 1

- What are the primary technology gaps for HTS machines?

- What system design trade-offs need to be made?

1.1
Superconducting Machines

- Superconducting (HTS) machine design and prototyping
- Superconducting stator and rotor windings optimisation
- Contactless excitation of the rotor field windings (flux pumps)
- Loss measurements of superconducting windings
- Aircraft propulsion system simulation to quantify emissions benefits

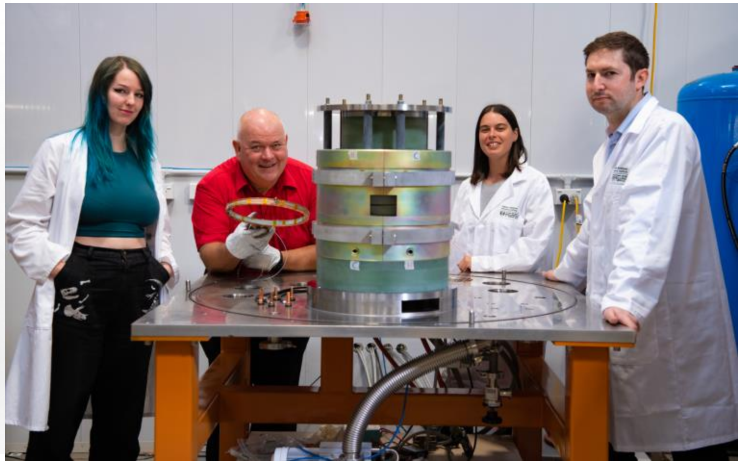
1.1 Hybrid aircraft - High TRL AC Homopolar Generator

Homopolar architecture:

- Single piece steel rotor
- Partially laminated steel stator
- Hybrid ceramic vacuum bearings.
- **20-30,000 RPM**

- High TRL
  - Stationary REBCO Coil.
  - Non-rotating HTS coil eliminates complicated cryogenic and high current rotating connections.

- **Demonstrator platform**
  - Flux pump field coils
  - Fibre optic quench protection



FABRUMSOLUTIONS skilfully engineered with style

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HTS-110

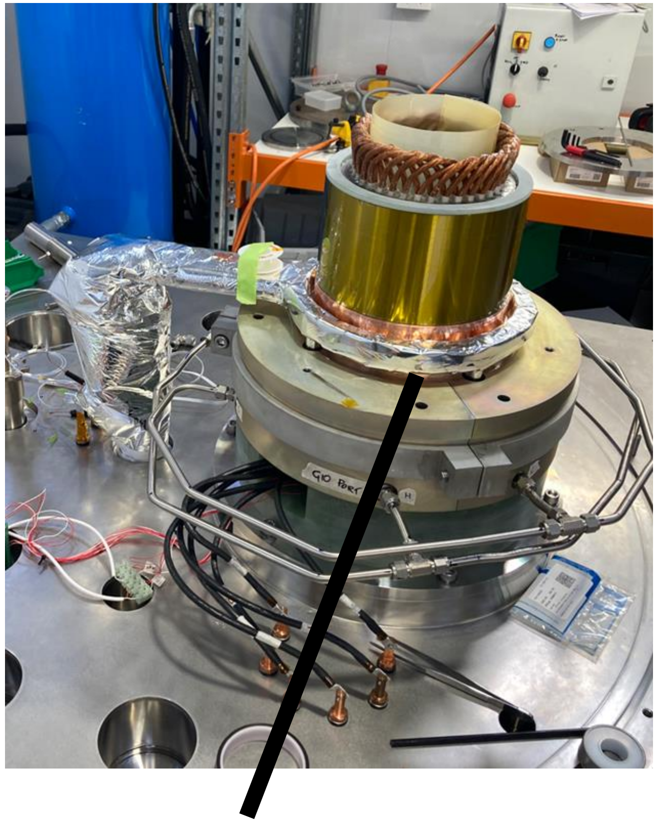
1.1 A test-bed to raise TRL of component systems

- A test bed to prove and raise technology readiness level
  - **Not** optimised for mass
  - Uses highest TRL superconducting components
- Enables testing of
  - Flux pumps
  - Cryogenic sensing
  - Bearings

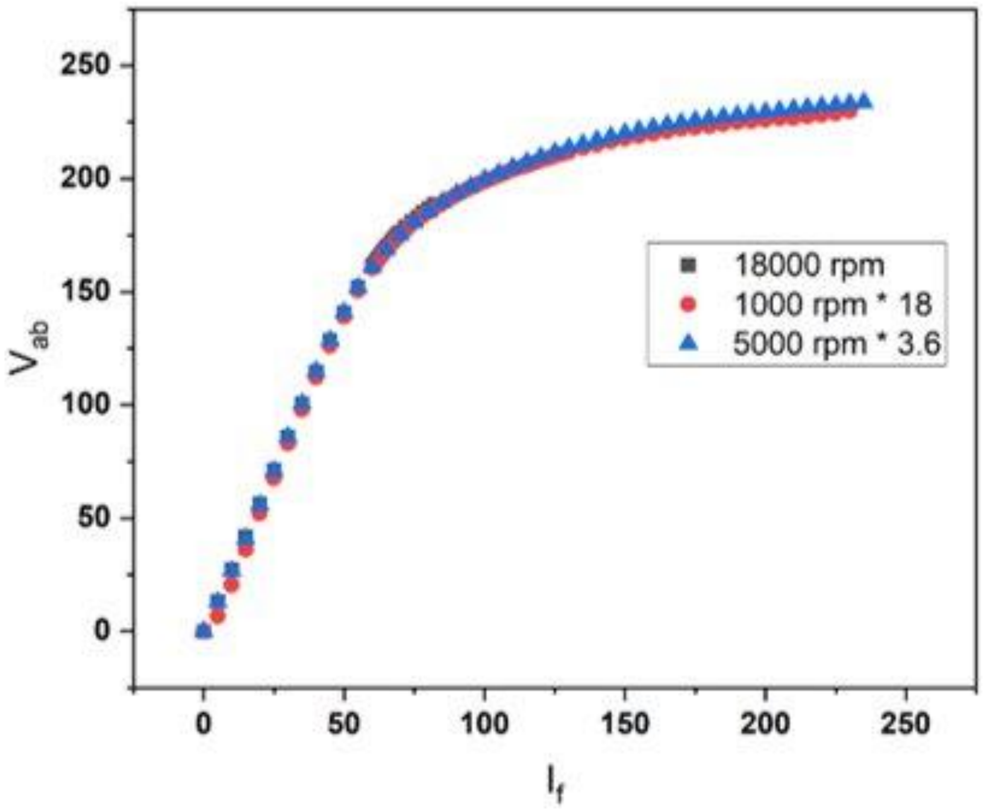
PERFORMANCE	
Rated line voltage, V	264
Rated current, A	33
Power rating, kVA	15
Field current - no-load, A	369
Power factor at full-load-lagging	0.99
Field current - full-load, A	460
Load angle at full-load, deg	2.1
Induced voltage at full-load, pu	1.25
Power generated at full-load, pu	1.02
Torque on armature at full-load, N-m	6.0
Torque on armature during a short-circuit, N-m	24
Stator iron core loss, kW	1.8
Armature resistive loss, kW	0.1

1.1 High TRL AC Homopolar Generator - Testing

- HTS field coil running at 14 K, > 250 A I_c @ 77K
  - 2x12 turns 4 mm Fujikura (17 m) ReBCO
- Chamber hard vacuum achieved: 1.6 E-7 mbar
- Rotor being driven to **18,000 rpm**
- Open circuit, spinning rotor, stator and short circuit testing

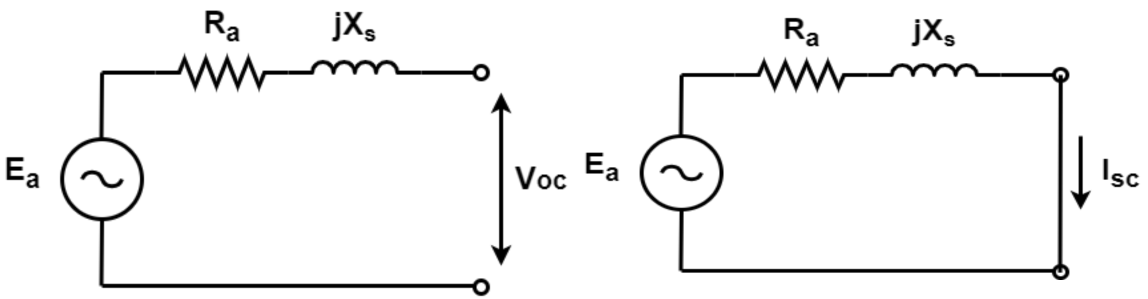


Top Stator Iron Removed Showing Exposed HTS Coil



Open Circuit Test Results

1.1 High TRL AC Homopolar Generator – Testing Summary of O.C and SC Tests at 5000 rpm

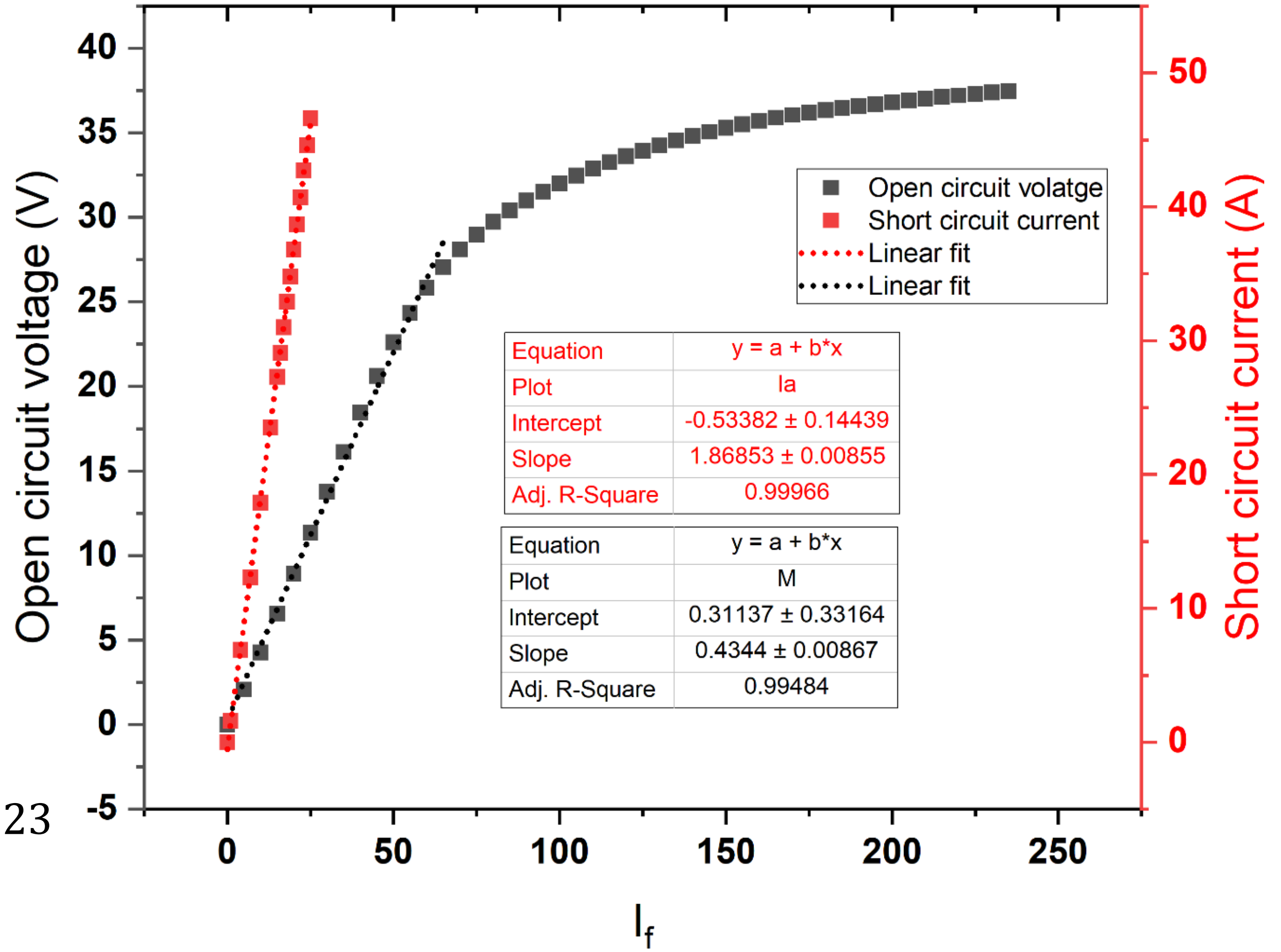


$$I_{sc} = \frac{E_a}{\sqrt{R_a^2 + X_s^2}} \Rightarrow X_s = \sqrt{\frac{E_a^2}{I_{sc}^2} - R_a^2}$$

$$R_a = 0.017\ \Omega$$

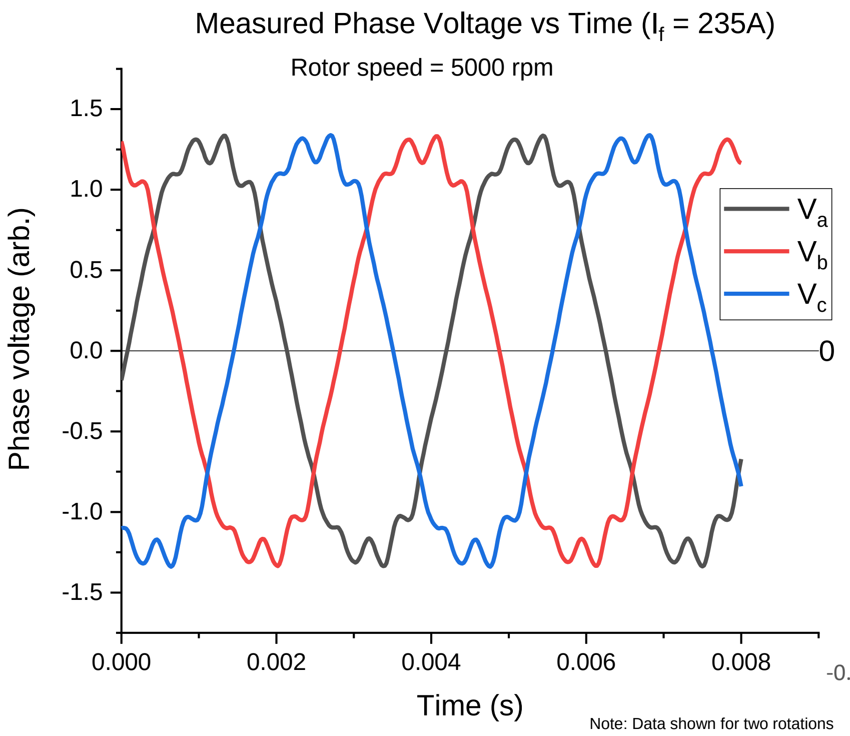
$$\frac{E_a}{I_{sc}} = \frac{Slope\ of\ the\ linear\ part\ of\ V_{oc}\ vs\ I_f}{Slope\ of\ I_{sc}\ vs\ I_f} = \frac{0.43}{1.87} = 0.23$$

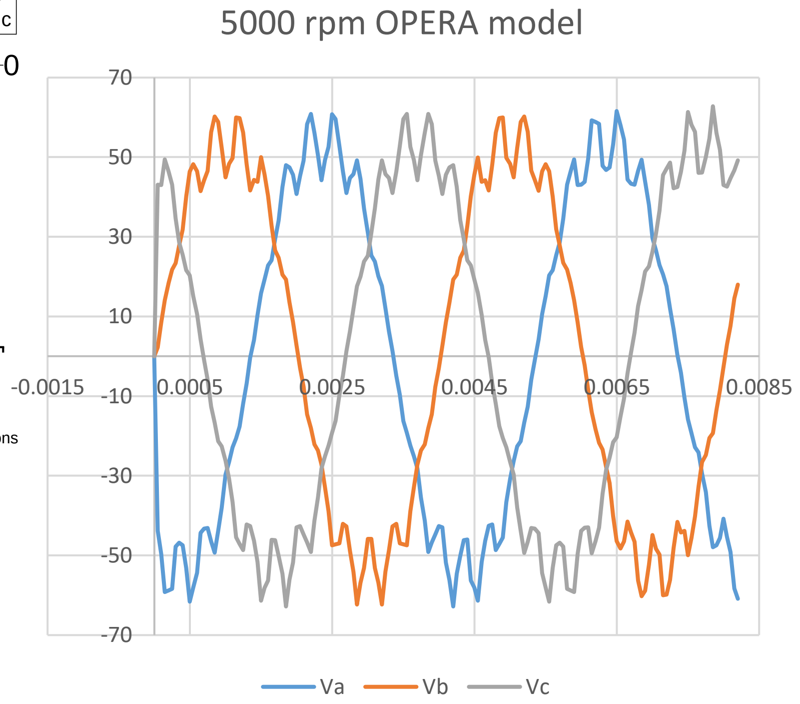
$$\Rightarrow \boldsymbol{X_s = 0.23\ \Omega}$$



1.1 High TRL AC Homopolar Generator - Testing

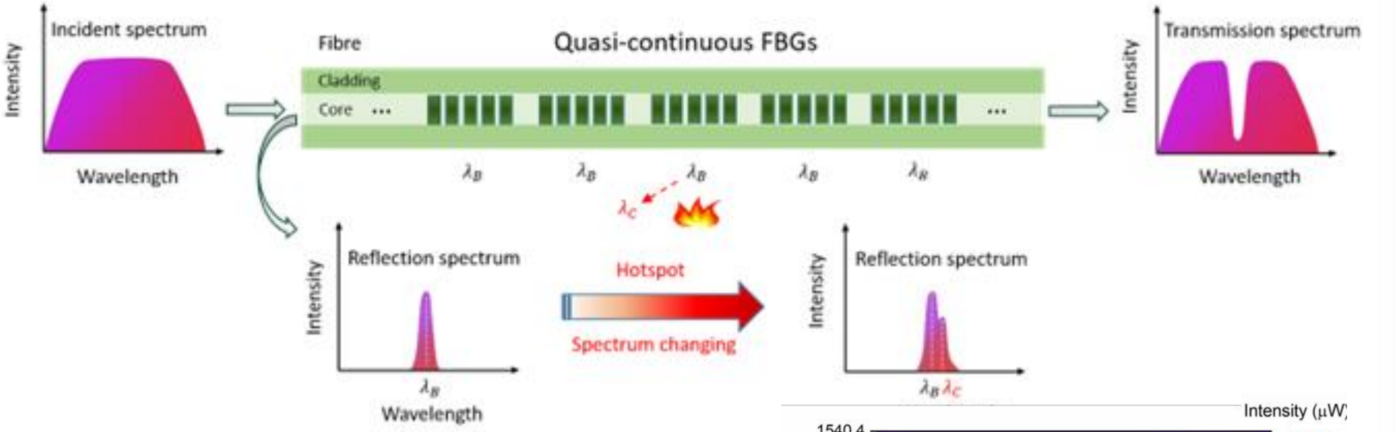
- Rotor being driven to **18,000 rpm**
  - World Record for HTS machine?
- Measured performance agrees closely with modelled and predicted performance
- IEE testing continuing
  - Although stator seems capable of far higher than design

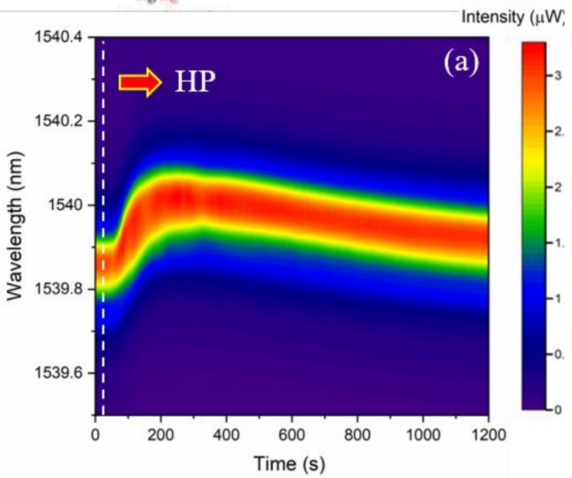




1.1 Quench protection in superconducting bus systems

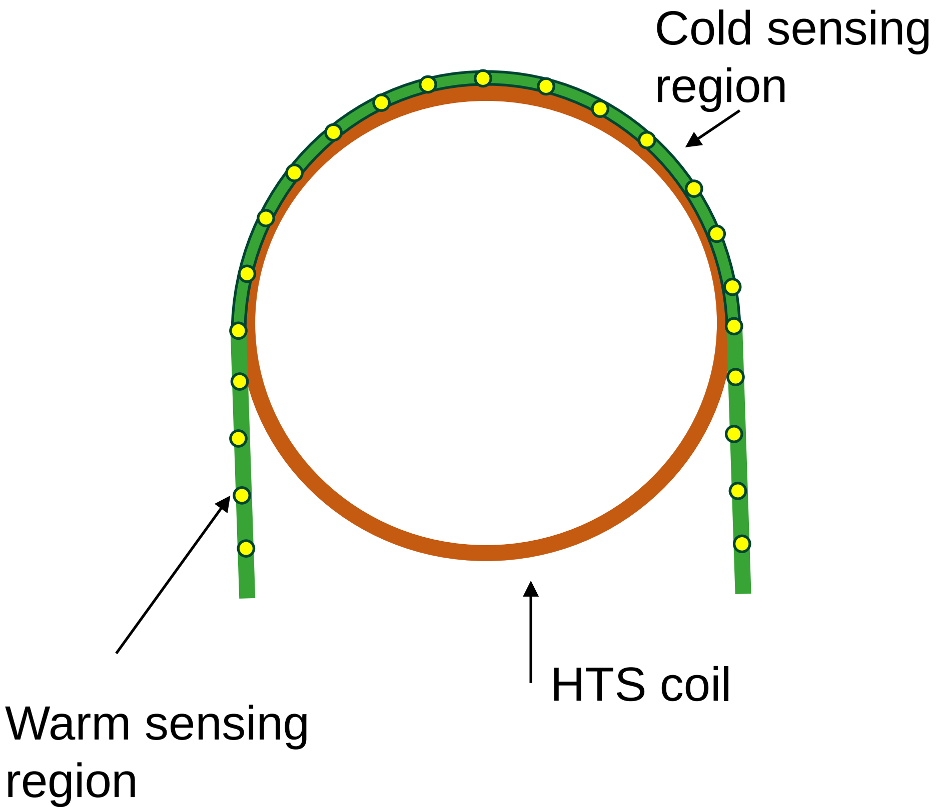
- Quench protection is very challenging using *conventional voltage tap methods*
  - Localised hot spots (normal zones) are slow to propagate
  - Voltage signal is slow to grow
- Local temperature quickly rises during a quench
  - Temperature sensors can potentially be used to detect hot spots early
  - Fibre Bragg gratings (sensors)
- Optical sensors can detect temperature rise rapidly enough to be useful for hot spot detection
  - < 0.3 seconds for a few K





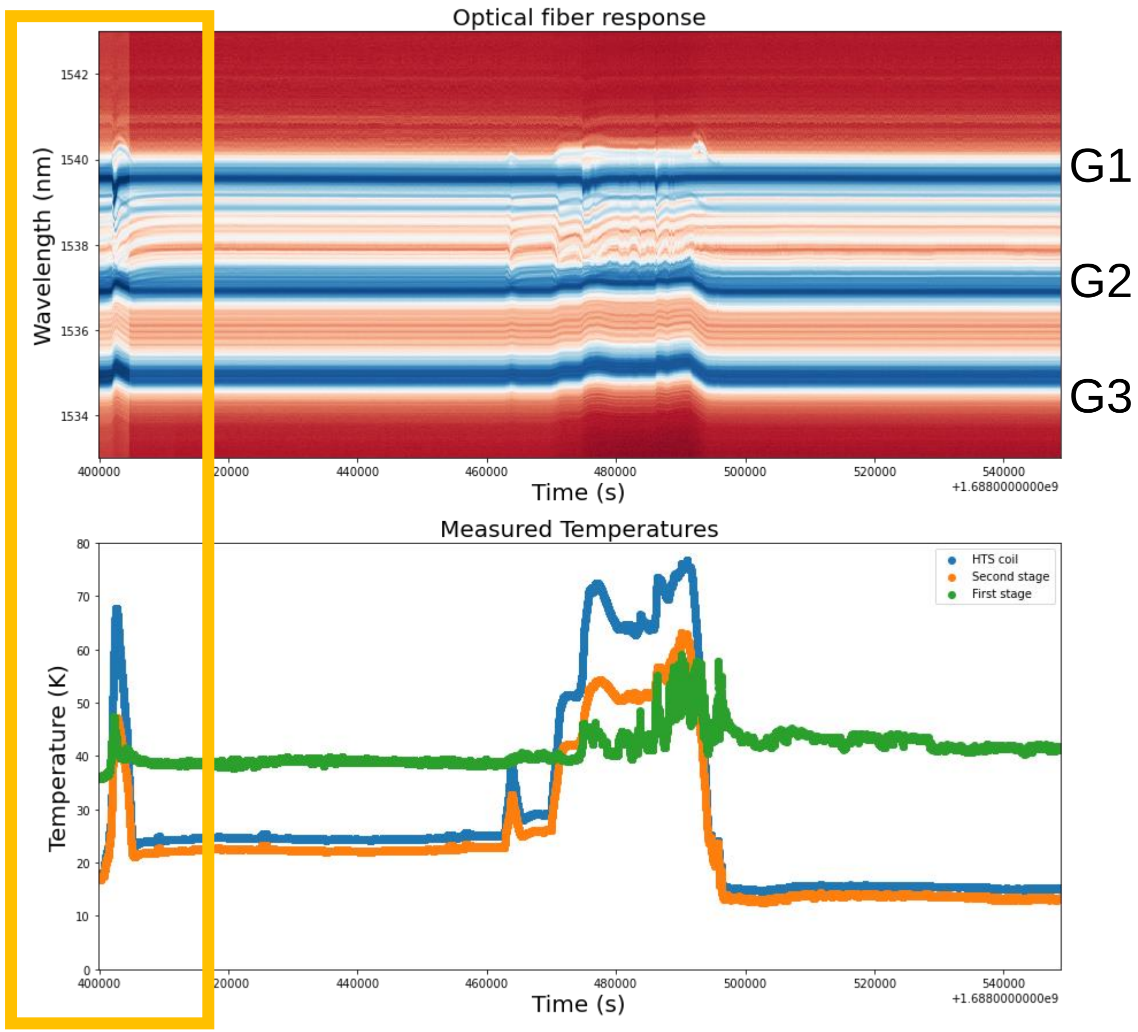
"Fiber optic quench detection for large-scale HTS magnets demonstrated on VIPER cable during high-fidelity testing at the SULTAN facility." https://doi.org/10.1088/1361-6668/abdba8
"Sensitive Fiber Optic Sensor for Rapid Hot-Spot Detection at Cryogenic Temperatures," https://doi.org/10.1109/JSEN.2022.3174894
"Evaluation of continuous fiber Bragg grating and signal processing method for hotspot detection at cryogenic temperatures." https://doi.org/10.1088/1361-6668/ac5d68
"Optimization of surface bonding methods for fiber Bragg grating sensors at cryogenic temperatures," https://doi.org/10.1016/j.yofte.2023.103419
"A novel algorithm for highly sensitive and rapid hotspot detection in HTS magnets using quasi-continuous fiber Bragg gratings," https://doi.org/10.1016/j.measurement.2023.112796

1.1 Quench protection in superconducting bus systems



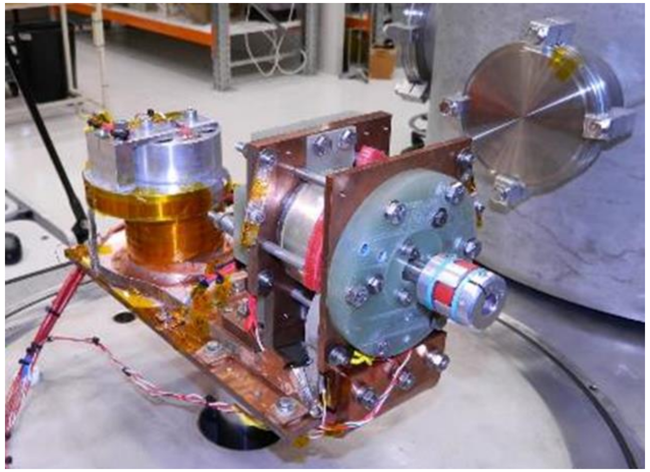
- cFBG installed with HTS coil
- Not all gratings are on the cooled section

1.1 Quench protection in superconducting bus systems - Heater tests



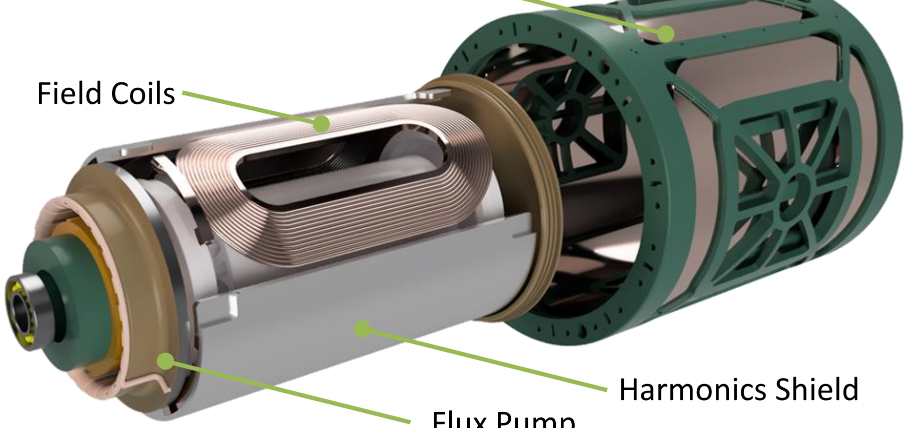
- System cooled to base temperature of ~15 K, then small heat load applied to coil
- The temperature response is clearly seen in the FBGs that are thermally and mechanically bonded to the HTS coil (G2 and G3)
- Clear response seen in optical data as temperature increases past ~30 K
- Analysis ongoing to find sensitivity limit

1.1 Aviation - Key enabling flux pump technology



- **Flux-pump**
  - 1000's of Amps in the palm of your hand
  - 90 % reduction in cooling system
- In aircraft, mass becomes important:
  - Mass of cryocooler
  - Mass of current sources
  - Mass of fuel
- Crucial to the global effort to develop superconducting propulsion

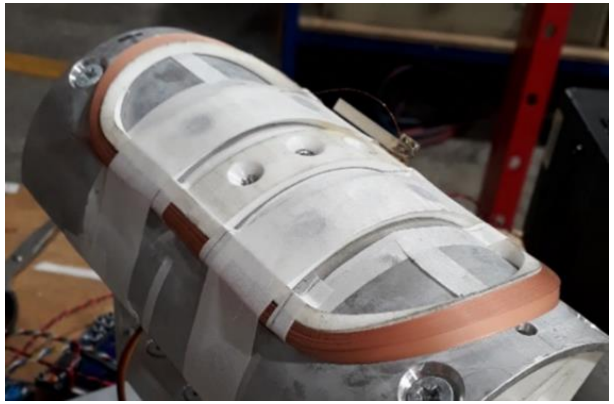
1.1 – 1.3 HTS Machines – Fully Superconducting

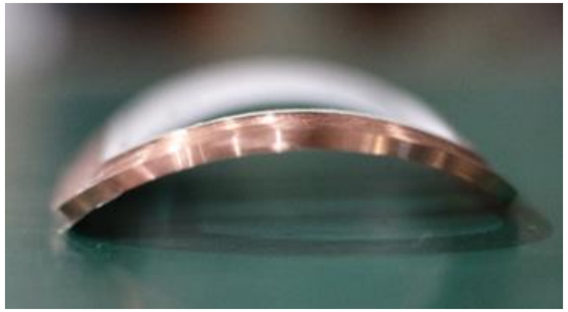


3 MW Aircraft Motor design is the focus

- Step 1: 4500 RPM, 100 kW Demonstrator
  - **High Specific Power: > 20 kW/kg including cryocooler**
  - $T_{amb.}$ = 300 K, power density = 27 kW/kg, Efficiency = 97.5%
  - $T_{amb.}$ = 120 K, power density = 29 kW/kg, Efficiency = 99.2%

- MgB_2 toothless saddle armature windings
- REBCO tape saddle coil field windings
- Several options for cryo-system including internal cryocooler, heat exchange to LNG and LH_2

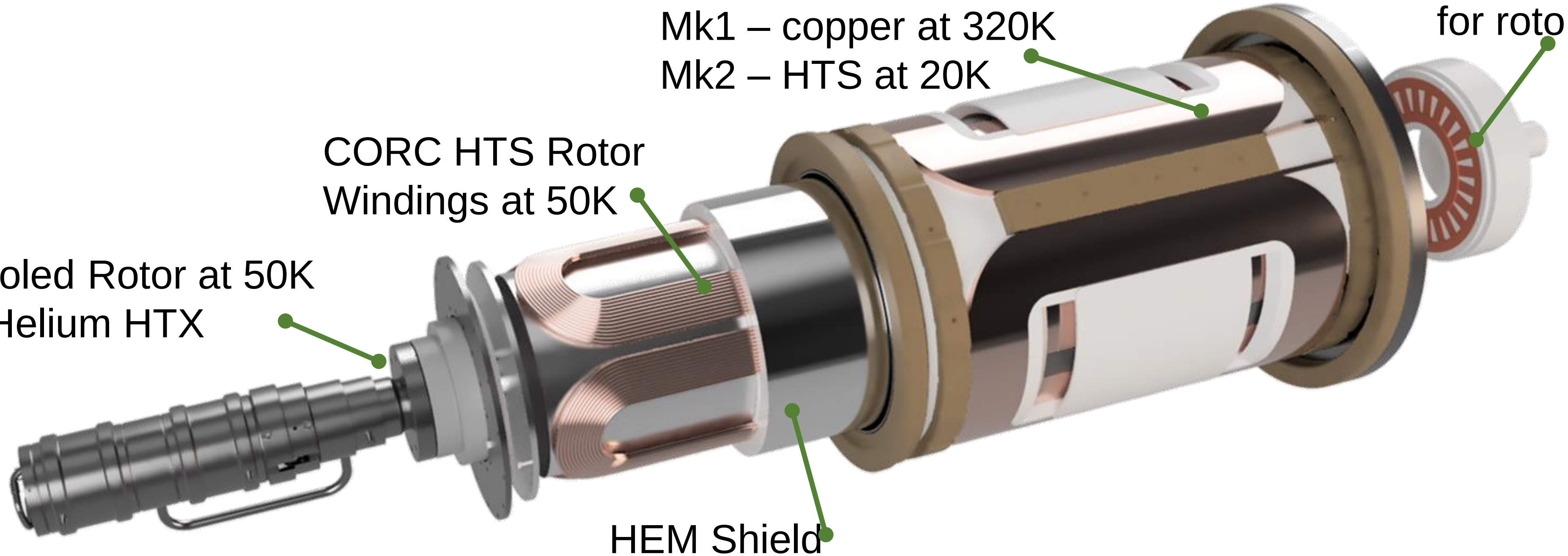




REBCO Tape saddle coils

S. S. Kalsi, R. A. Badcock, J. G. Storey, K. A. Hamilton and Z. Jiang, "Motors Employing REBCO CORC and MgB2 Superconductors for AC Stator Windings," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 9, pp. 1-7, Dec. 2021, Art no. 5206807, https://doi.org/10.1109/TASC.2021.3113574

1.1 – 1.3 100 kW technology demonstrator



Wadsworth, Aaron, Brandon Pais, Shaun Kyle, Duleepa J. Thrimawithana, Rodney A. Badcock, Andrew Lapthorn, Bill Heffernan, Rachel A. Oliver, David J. Wallis, and Martin Neuberger. "Evaluating Common Electronic Components and GaN HEMTs Under Cryogenic Conditions." In *2021 IEEE Southern Power Electronics Conference (SPEC)*, pp. 1-6. IEEE, 2021. https://doi.org/10.1109/SPEC52827.2021.9709441

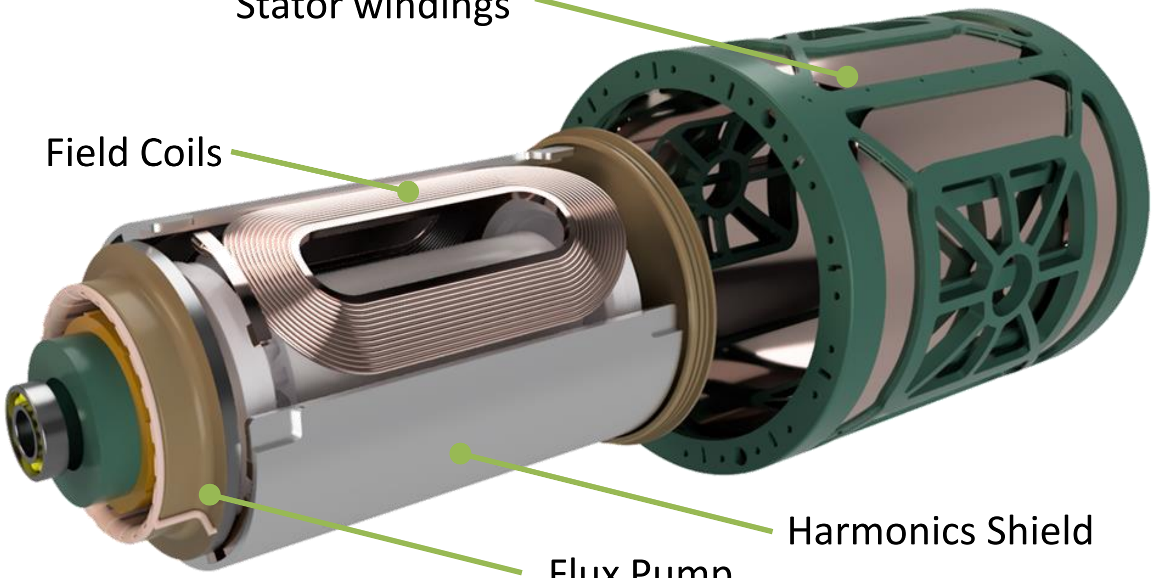
S. You, S. S. Kalsi, M. D. Ainslie, R. A. Badcock, N. J. Long and Z. Jiang, "Simulation of AC Loss in the Armature Windings of a 100 kW All-HTS Motor With Various (RE)BCO Conductor Considerations," in IEEE Access, vol. 9, pp. 130968-130980, 2021, https://doi.org/10.1109/ACCESS.2021.3114398

K. Hamilton, R. Mataira, J. Geng, C. Bumby, D. Carnegie and R. Badcock, "Practical Estimation of HTS Dynamo Losses," in IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 4703105, https://doi.org/10.1109/TASC.2020.2980830

1.2 HTS Machines – Material Challenges

- Several options for cryo-system including rotating cryocooler, heat exchange to LNG and LH_2
- MgB_2 Stator coils have target operating temperature of 20K
- Stator drives very high, alternating magnetic fields of order 1T at 150Hz
- Inductive heating at 20K would be a major issue for cryo-plant weight and power

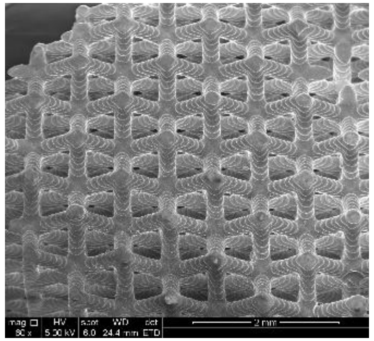
- Therefore – aim is to specify electrically non-conducting materials for the stator cryostat and structural components
    - Combination of traditional processes (filament wound, laminated and milled) and AM
    - Complex parts required to route cryogens, support windings and loads from vacuum insulation

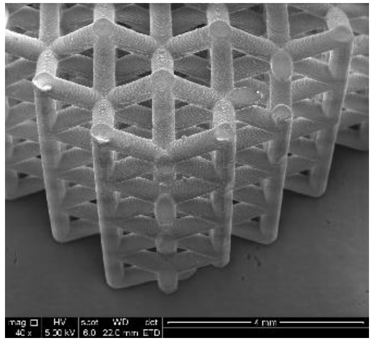


1.2 Additive manufacturing of refrigeration materials

Regenerator matrix printing

- Exploring regenerator matrix design that 3D printing now allows



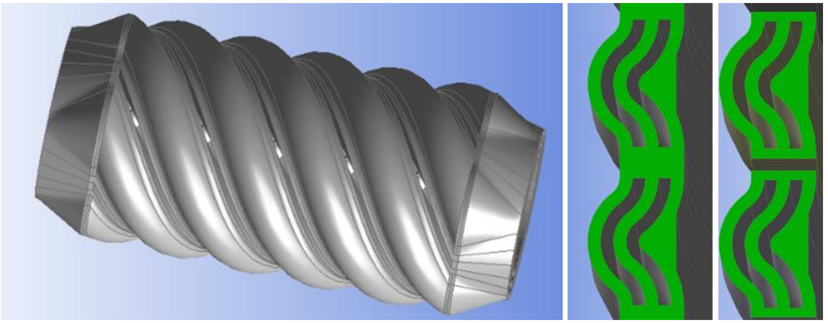


Cooling ramifications when we have LH_2 or LNG fuel

- Internal white paper on cooling of superconducting motors on aircraft

Counterflow recuperative spiral heat exchanger

- Designed an effective cryogenic coolant circulation system
  - Heat exchange from ~ 30 K to ambient temperature
  - Successfully fabrication by selective laser melting 316L stainless steel
- Confirms that better heat exchanger solutions are possible that stretch the limits of the complexity of forms using additive manufacturing

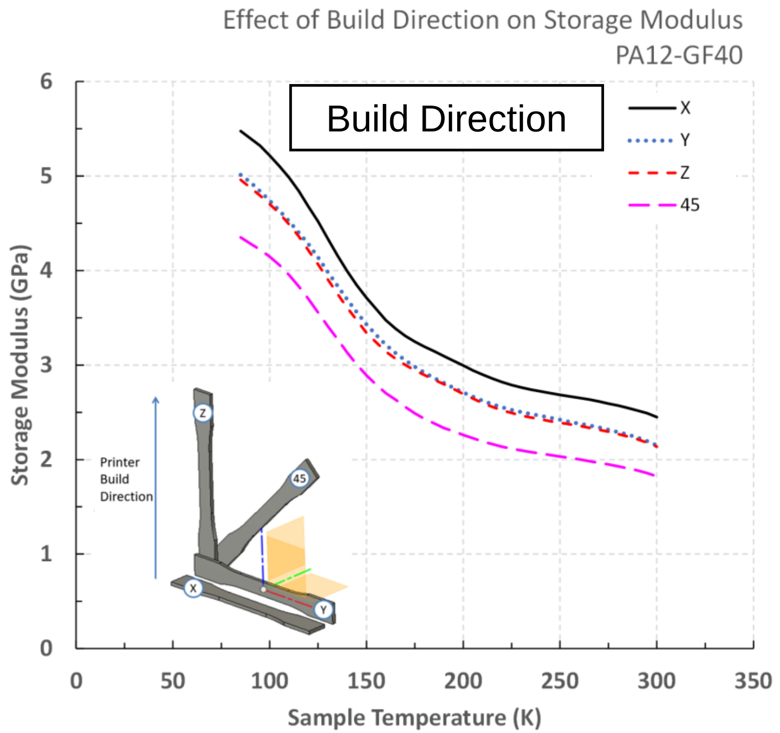


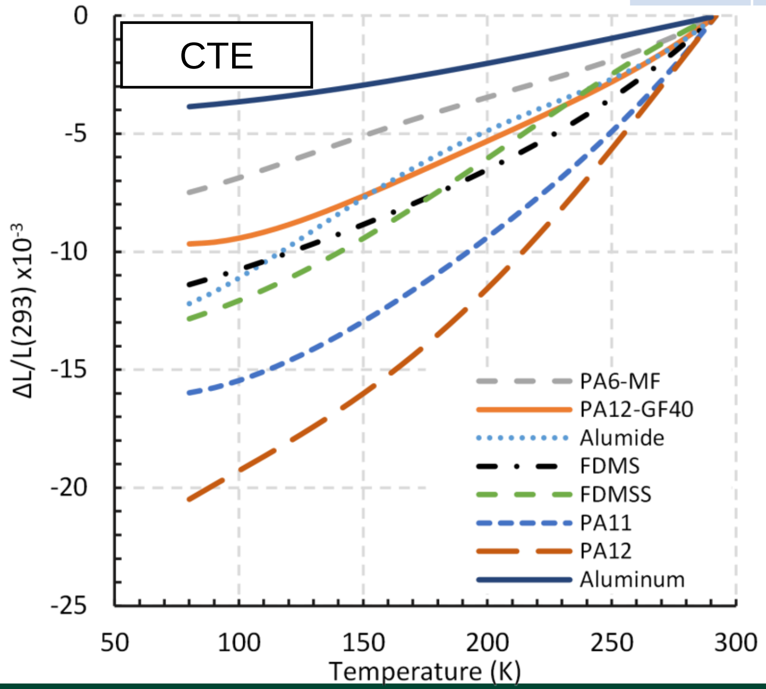
1.2 Additive manufacturing of cryogenic polymers

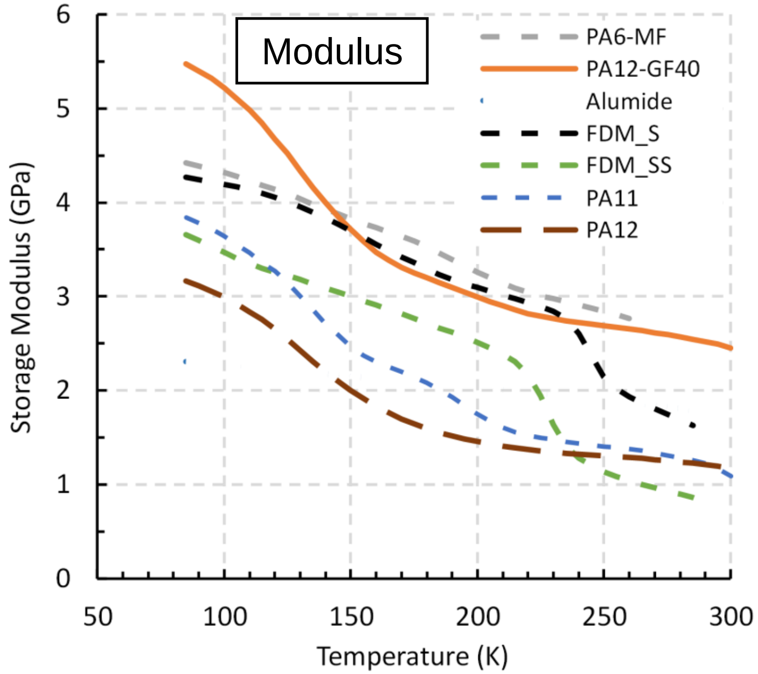
Highlights

- Cryogenic characterization of AM polymers
- Significant dataset developed on commercial polymer properties:
    - Modulus, tensile strength and CTE
- Informing 100kW prototype design

Item	Designation	Matrix Polymer	Filler	Process
1	PA12-GF40	PA12	Glass Powder	SLS
2	PA6-MF	PA6	Mineral Powder	SLS
3	PA12	PA12	None	SLS
4	PA11	PA11	None	SLS
5	Alumide	PA12	Aluminium Powder	SLS
6	FDMS	PLA	Iron Powder	FDM
7	FDMSS	PLA	Stainless Steel Powder	FDM

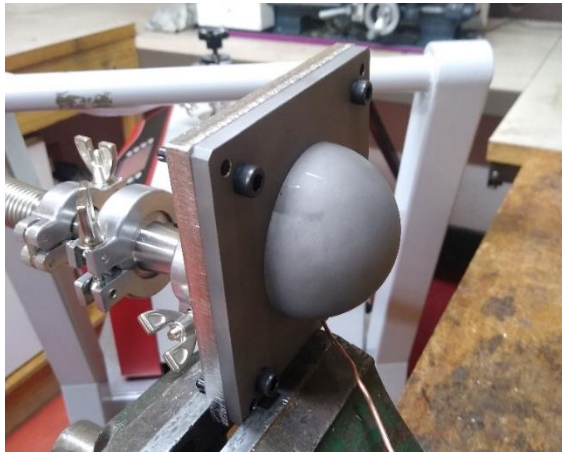






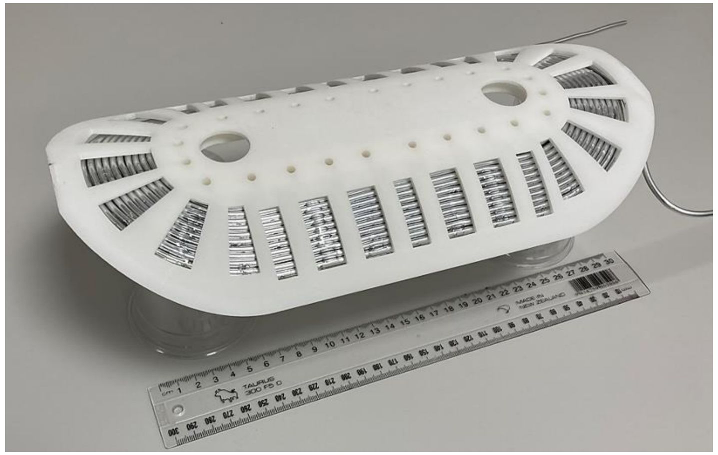
1.2 Additive manufacturing of cryogenic materials

- Developing a reliable library of material properties to inform engineering design of components for cryogenic electrical machines
  - Step 1: Evaluate materials available from commercial print agencies
- Already proving vacuum and Helium tight systems
- Future Work
  - We are hoping to work with other labs to develop a cross-checked data set to add confidence to our results
  - Motor design and development work is ongoing with further sub-system tests on AM parts underway



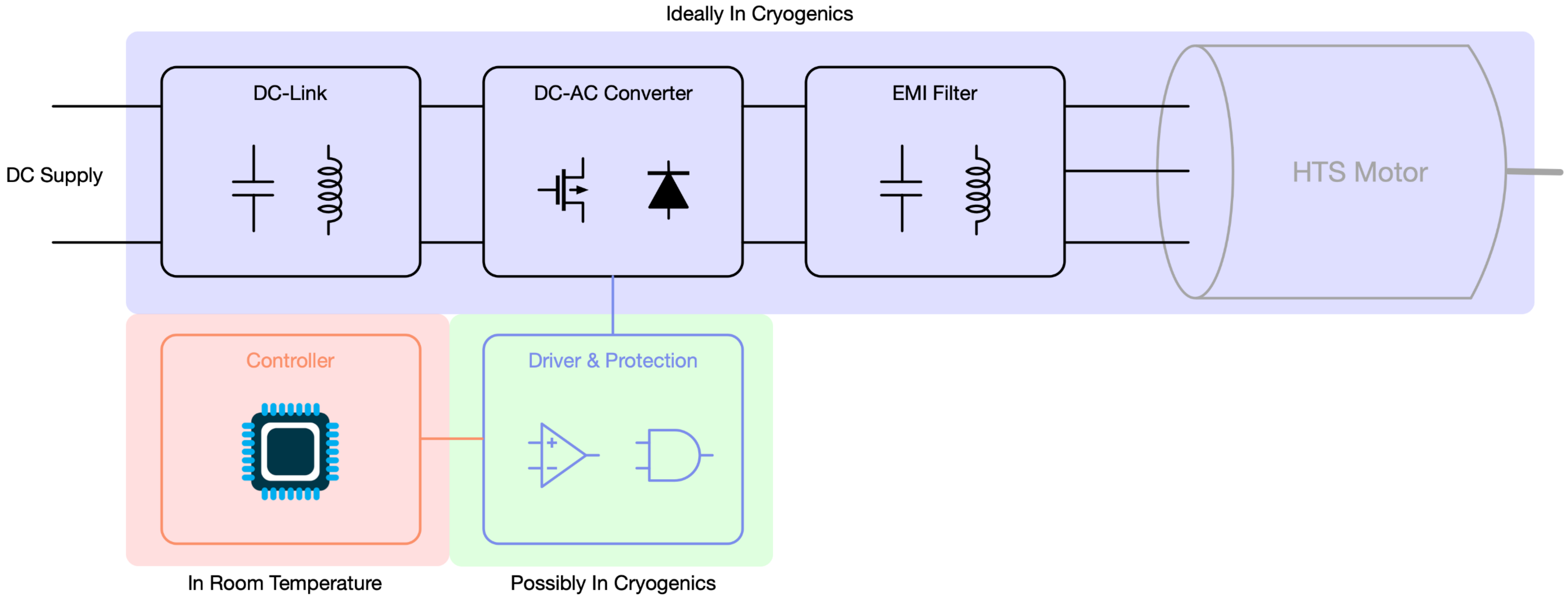
AM 2mm wall thickness SS316L dome test piece in helium-vacuum test rig

Sectioned components of AM stainless steel superconducting rotor cooling core



AM HTS coil pack former for cryogenic use

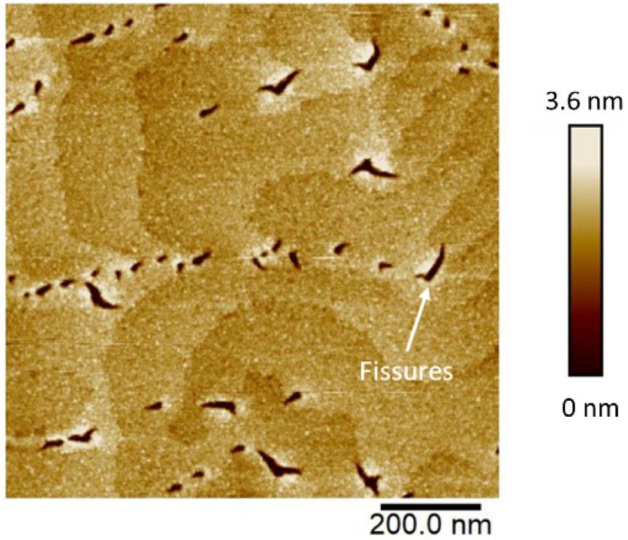
1.3 The Power Electronics Subsystem

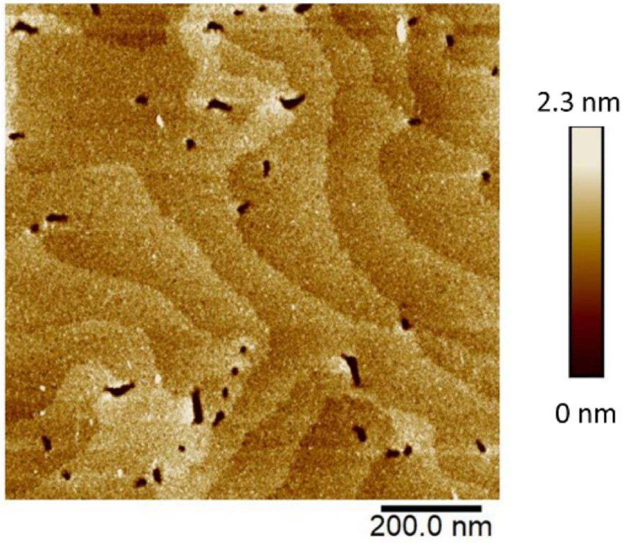


1.3 Cryogenically designed GaN devices

- Samples cycled between 340K to 80K
- Atomic force microscopy shows no significant change
- Suggests repeated thermal cycling does not damage the heterostructure

Before Thermal Cycling
Fissures = 1.05% ± 0.08%

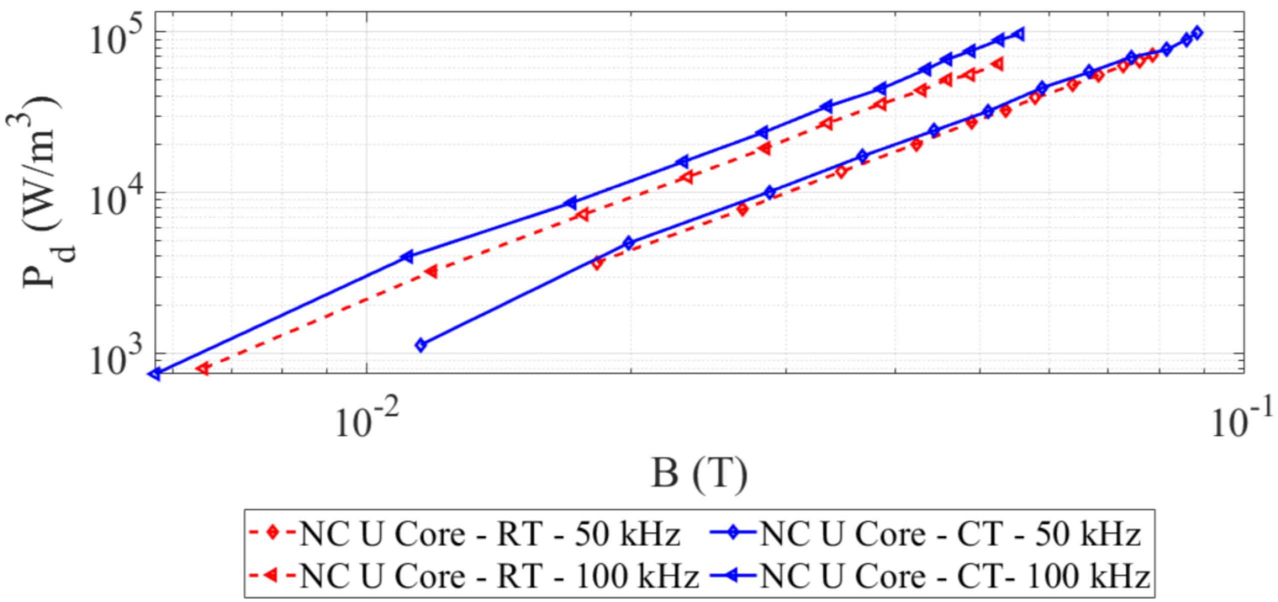


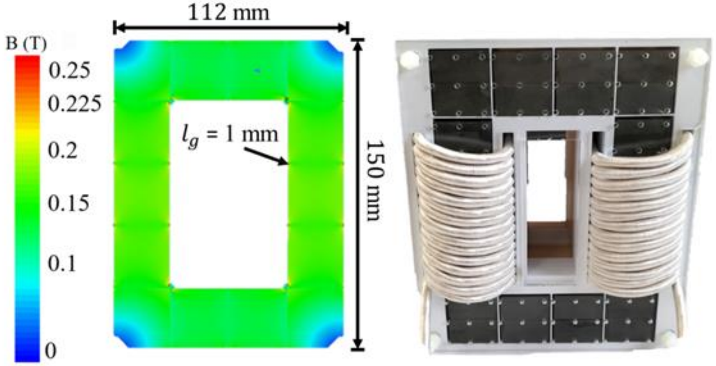


After Thermal Cycling
Fissures = 1.06% ± 0.07%

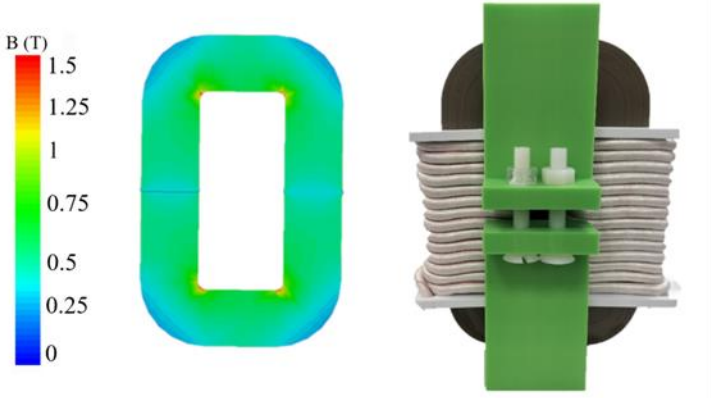
1.3 Cryogenic Cores

- Nanocrystalline core
  - Functions in cryo
  - Improves density
  - Slight loss in efficiency





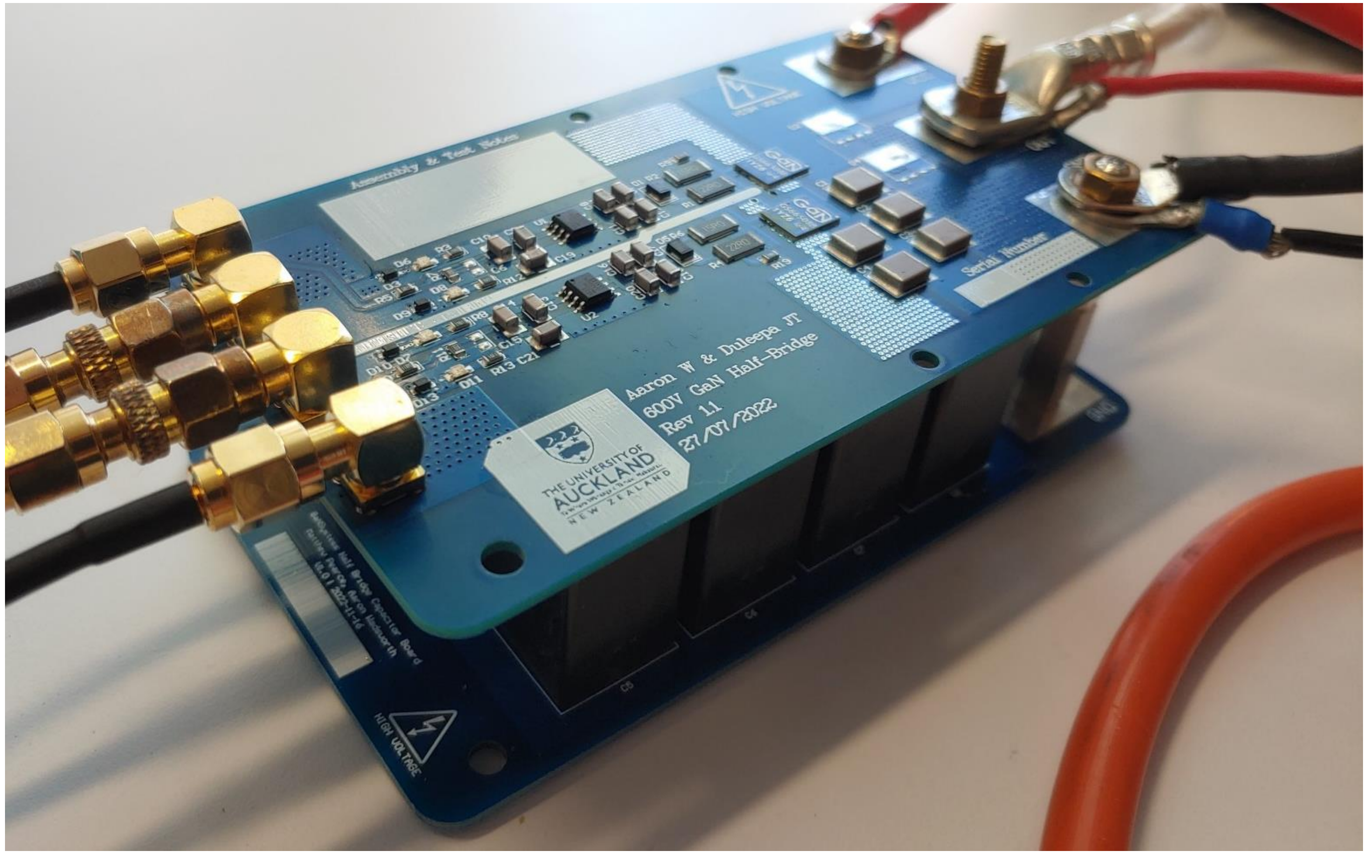
Ferrite Core (6kg/1170cm3)

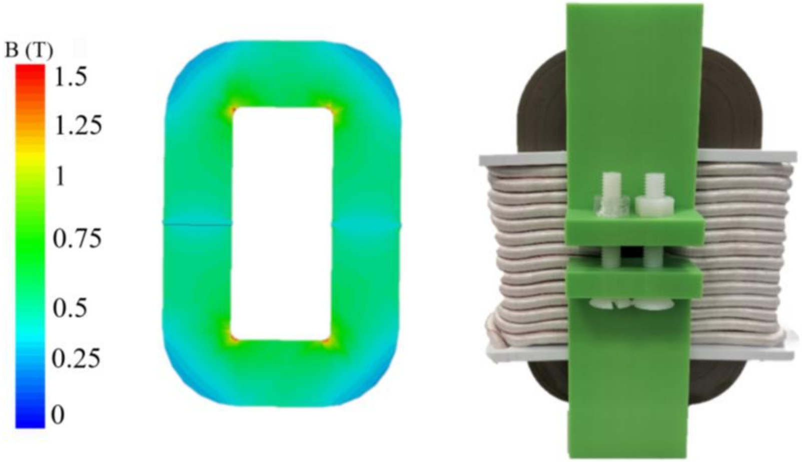


NC Core (2.8kg/380cm3)

1.3 Cryogenic GaN converter

- All power stage components including nanocrystalline magnetics in cryo

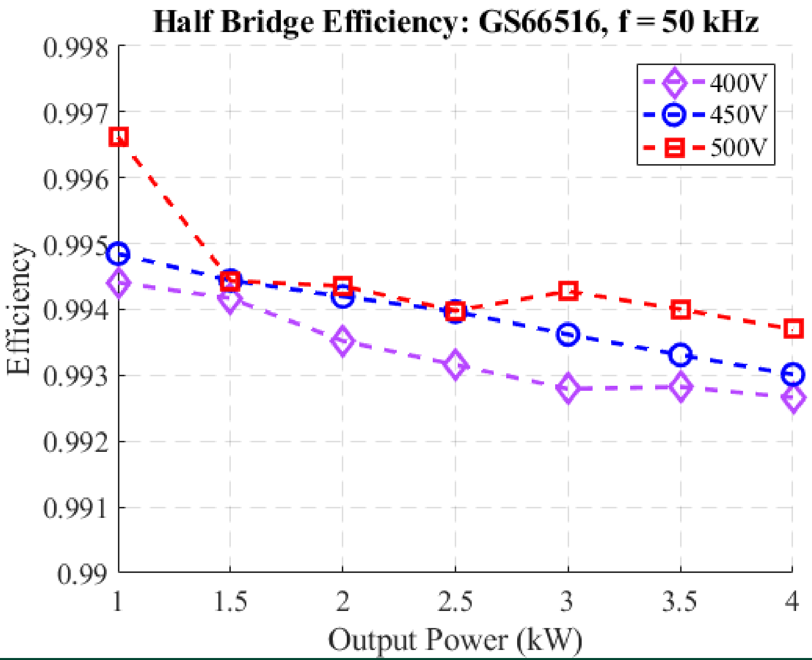




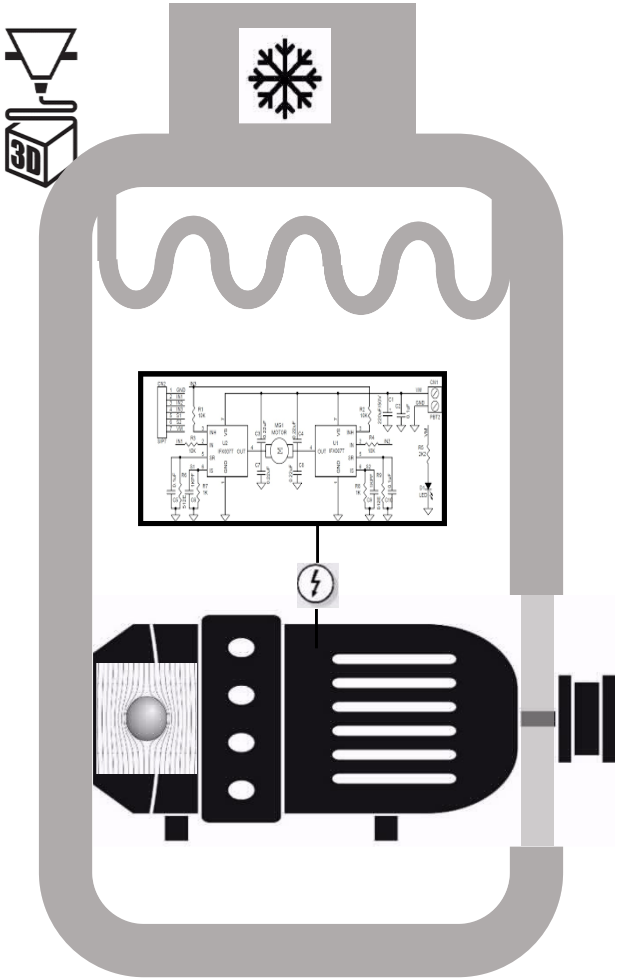
NC Core (2.8kg/380cm3)

1.3 Cryogenic electronics - GAN bridges

- GaN based half-bridge converters that operate under cryogenic conditions
  - 650V 60A
  - Employs drivers and passives that were identified to work under cryogenic conditions
- Tested each half bridge to 4kW at a switching frequency of 50 kHz
  - Peak efficiency of 99.38% recorded at 4kW for GS66516 board when using a 170uH inductor
- Continuing cryogenic litz wire characterisation and design …



Multidisciplinary system research at the leading edge



- **Fully Superconducting Machines**
  - New motor topologies combining HTS stator and rotor windings
- **Cryogenic Cooling Systems**
  - Optimized mechanical cryocoolers
  - Additively manufactured cryo-components
  - Whole-of-system modelling
- **Lightweight Power Electronics**
  - New concepts for size and weight optimization:
  - GaN-based cryogenic electronics
  - Packaging/interconnects, and cooling options.
- **Industry-ready Training Strategies**

Summary

- We are chasing challenges that can apply to all rotating machines
  - Cryogenic heat exchangers and power electronics
  - Reliable superconducting motors
  - 1000 Amp power supplies needing only a few watts input
  - Safety systems
  - AC loss modelling tool
    - Reliable prediction and manufacturing of motors
- We want to raise TRL of whole propulsion system - then will cryo-electric planes fly
  - Already running a high speed generator / motor using high reliability HTS magnet
  - There are so many opportunities to accelerate technology implementation and adoption
- We are *making it happen* – would love to collaborate more widely
  - We need to work together to solve the global challenge we face
  - The New Zealand Government, Air New Zealand, Civil Aviation Authority, Researchers and technology developers *****want***** to work with you


36th International Symposium on Superconductivity
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ISS2023 aims to gather many scientists, engineers, academic students, corporate executives and other participants from all over the world, and to facilitate fruitful discussions for the promotion of superconductivity technologies.
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