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Invited presentation J3Or1A-03 given at CEC-ICMC 2021, July 19-23, 2021, Virtual.

Paihau—Robinson Research Institute

VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA

High power density electric motors for large-scale transport

R.A. Badcock, H.W. Weijers, A. Caughley, K. Hamilton, D. Thrimawithana, A. Lapthorne, S. Singamneni, G. Lumsden

July 2021

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

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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

1.1 Superconducting Machines

- Victoria University of Wellington – Te Herenga Waka
- The University of Auckland – New Zealand
- Kyoto University
- KGPS

1.2 Cryogenic Systems

- Victoria University of Wellington – Te Herenga Waka
- KAIST
- Callaghan Innovation – New Zealand's Innovation Agency
- AUT

1.3 Power Electronics

- The University of Auckland – New Zealand
- Victoria University of Wellington – Te Herenga Waka
- UC University of Canterbury
- University of Cambridge

Training – Industry-Ready Capability

- Ara Institute of Canterbury
- Manukau Institute of Technology – Te Whare Takiura o Manukau
- UC University of Canterbury

The AETP Programme – Connected and Engaged

everson tesla incorporated

AIR NEW ZEALAND

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

Raytheon Technologies

Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives ASCEND

soundsAIR

AIR FORCE RESEARCH LABORATORY

AFCRYO CRYOCOOLER MEMBRANE TECHNOLOGY

Hyper Tech Research, Inc.

BOEING

HTS-110

FABRUMSOLUTIONS

AIRBUS

AuCom THE SOFT START SPECIALISTS

ABB

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

ENPHASE

llama ENGINEERING

WiTricity® Powering life, wirelessly.

KGPS

Victoria University Wellington – Superconducting Application Team

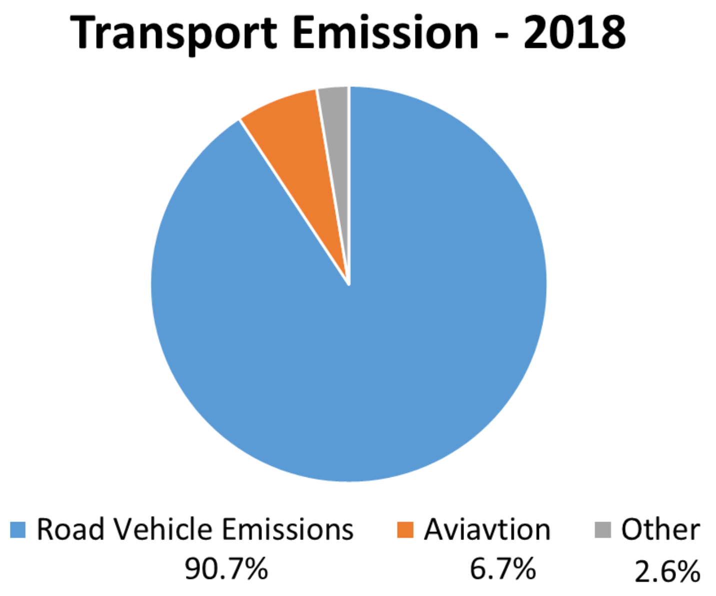
Lead Agency: Robinson Research Institute

An applied science and engineering institute

Professional team that have gained New Zealand a reputation for excellence in the application of superconductivity for MRI, Electrical Machines, Magnets and Space

New Zealand Context

- 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



- **Electric aviation could make an enormous impact on our fuel imports and greenhouse gas emissions**
  - What power do we transfer? How do we store the energy?

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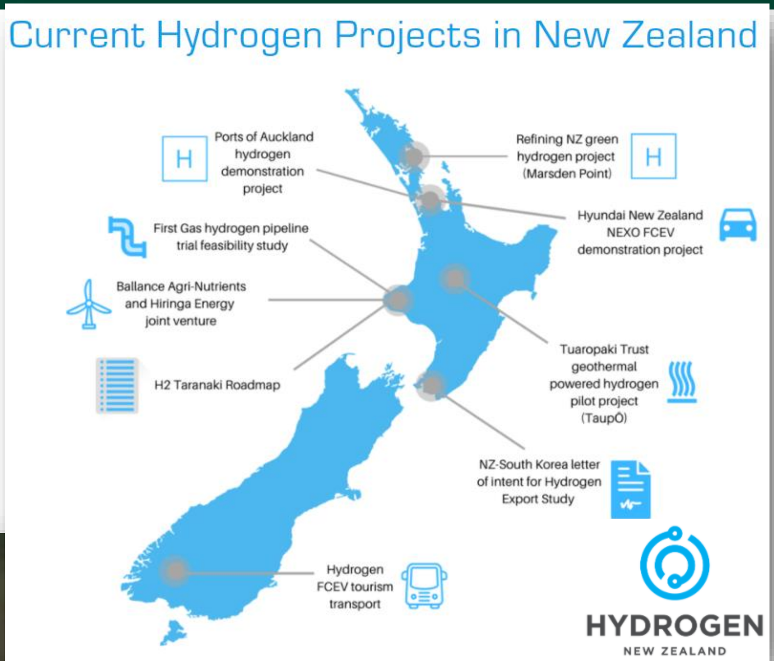
Will electric aviation also use hydrogen?



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The AETP Programme – Workstreams

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

1.1 Superconducting Machines
Victoria University of Wellington Te Herenga Waka; The University of Auckland, New Zealand; Kyoto University; KGPS

1.2 Cryogenic Systems
Victoria University of Wellington Te Herenga Waka; KAIST; Callaghan Innovation – New Zealand's Innovation Agency; AUT

1.3 Power Electronics
The University of Auckland, New Zealand; Victoria University of Wellington Te Herenga Waka; UC University of Canterbury; University of Cambridge

Training Industry-Ready Capability
Ara Institute of Canterbury; Manukau Institute of Technology; UC University of Canterbury

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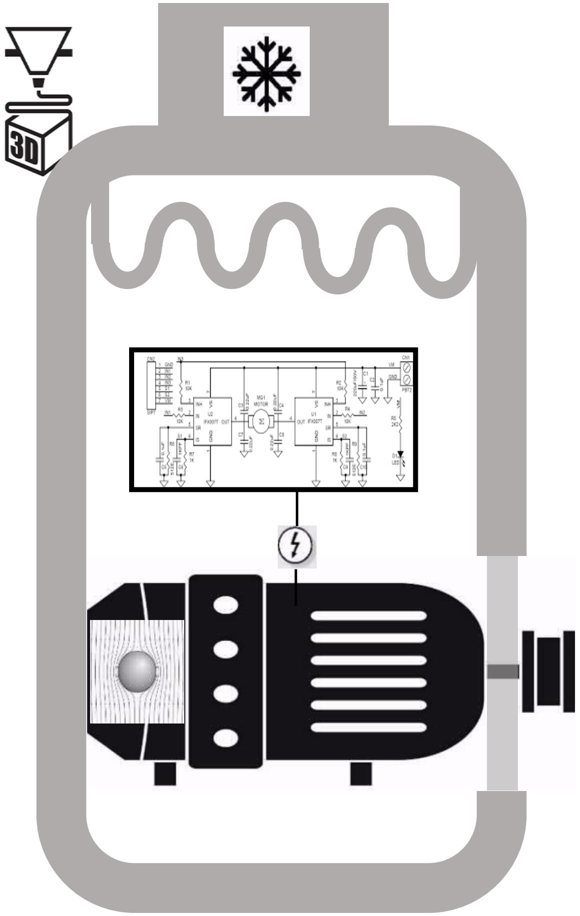
AETP - Multidisciplinary research at the leading edge



Technology problem
Low weight, high-power optimization for whole system

1. **Fully Superconducting Machines**
- new motor topologies combining HTS stator and rotor windings

2. **Cryogenic Cooling Systems**
- optimized mechanical cryocoolers
- additively manufactured heat exchangers
- whole-of-system modelling

3. **Lightweight Power Electronics**
- new concepts for size and weight optimization:
- GaN-based cryogenic electronics
- packaging/interconnects, and cooling options.

4. **Industry-ready Training Strategies**

The AETP Programme – Workstreams

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Training Industry-Ready Capability
- Ara Institute of Canterbury
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- UC University of Canterbury

The AETP Programme – Workstream 1

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

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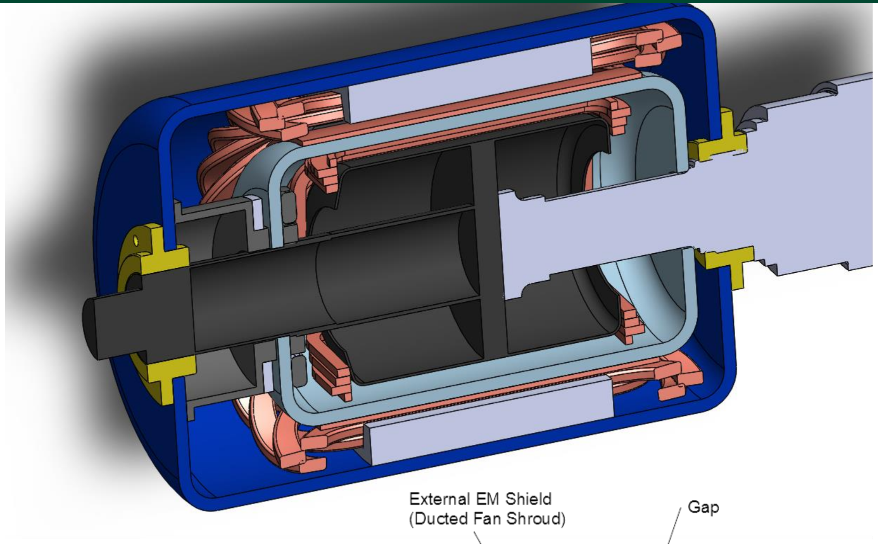
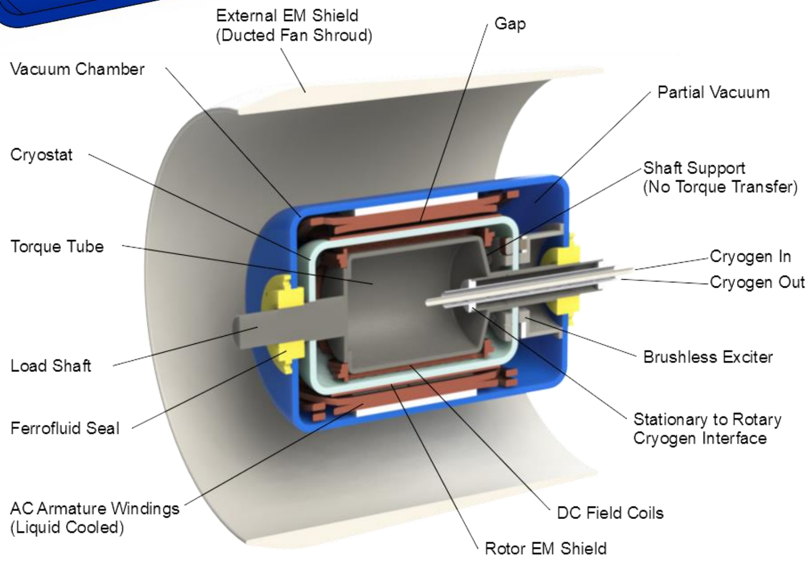
HTS Machines – Fully Superconducting

3 MW Aircraft Motor design

- 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





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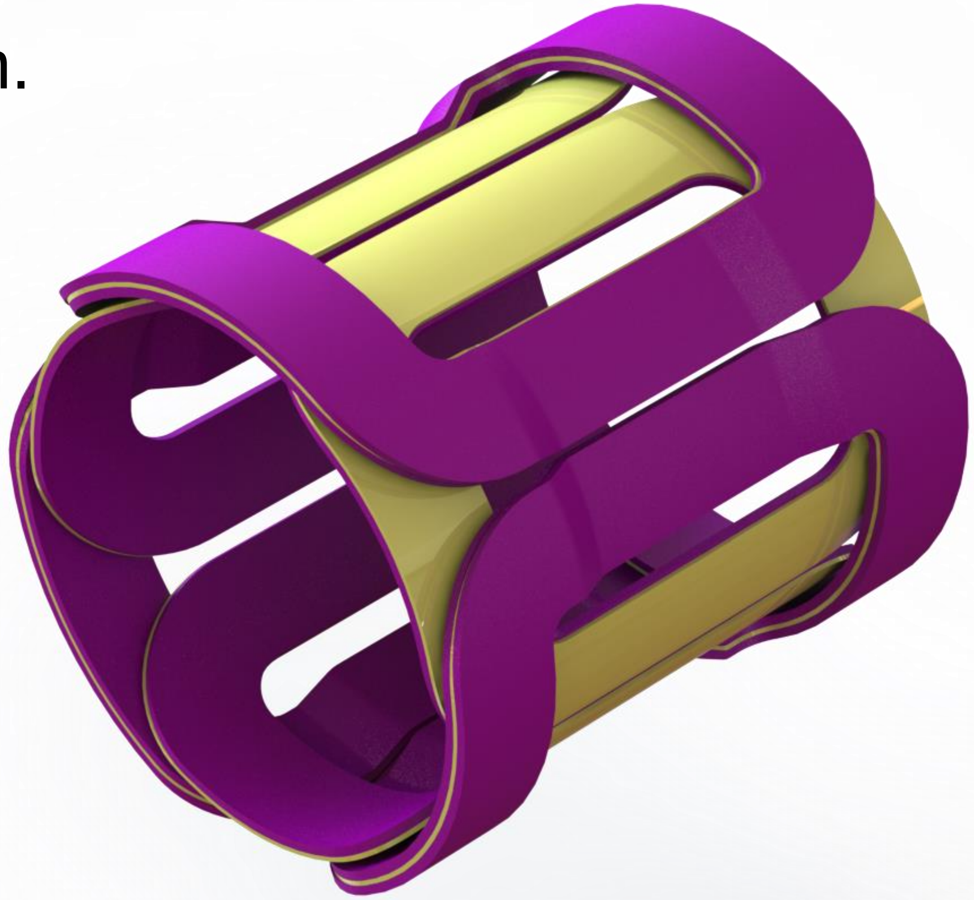
Stator Optimisation - MgB_2 Armature Windings

- Continuous stator toothless design.
- Small outer radius.
- High current density.
- High magnetic field output.
- Low AC Loss.
- Iron teeth not required.



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HTS Machines - High TRL AC Homopolar Motor

- High speed: 20,000 – 30,000 RPM.
- Non-rotating HTS field coils.

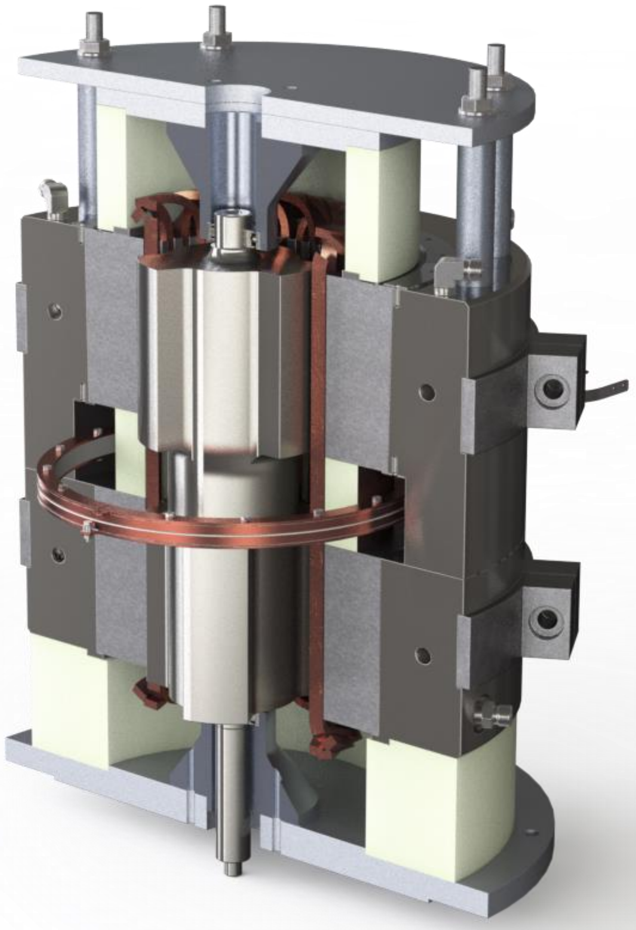
- Flux pump demonstrator.
- HTS Dynamo demonstrator.
- Fibreoptic monitoring demonstrator.

HTS Machines - High TRL AC Homopolar Motor

Homopolar architecture:

- Single piece steel rotor.
- Stationary ReBCO Coil.
- Partially laminated steel stator.
- Hybrid ceramic vacuum bearings.
- Ferrofluid vacuum coupling.

Non-rotating HTS coil eliminates complicated cryogenic and high current rotating connections.



Superconducting Flux Pumps

- **Flux Pumps energise superconducting circuits *wirelessly*.**

- ***Motivation***:
  - How significant are the motor performance improvements when using flux pumps to supply motor field coil current?
  - Build flux pumps as current supplies for superconducting motors in marine and aerospace applications.

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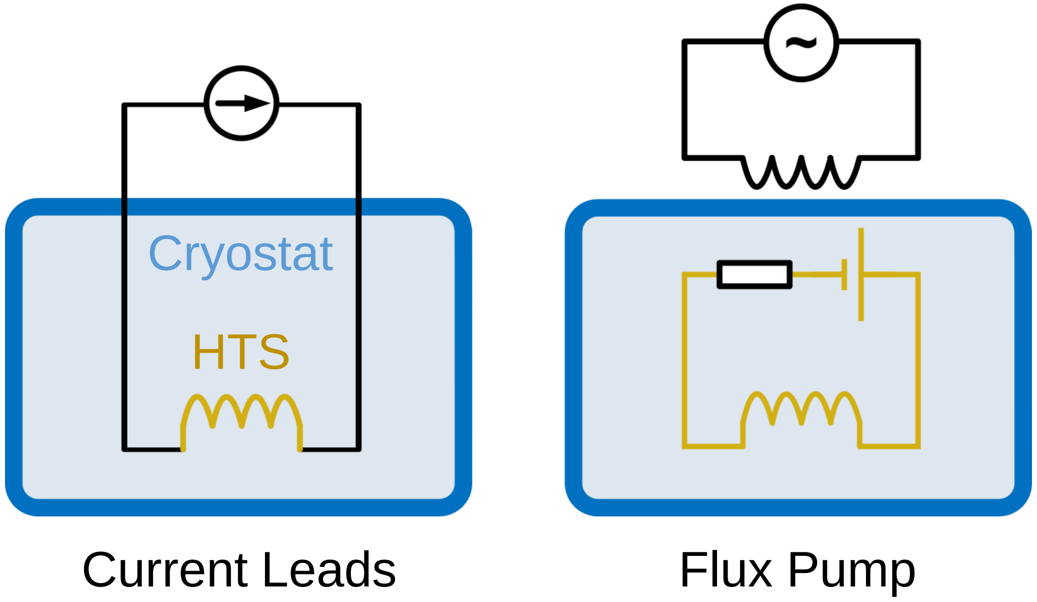
Superconducting Flux Pumps

- Fully superconducting power supplies.
- Kiloamp current output demonstrated.

- **No feedthrough:**
  - Power supplied wirelessly through the cryostat wall with no thermal conduction.
- **Quasi-persistent HTS circuit current:**
  - Constant HTS current operation only requires small power input to flux pump.
- **Reduction in Cryogenic Load:**
  - No thermal conduction path.
- **Rotating (HTS Dynamo) or solid state.**



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Superconducting Flux Pumps

- **HTS flux pump**
  - **Travelling wave flux pump**
    - HTS dynamo
    - Linear travelling wave flux pump
  - **Transformer-rectifier**
    - Circuit topology
      - Half-wave
      - Full-wave
    - Switching
      - Thermal (same as LTS rectifiers)
      - AC field
      - Self-switching
      - Power electronic switches (technically not a flux pump)

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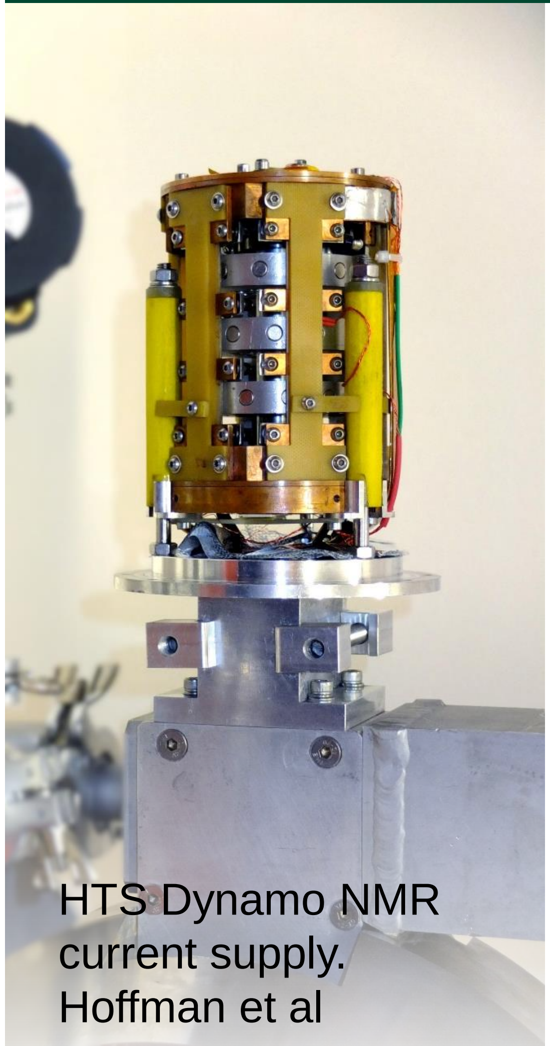
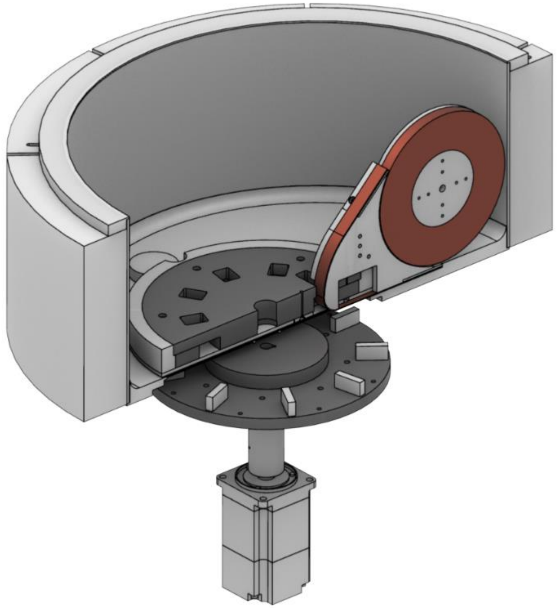
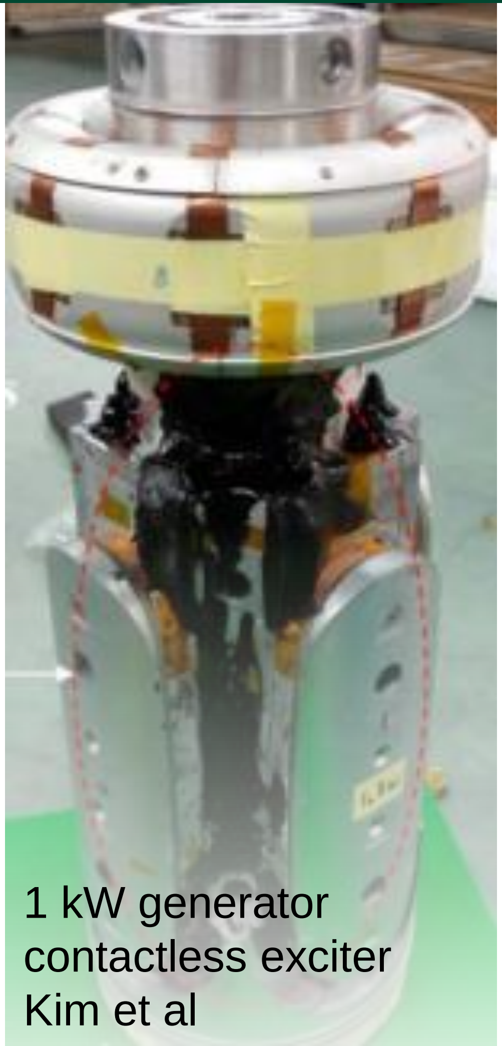
Superconducting Flux Pumps – Dynamos



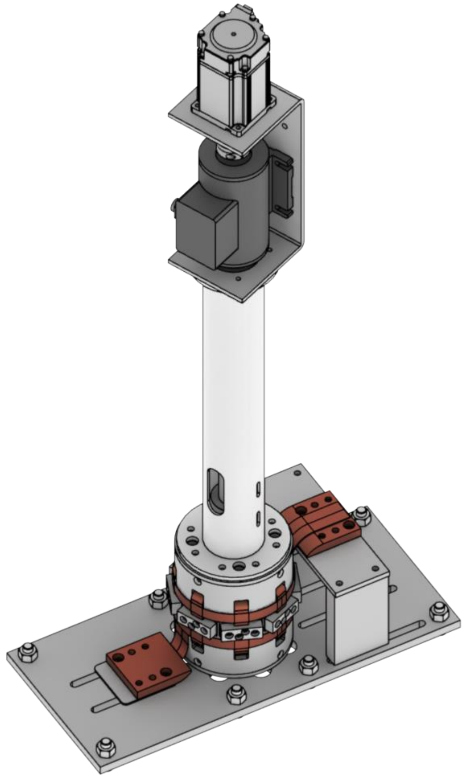
HTS Dynamo NMR current supply.
Hoffman et al



Through cryostat wall HTS Dynamo.
Bumby et al



1 kW generator contactless exciter
Kim et al

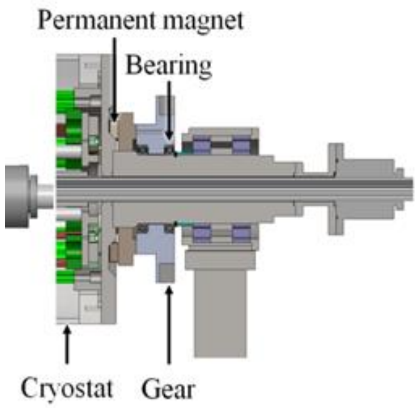


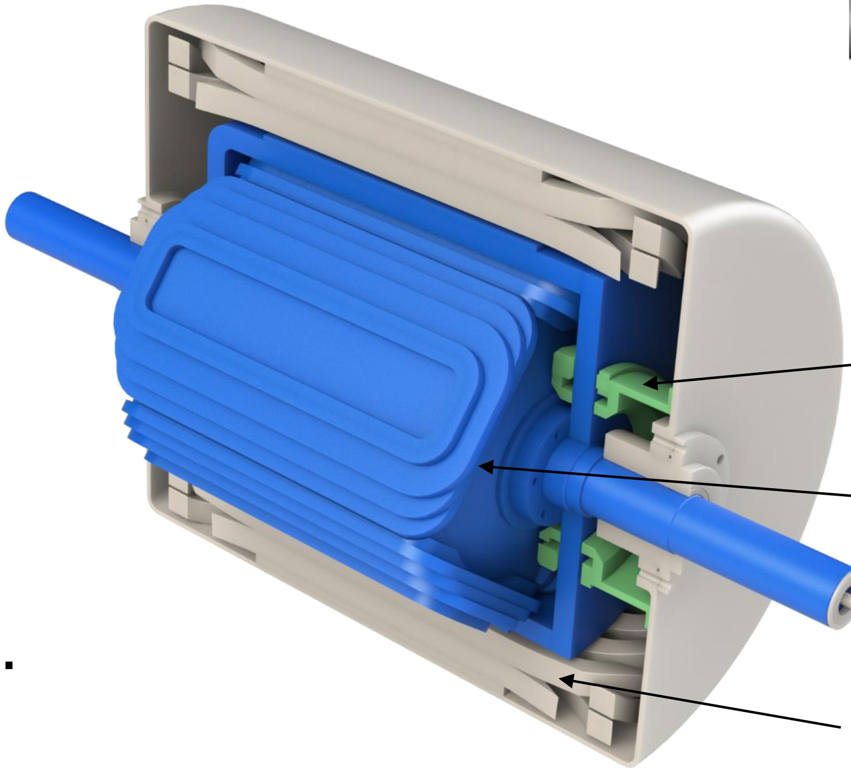
Kiloamp Squirrel Cage HTS Dynamo
Hamilton et al

Superconducting Flux Pumps – for Aircraft

- Dynamo design
- Wireless energisation of superconducting coils.
- Current delivery across rotating joint.

- Well suited to motors with superconducting field coils.
- Miniature PSU.

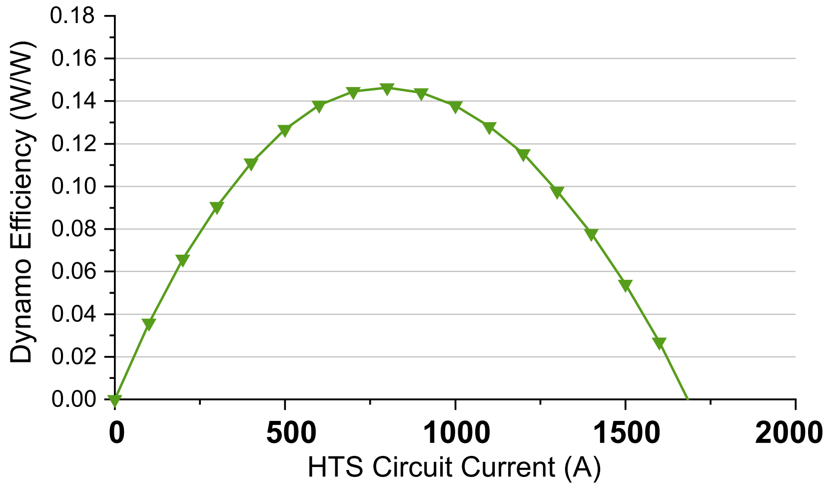




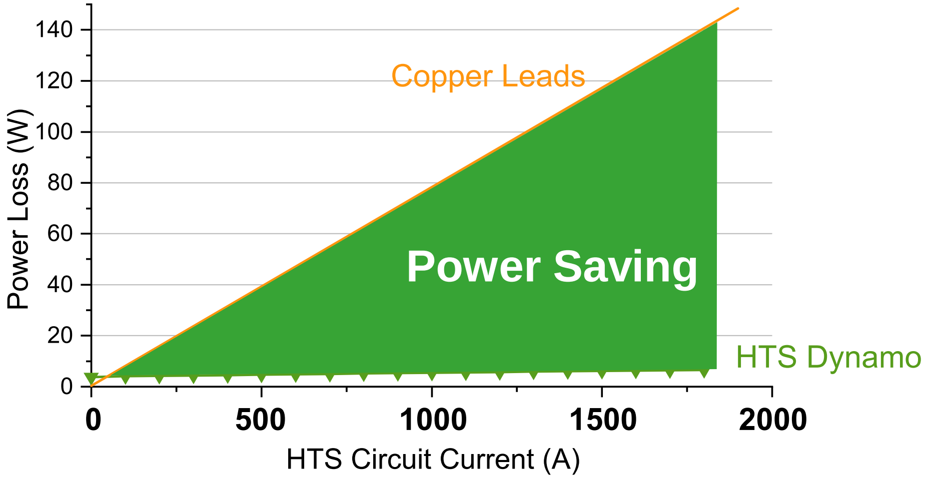
Hamilton, K et al. - Practical Estimation of HTS Dynamo Losses – DOI: 10.1109/TASC.2020.2980830

Superconducting Flux Pumps – for Aircraft

- Measured HTS Dynamo performance:
  - Low losses compared to copper leads.
  - Low weight compared to DC supply.
  - Loss remains low at high current.
  - Weight remains low at high current.



- In aircraft, weight becomes important:
  - Low loss = Low cryocooler load and weight.
  - Low loss and low weight = Reduced fuel use.



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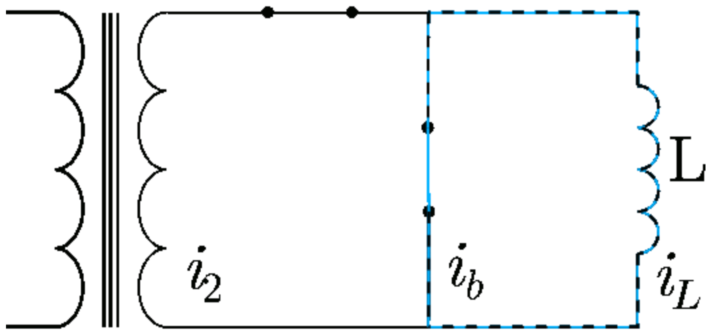
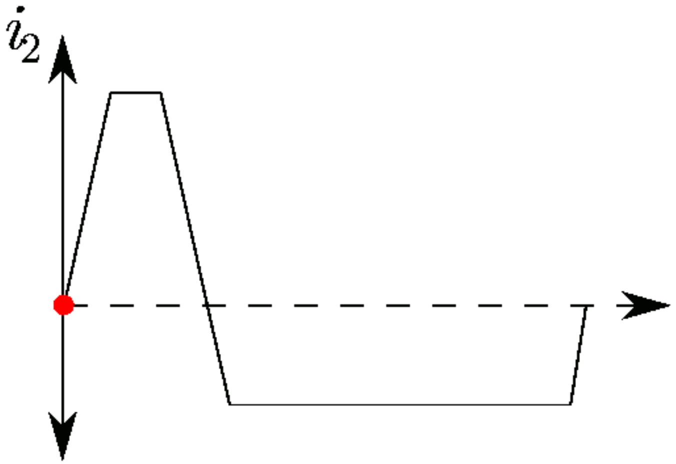
Superconducting Flux Pumps – Solid State

Transformer-Rectifier

- AC current -> DC voltage rectifier
- Switching by variable resistance [2]
- Superconducting properties provide voltage

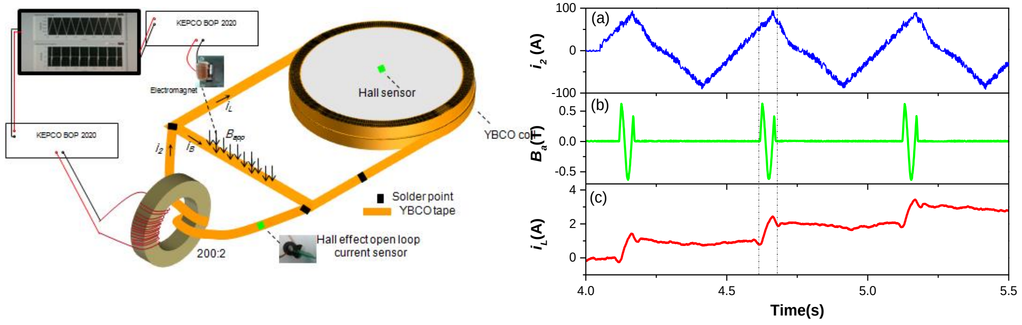




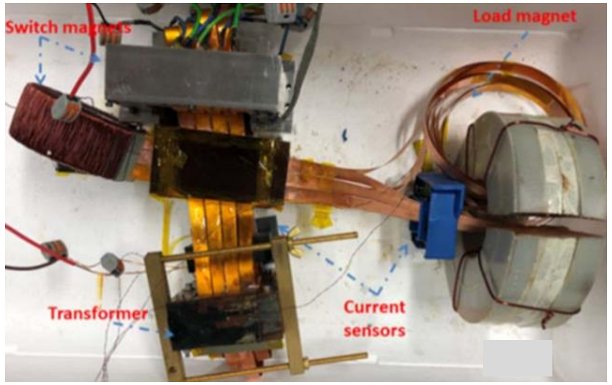
[2] J. Geng *et al, Appl. Phys. Lett.*, **108** (26), 262601 (2016).

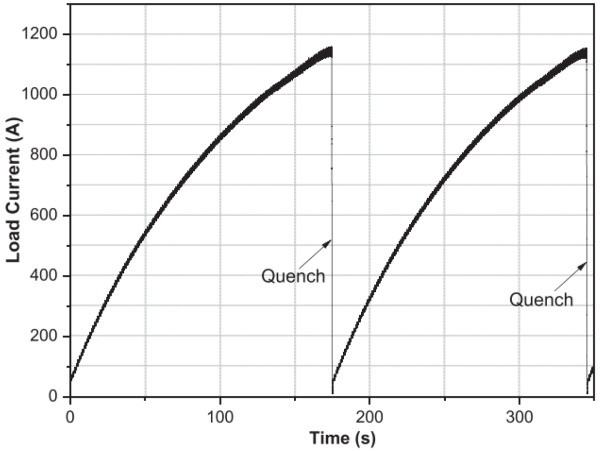
Superconducting Flux Pumps – Solid State

AC field switched rectifiers



First field switched HTS rectifier [1]





First reported HTS rectifier that exceed 1 kA [2]

The device uses ac field to generate dynamic resistance in the superconducting switches, achieving accurate flux pumping.

[1] Geng et al, 107 (14), 142601, 2015
[2] Geng et al, SUST 32 (7), 074004, 2019

Stator Optimisation - Research Aims

- Demonstrate and test low-loss twisted MgB_2 and Bi2212 superconducting wires incorporating ultra-fine (~20 um) filaments.
- Develop new finite element modelling techniques to predict the AC stator losses in a synchronous superconducting motor, and validate through experimental measurements of stator windings.
- Design a concept first-in-world fully superconducting synchronous machine (targeting 3 MW, 4 pole, 4500 rpm); and, for the first time, build a 100 kW all-superconducting machine.
- Test the dynamic performance of an experimental-scale (< 500kW) motor at the CHEETA test pit at University of Illinois and the AFRL high dB/dT spin test rig in Dayton Ohio.

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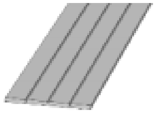
Loss Measurements

Reducing AC loss in stator windings is one of key issues to achieve practical fully – superconducting rotating machines.



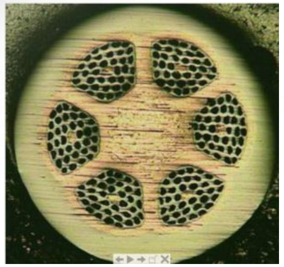
Striated REBCO wire

Conductor candidates

- REBCO coated conductors
  - Large achievable filament size using laser ablation (>100 μm)
  - Degradation of critical current density due to laser ablation
  - Difficulty in making saddle-shaped coils

CORC

- MgB_2 wires
  - Fine filament size (< 10 μm)
  - Round shape wires – easy to make saddle coils
  - With a *T*c of 39 K, MgB2 wires are suitable to be operated at 20 K or LH2 temperature



MgB_2
(Hyper Tech Website)

- No experimental AC loss data exist for MgB2 wires at high magnetic field at 20 K.

Loss Measurements

Objectives for MgB_2 Stators

- Experiments
  - An in-house AC loss measurement system is being built (details in next slide)
  - AC loss measurements in low-loss MgB_2 wires/coils at various operating temperatures at high magnetic field – In-house built system
  - AC loss measurements in low-loss MgB_2 wires/coils at various operating temperatures under rotating magnetic field – in collaboration with AFRL/OSU
  - Coupling loss measurements in low-loss MgB_2 wires at LHe – in collaboration with Kyoto University
  - Hysteresis loss measurement in low-loss MgB_2 wires/coils at various operating temperatures using PPMS
- Simulations
  - 3D AC loss simulation in MgB_2 wires considering full 3D multi-filamentary geometry – in collaboration with Cambridge University
  - 2D AC loss simulation in a fully – superconducting 3 MW motor using MgB_2 wires in the stator windings and REBCO conductors in the rotor windings – in collaboration with Cambridge University/Swarn Kalsi (KGPS)

Loss Measurements

AC loss rig

- AC magnetic field: ~ 500 mT peak
  - (Copper magnet cooled by liquid nitrogen)
- Temperature range for superconductor samples: 15 K – 80 K (He gas-cooled using AL600 cryocooler)
- Frequency range: – 200 Hz
- Type of measurements:
  - Magnetization loss
  - Dynamic resistance/loss
- Sample DC current: ~ 500 A
- Superconductors: MgB2, REBCO, Bi2212, Iron based SCs
- Sample envelope: 40 mm (W) x 250 mm (L) x 20 mm (H)

AL600 cryocooler (CRYOMECH)

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Propulsion System Simulation

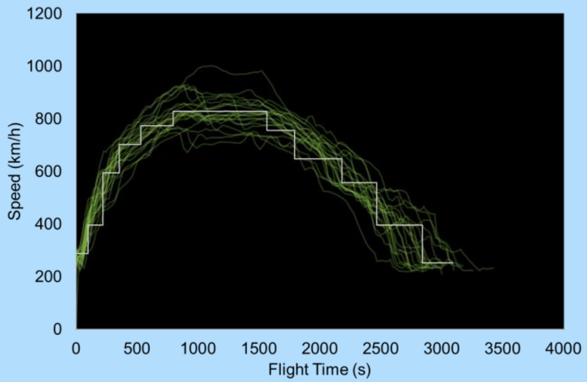
- ***Quantifying carbon emission reduction potential of electric aviation propulsion.***
  - What is the best approach to mitigate carbon emissions from aviation?
  - Modular framework to quantify the impact of new electric propulsion architectures on emissions from real long- and short-haul flight profiles.
  - Inform aircraft developers, owners and regulators of the relative benefits of pursuing either ‘incremental’ or ‘step-change’ approaches to reducing CO_2 emissions from the aviation sector.

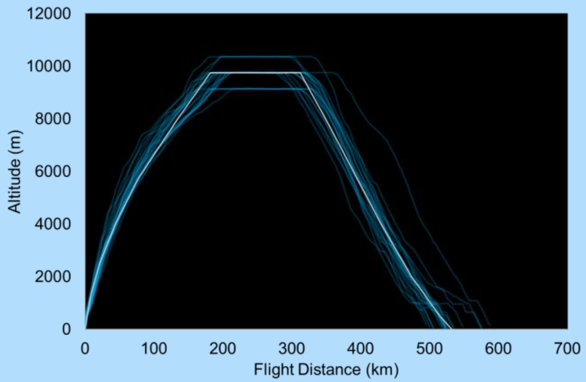
Propulsion System Simulation

Flight data credit: Andrew Hewitt, Air New Zealand

Example route tested with simulated 737:

- Estimated fuel burn for 737 AKL-WGN within 1% of AirNZ reported fuel burn.
- Flight Profile then used to assess potential reductions if electric.





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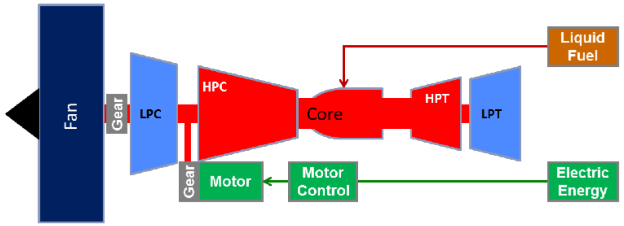
Propulsion System Simulation

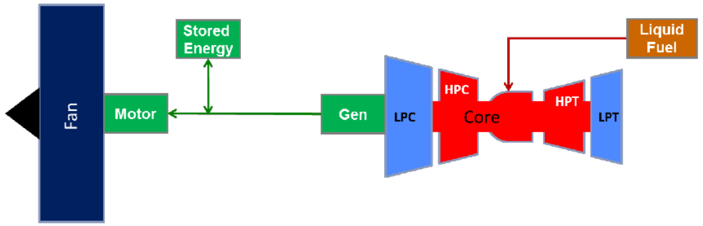
- Modular software powertrain models.
- Can simulate various powertrain layouts.

Parallel Gas-Electric Hybrid



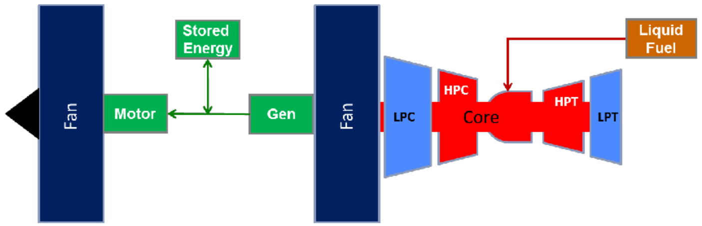
All thrust from main fans, fan power from liquid fuel through GT and battery though LS motor

Full Series Turboelectric Hybrid



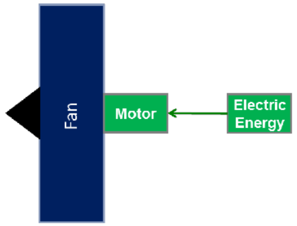
GT creates electric power from liquid fuel, electric power distributed to multiple electric fans for thrust, battery used load leveling

Partial Series Turboelectric Hybrid



Full Series Turboelectric Hybrid, with addition of thrust from GT LS fan

All Electric (not a Hybrid)



Electric power from battery distributed to multiple electric fans for thrust

Parallel Hybrid Propulsion System for a Regional Turboprop: Conceptual Design and Benefits Analysis, T.Spierling, C.Lents, United Technologies, EATS 2019

Novel HTS Machine Subcomponents

- **HTS bearings: Superconducting HTS bearings**
  - Robinson is investigating novel processing routes to produce shaped bulks.
  - We will apply this new capability to develop entirely novel hybrid-bearing designs.
- **High-saturation-field soft ferromagnets**
  - Field strengths in machines are limited by the 1.5T saturation field of the rotor material.
  - We are experimentally screening sputtered thin films for B_{sat} > 2.3T.
- **Quench prevention: Fibre optic early quench detection**
  - Distributed sensing of local temperature increases which cause a risk of quench.
  - Robinson is developing a novel optical fibre system backed up by our improved AC loss model.

The AETP Programme - Workstreams

Electrifying Large-Scale Transport Aotearoa

1.1 Superconducting Machines

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- The University of Auckland New Zealand
- Kyoto University
- KGPS

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The AETP Programme – Workstream 2

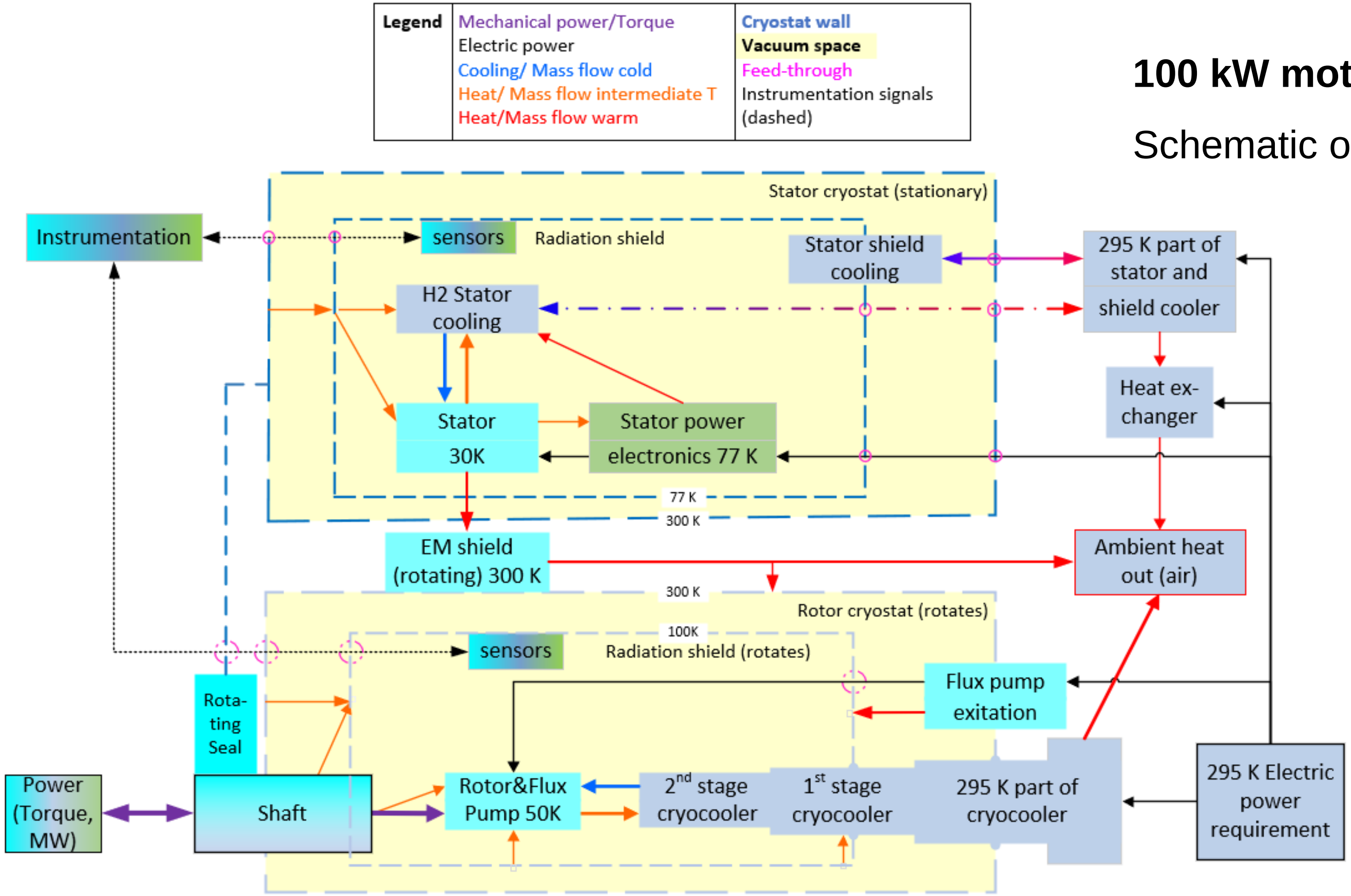
ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

1.2
Cryogenic Systems

VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA
KAIST
Callaghan Innovation New Zealand's Innovation Agency
AUT

- System optimization for low mass and high efficiency
- Cryogen-cryogen heat exchanger performance
- Additive manufacturing with cryogenic materials
- Novel cryo-cooler development for aero
- Exploiting LH_2 fuel synergies

The AETP Programme – System Modelling



100 kW motor with superconducting stator

Schematic of flow of energy between components

- Liquid Hydrogen cooling for stator at 20 K
- Rotating 2-stage cryocooler for Rotor and Flux Pump
- Stepping stone for 3 MW design

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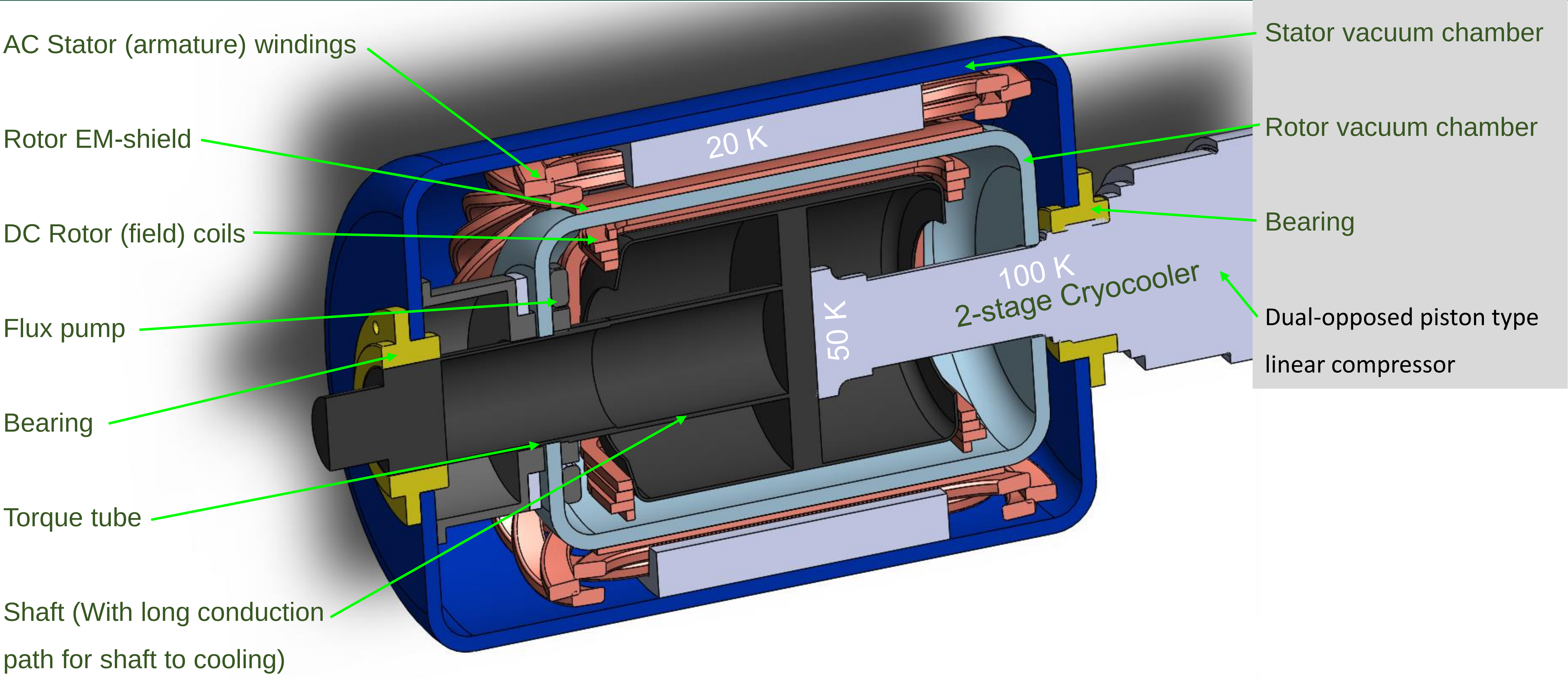
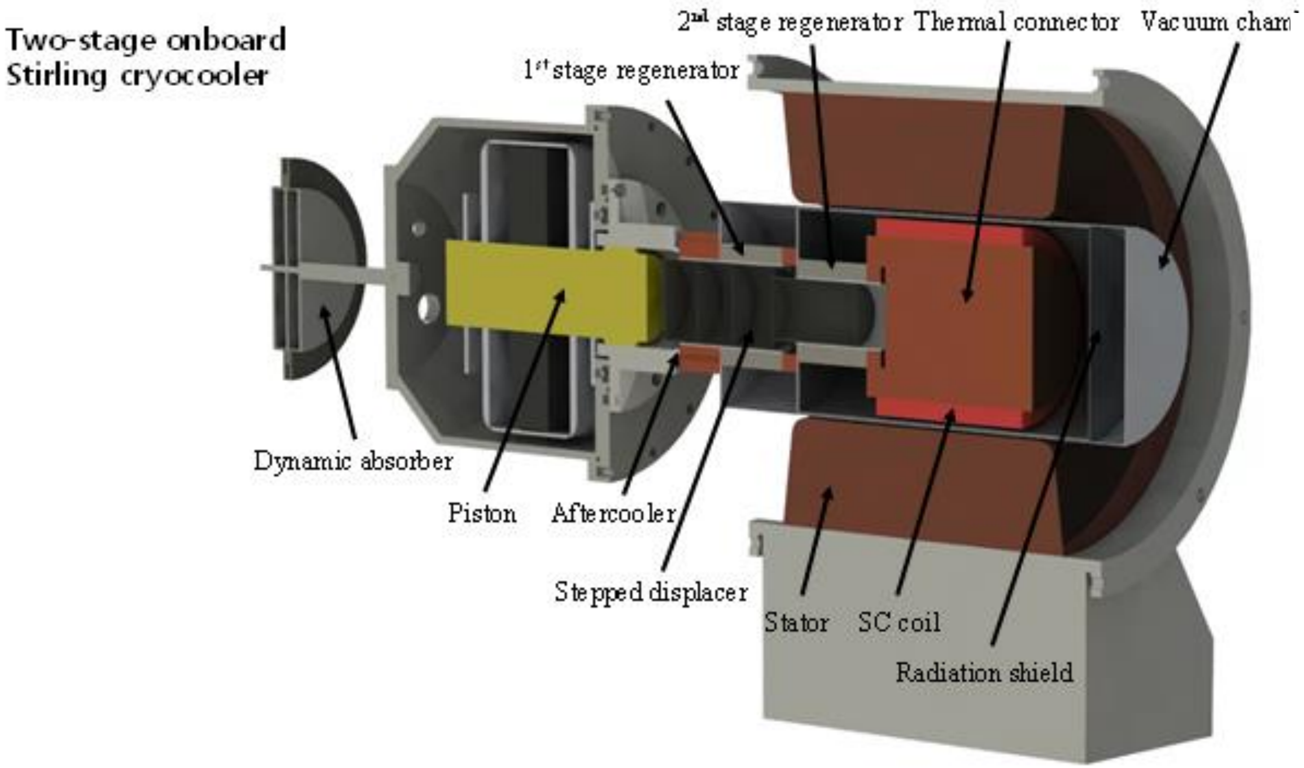
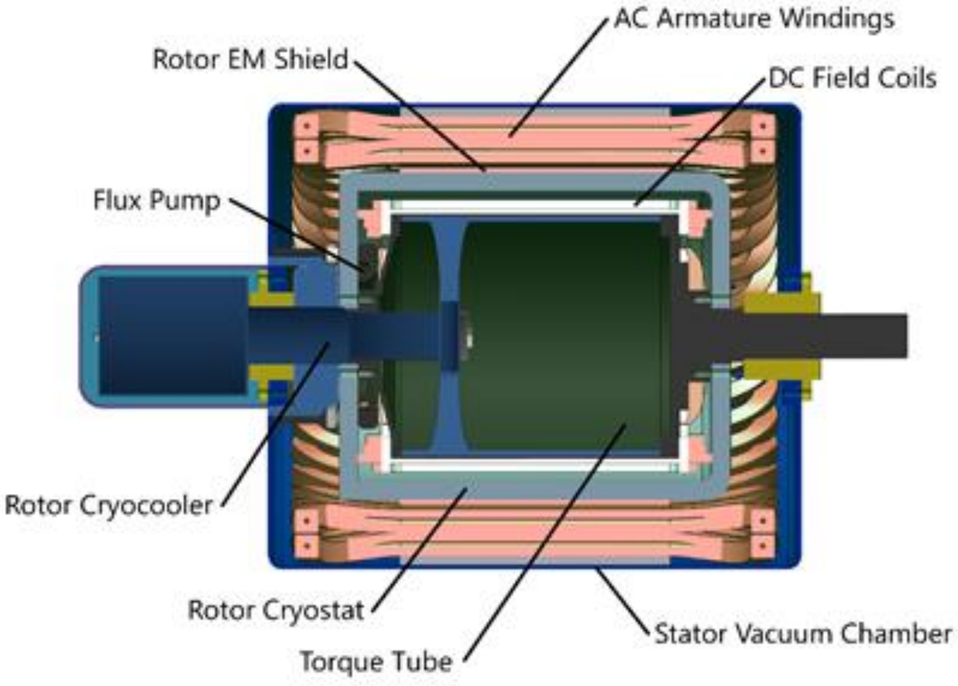
The AETP Programme – Rotating Cryocoolers (Slide option1)



The AETP Programme – Rotating Cryocoolers (Slide option2)



Cryocooler conceptual schematic

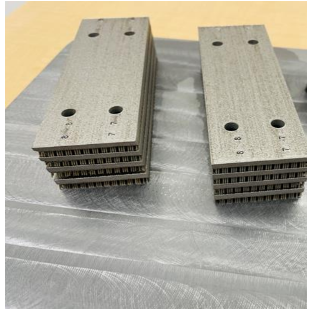


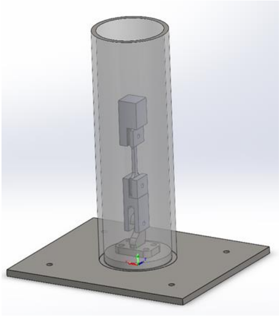
Motor Longitudinal Section

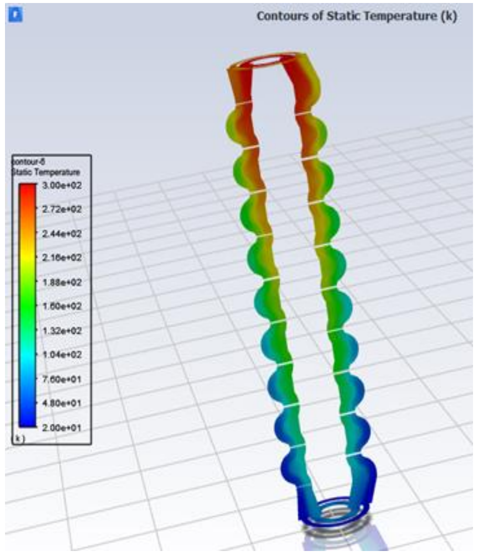
The AETP Programme – Additive manufacturing

Progress is planned on 3 fronts:

1. Evaluation of additive manufacturing solutions for counterflow heat exchangers
2. Characterisation of additively manufactured materials in cryogenic and trans-cryogenic environments
3. Exploring the development of complex geometrical forms for efficient thermal management and structural support in the motor.







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The AETP Programme - Workstreams

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

1.1 Superconducting Machines

Victoria University of Wellington Te Herenga Waka; The University of Auckland New Zealand; Kyoto University; KGPS

1.2 Cryogenic Systems

Victoria University of Wellington Te Herenga Waka; KAIST; Callaghan Innovation – New Zealand's Innovation Agency; AUT

1.3 Power Electronics

The University of Auckland New Zealand; Victoria University of Wellington Te Herenga Waka; UC University of Canterbury; University of Cambridge

Training – Industry-Ready Capability

Ara Institute of Canterbury; Manukau Institute of Technology; UC University of Canterbury

The AETP Programme – Workstream 3

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

- Wide-gap GaN devices for weight and efficiency
- Characterising silicon systems at cryogenic Temps.
- Switched-mode motor drives for superconducting coils
- High-power, lightweight, compact controllers for aerospace motors

1.3
Power Electronics

The University of Auckland – Te Whare Wānanga o Tāmaki Makaurau – New Zealand
Victoria University of Wellington – Te Herenga Waka
UC University of Canterbury – Te Whare Wānanga o Waitaha – Christchurch New Zealand
University of Cambridge

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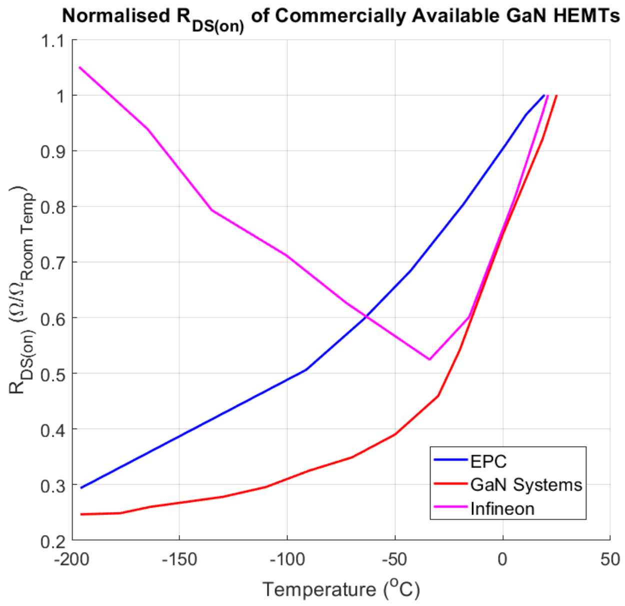
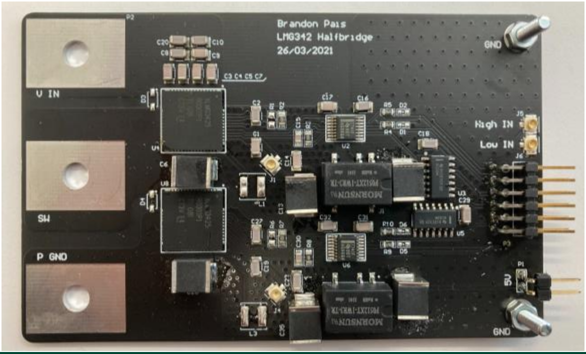
Light Weight Converters for HTS Machines

- Research program aims to investigate system level benefits of operating power electronics at or near cryogenic temperatures
  - Investigating operation of commercial WBG switches as well as passive and active devices at low temperatures
  - Developing new WBG switches and passives with improved properties
  - Developing converters that can operate at low temperatures to drive fully superconducting motors
  - Investigating reliability of these novel solutions





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The AETP Programme - Workstreams

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

1.1 Superconducting Machines

Victoria University of Wellington Te Herenga Waka
The University of Auckland New Zealand
Kyoto University
KGPS

1.2 Cryogenic Systems

Victoria University of Wellington Te Herenga Waka
KAIST
Callaghan Innovation – New Zealand's Innovation Agency
AUT

1.3 Power Electronics

The University of Auckland New Zealand
Victoria University of Wellington Te Herenga Waka
UC University of Canterbury
University of Cambridge

Training – Industry-Ready Capability

Ara Institute of Canterbury
Manukau Institute of Technology – Te Whare Takiura o Manukau
UC University of Canterbury

The AETP Programme – Workstream 4

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

- Curriculum development
- Preparing industry for future technologies
- Supporting diversity in STEM

Training
Industry-Ready Capability

Ara Institute of Canterbury – Ara rau, taumata rau

MANUKAU INSTITUTE OF TECHNOLOGY – Te Whare Takiura o Manukau

UC UNIVERSITY OF CANTERBURY

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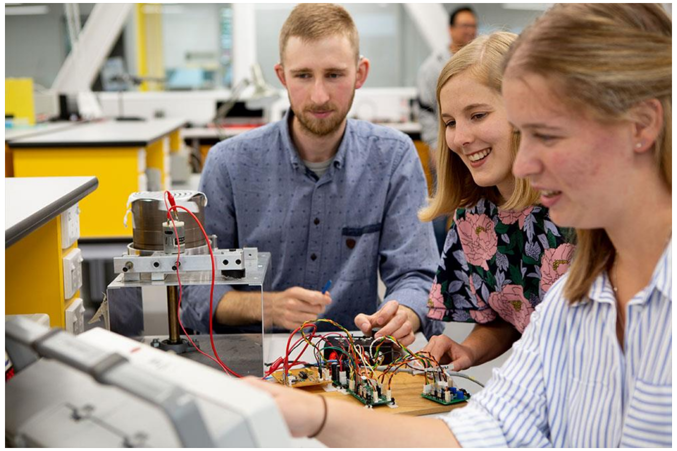
Curriculum Development

- New course for the Electrical Engineering Strand of the NZ Diploma in Engineering with the aim of upskilling future technicians
- Level 6 course with the following learning outcomes
  - Demonstrate an understanding of superconductor theory
  - Demonstrate knowledge of cryogenic systems
  - Demonstrate knowledge of rotating electric machine used in high power to weight applications
  - Demonstrate an understanding of wide band-gap device technology
  - Demonstrate knowledge electric drive topologies.

2.3 ELECTRICAL ENGINEERING STRAND

Year 1 – Levels 4 and 5		*Year 2 – Levels 5 and 6*	
Engineering Fundamentals L4 DE4101 Common Compulsory	**Power Engineering L5** DE5401 Power Compulsory	**Electrical Machines L5** DE5404 Power Compulsory	**Engineering Project (Electrical) L6** DE6102 Common Compulsory
Engineering Mathematics 1 L4 DE4102 Common Compulsory	**Introduction to NetworksL5** **OR** **CAD Electrical L5** DE5408 or DE5423 Compulsory Elective	**PLC Programming 1 L5** DE5402 Power Compulsory	**Engineering Management L6** DE6101 Common Compulsory
Technical Literacy L4 DE4103 Common Compulsory	**Electrical and Electronic Applications L4** DE4402 Electrical Compulsory	**Elective L5 or L6**	**Elective L6**
Electrical Principles L4 DE4401 Electrical Compulsory	**Electronic Principles L5** DE5403 Electrical Compulsory	**Elective L6**	**Elective L6**
Year 1 = 120 credits		Year 2 = 120 credits	

NOTE : EITHER DE5408 Introduction to Networks OR DE5423 Computer Aided Electrical Drawing must be selected in Y1



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Preparing industry for future technologies

- Pathways for preparing industry include
  - Student Internships
  - Industry Advisory Panel

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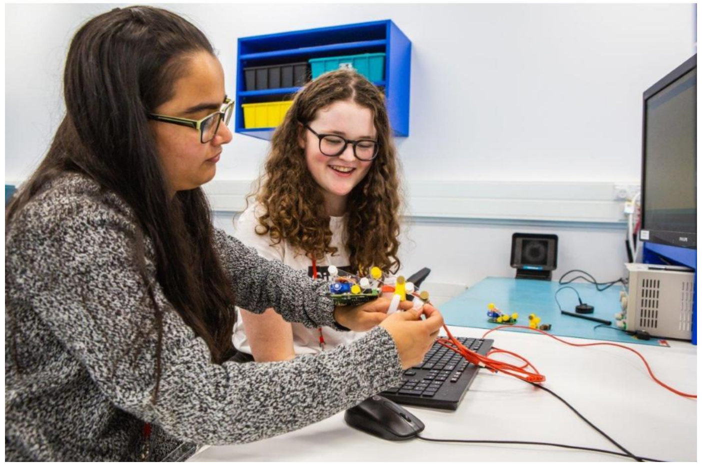
Supporting diversity in STEM

- Tech Bootcamps with indigenous iwi focus
- Scholarships at Technical Institutes
- Student and Outreach Coordinator - Robinson

Ara Institute of Canterbury
Ara rau, taumata rau

MANUKAU INSTITUTE OF TECHNOLOGY
Te Whare Takiura o Manukau

UC UNIVERSITY OF CANTERBURY



The AETP Programme – Summary

ELECTRIFYING LARGE-SCALE TRANSPORT AOTEAROA

1.1 Superconducting Machines

- Victoria University of Wellington – Te Herenga Waka
- The University of Auckland – Te Whare Wānanga o Tāmaki Makaurau – New Zealand
- Kyoto University – Kyoto Japan – Founded 1897
- KGPS

1.2 Cryogenic Systems

- Victoria University of Wellington – Te Herenga Waka
- KAIST
- Callaghan Innovation – New Zealand's Innovation Agency
- AUT

1.3 Power Electronics

- The University of Auckland – Te Whare Wānanga o Tāmaki Makaurau – New Zealand
- Victoria University of Wellington – Te Herenga Waka
- UC University of Canterbury – Te Whare Wānanga o Waitaha – Christchurch New Zealand
- University of Cambridge

Training Industry-Ready Capability

- Ara Institute of Canterbury – Ara rau, taumata rau
- Manukau Institute of Technology – Te Whare Takiura o Manukau
- UC University of Canterbury

Paihau—Robinson Research Institute

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VICTORIA UNIVERSITY OF
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CEC/ICMC J3Or1A-03 [Invited]
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