IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation AT-1 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

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Development of High-T_c superconductor applications in New Zealand

C.W. Bumby *et al.*

Robinson Research Institute, Victoria University of Wellington, New Zealand

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This Asian Topics presentation was made to the 1st Asian International Cryogenic Materials Conference – Cryogenics and Superconductivity Society of Japan 50th Anniversary Conference (1st Asian ICMC – CSSJ 50) on 8th November 2016 in Kanazawa (Japan).
It provides an overview of selected HTS technology development projects taking place in New Zealand.
Throughout this talk the abbreviation HTS refers to High-T_c Superconductors.

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HTS in NZ

- New Zealand has a long history in the field of HTS research – dating back to the discovery of BSCCO-2223 by Tallon & Buckley in 1988 (*Nature* ***333*** *153 (1988)*).
- Research activity now centred at Robinson Research Institute at Victoria University of Wellington.
  - Activities span fundamental materials science to engineering applications.
- Commercial manufacturers:
  - HTS-110 (HTS magnets)
  - GCS Ltd. (HTS Roebel cable)
  - Fabrum (composite cryostats and cryo-coolers)

HTS-110

FABRUMSOLUTIONS

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NZ's HTS research programme is centred around the Robinson Research Institute (RRI) at Victoria University of Wellington.
Key commercial manufacturers in NZ include HTS-110 Ltd. (cryogen-free HTS magnets) and Fabrum Ltd. (cryocoolers and composite cryostats).

RRI: http://www.victoria.ac.nz/Robinson
HTS-110: http://www.hts-110.com/
Fabrum: http://www.fabrumsolutions.com/cryogenics/

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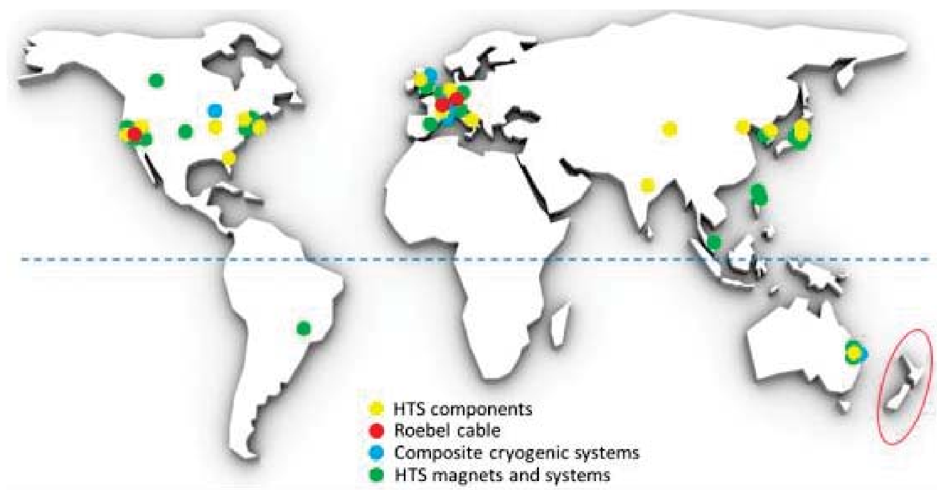
NZ-HTS R&D Strategy

Goal: To commercialise high-T_c superconducting technologies

Strategy

1. Develop knowledge for step changes in the technology
2. Develop and prove key HTS components
3. Partner internationally to demonstrate proof-of-concept systems or sub-systems
4. Work with industry on joint business opportunities

Testing superconducting high-current generator cable at Siemens



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NZ's HTS R&D activities have focussed on commercial applications of the technology.
Key HTS components have been developed and supplied to major international programmes around the globe.
Projects often involve partnering with domestic or international companies to leverage specific expertise, and validate pathways to market.

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Project Examples

- Scientific HTS magnets by HTS-110 Ltd.
- HTS MRI system design and build (1.5 T and 3 T)
- Roebel cable with GCS Ltd.
  - Supplied to Siemens, CERN, NZ-TX project and others
- HTS 1 MVA, 3-phase transformer design and build
- HTS Generators
  - High-speed 2 MW generator 1G rotor development with US companies and US Air Force
  - Brushless exciters for HTS generators

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A wide range of HTS development projects have been undertaken by NZ researchers.
This talk provides only a short overview of some selected examples.

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X-ray and neutron beam-line magnets

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HTS-110 – HTS magnets

- HTS-110 is a New Zealand company specialising in the design and manufacture of HTS magnets for applications that require homogenous, high magnetic fields.
- HTS-110 products are robust, compact, and cryogen free.
- Custom HTS magnets for synchrotron and neutron beamlines, materials characterisation, electrical transport measurements.
- Commercial and research sector customers.

- Established in April 2004, building on 20 years of HTS R&D in government research labs.
- Now a subsidiary of Scott Technology, an NZ-listed company.

HTS-110

HTS-110 is a private company which is now owned by Scott Technology, an NZX listed company.
Originally a spin-out company from NZ's HTS programme, the company has been commercially producing and selling cryogen-free HTS magnets since 2004.
A major business line is the custom design and manufacture of scientific magnets for X-ray and neutron beamlines.

Recent beamline magnets

- Resonant magnetic scattering and high resolution XRD instruments
- BSCCO coils
- 5-6 Tesla
- <100 kg
- BESSY/Darmstadt (Germany), LNLS (Brazil)

Beamline magnets are:

- Space constrained
- Require good optical and sample access (= complex cryostat shapes)
- Often require Rotation and field-ramping
- require low stray field
- Complex custom design

Benefits of HTS

- Compact windings and cryostat
- High temperature operation (> 20K)
  = Flexible cryostat design
  = High thermal stability → robust, simple operation
- Low fringe field with iron yoke
- Fast-ramping driven magnets
- Operating temperatures 20-35 K
  - Modest-sized cryocoolers

Drawbacks of HTS

- Anisotropic wire properties need to be considered
- Cost of wire (still!)

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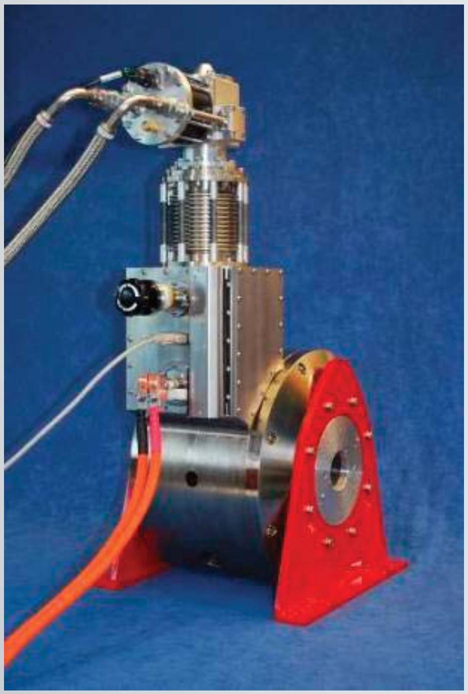
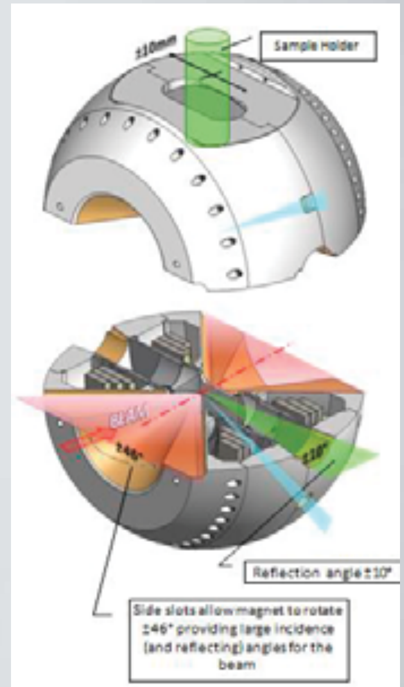
These BSCCO magnets apply uniaxial fields up to 6 T at the sample, whilst enabling access for both incident and scattered beams. This enables beamline scientists to undertake a range of high field experiments.
HTS magnets are compact, robust and can be rotated around the sample, thus allowing arbitrary alignment of beamline and field.

Beamline magnets – UHV

- UHV magnets must survive bake-out of chamber
  - Need to protect your cryostat and coils!





- Magnetic Scattering - ALBA-Cells (Spain)
- 2.2 T, 50 mm pole gap
- Cryo-cooler runs during bake-out

- 2.2 T dipole magnet (40mm axial bore, 90 mm pole gap)
- Water cooling of cryostat outer-wall
- For X-ray Magnetic Circular Dichroism (XMCD) - National University of Singapore

HTS-110

Magnets compatible with UHV and can be placed either inside or outside a UHV chamber. Different situations require different solutions.
A key challenge is managing the high temperatures experienced on the chamber during bake-out. This requires well designed magnet cryostat cooling systems in order to protect the HTS coil system.

Neutron beam-line magnets -examples

2.2 T dipole magnet for neutron TOF scattering

- Commissioned: 2014 at the Heinz Maier-Leibnitz research neutron source (FRM II) , Technische Universitat Muenchen
- 80 mm bore (RT)
- Ability to tilt in any direction
- Scattering angle up to 150° in-plane
- Dimensions: 596 X 363 X 794 mm

3 T dipole magnet for neutron scattering

- Commissioned for NIST
- Total mass <180 kg (compatible with rotating stage)
- Large 160 x 52 mm through-slot for neutron beam (RT)
- Additional ϕ52 mm orthogonal access bore
- Field homogeneity at sample (20 x 20 mm area) better than 1% throughout field range

HTS-110

Neutron experiments can require large scattering angles and bores. Magnets often required to tilt relative to beam axis.
HTS-110 has supplied a wide range of such magnets under commercial contracts.
Individual enquiries should be made to: info@hts-110.com
http://www.hts-110.com/

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Beam-line magnets - Summary

- HTS-110 have been undertaking custom HTS coil design and build for > 10 years
- Both BSCCO and YBCO magnets produced
- Leverage HTS advantages → turn-key systems for user operators
  - Ramping speed/stability
  - Small footprint
  - Cryo-cooled (=helium-free)
  - Rugged construction
- But there are only so many high end beam-line facilities in the world….

→ We need to grow other markets….

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Market for custom designed Beam-line magnets is sophisticated and HTS technology has been widely adopted.
But growth of the HTS industry requires new and larger markets to be developed.

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Materials characterisation:

$I_c(T,B,\theta)$ measurement system

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Another sophisticated potential market is for scientific laboratory magnets

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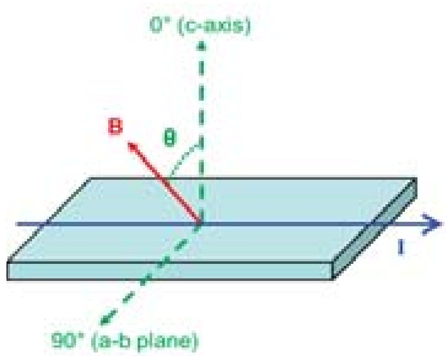
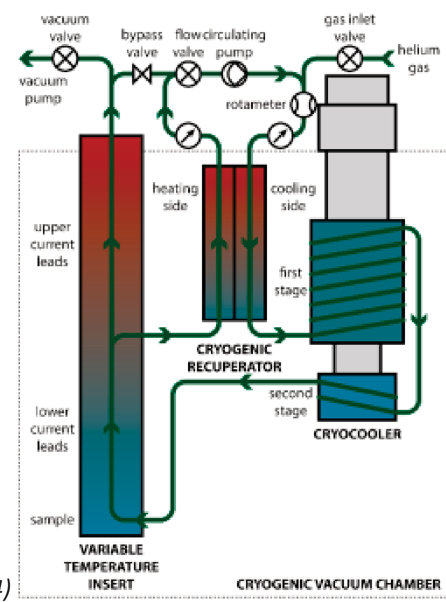
1 kA-class I_c Measurement system HTS Magnet System

- High current I_c measurements are challenging….
- Addressed through design and build of integrated high-current, high-field measurement system
  - Split–pair cryogen-free BSCCO magnet (HTS-110) with
  - Independent variable-T sample chamber
  - Recirculating He gas enables cryo-cooled current leads
- Fully automated $I_c(T,B,\theta)$ measurements
  - Ramp 0 to 8 tesla in 10 minutes
  - Currents to 800 A
  - Temperatures down to 20 K





N M Strickland et al. Rev. Sci. Instr. **85** 113907 (2014)

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A partnership between Robinson institute and HTS-110 has developed this automated measurement system for characterising HTS wire. The cryo-cooler cooled system employs an 8 T split pair BSCCO magnet and employs recirculating He gas to cool a pair of >800A current leads. This system is now commercially available from HTS-110.

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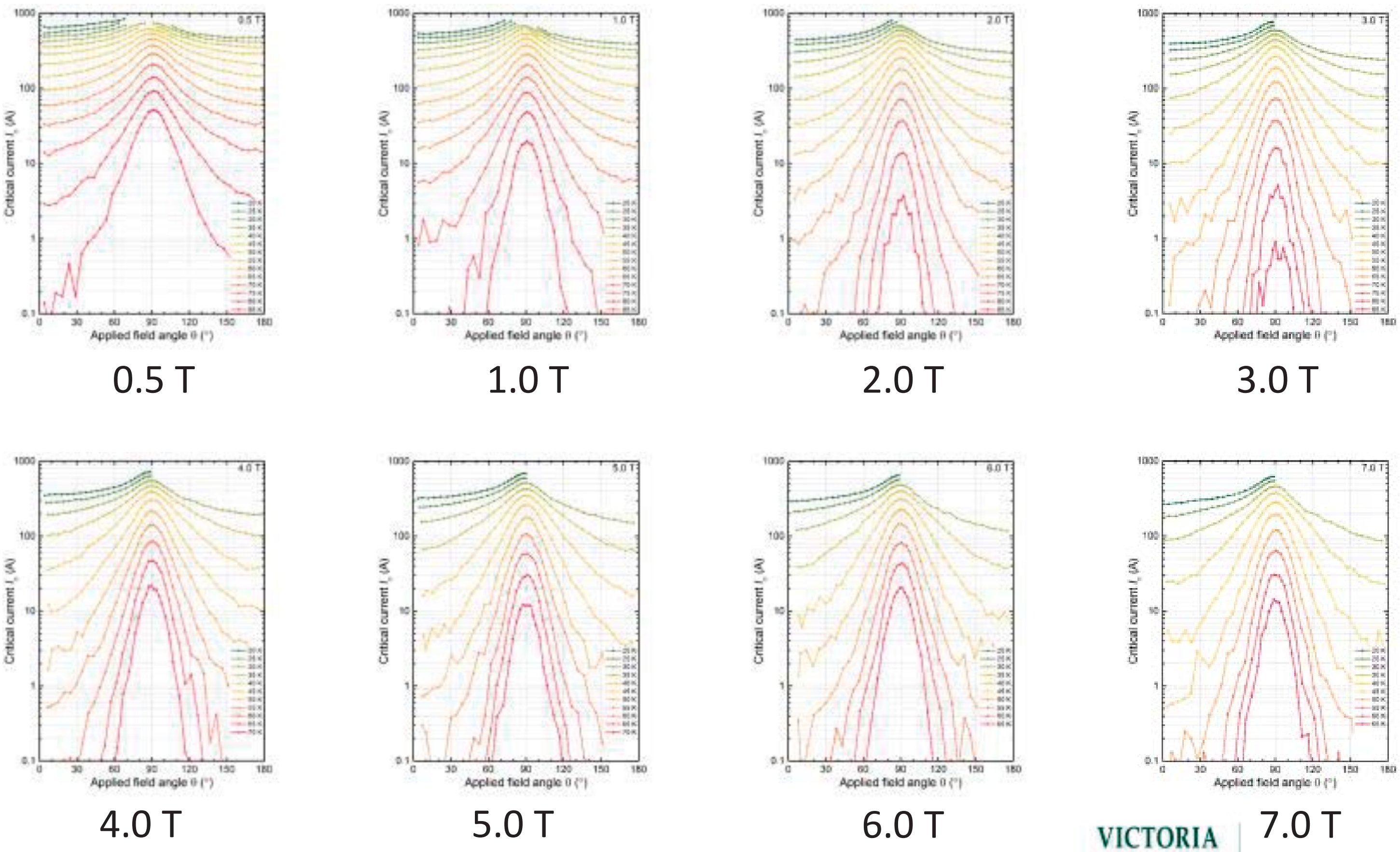
Characterisation of Sumitomo 1G wire



SUMITOMO ELECTRIC

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$I_c(T,B,\vartheta)$ data is automatically obtained by undertaking I-V scans at pre-defined values of sample angle, field and temperature.

This example shows a snapshot of the typical data obtained from a single overnight run.

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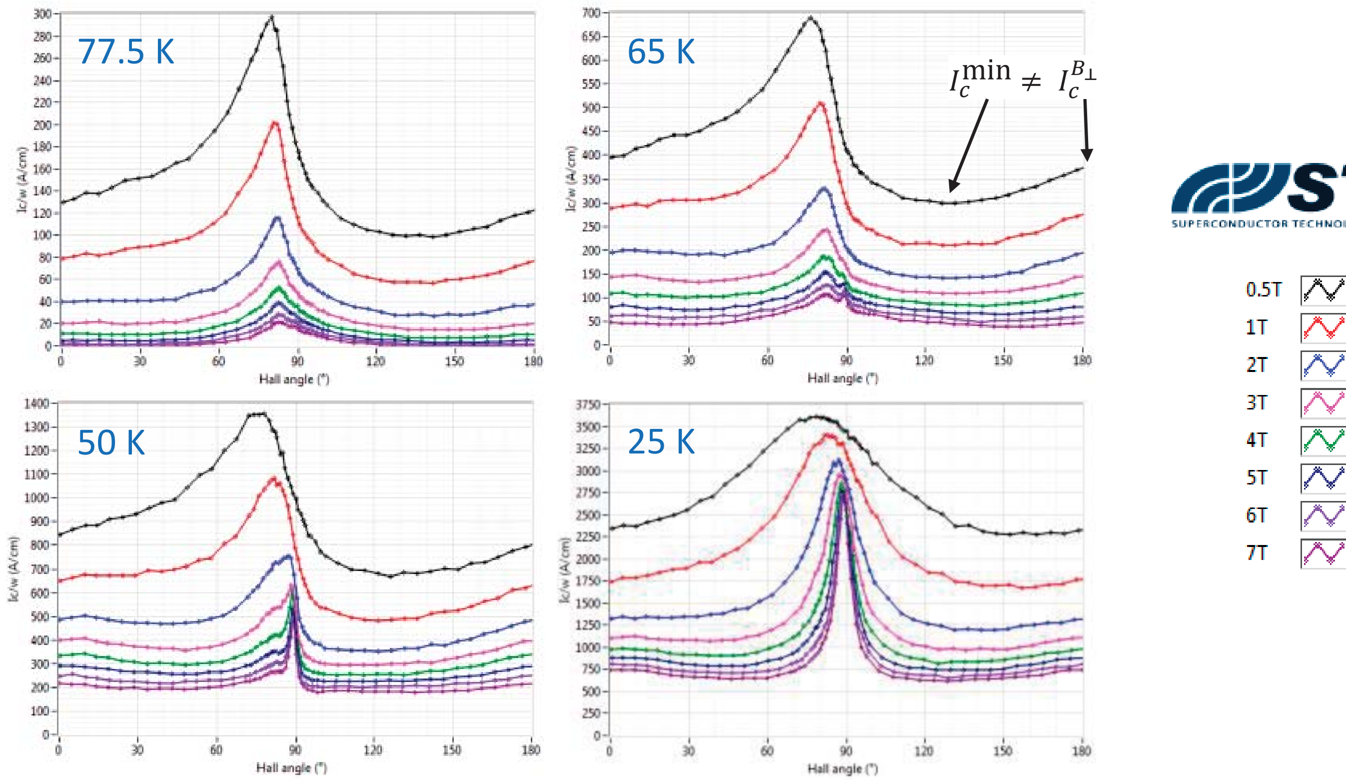
Characterisation of STI 2G Wire



Example data-sets from various commercially-supplied wires are here:
https://figshare.com/collections/A_high_temperature_superconducting_HTS_wire_critical_current_database/2861821

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A key motivation for these sorts of measurements is that the minimum I_c for a given wire often does not occur when B is oriented perpendicular to the tape. Can only be identified by a full theta scan.
Example datasets from some commercially sourced wires are available at the link given here. However, the only reliable way to accurately predict wire performance is to measure a sample of the actual wire.
RRI routinely undertakes contract testing of externally provided samples.

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HTS MRI development

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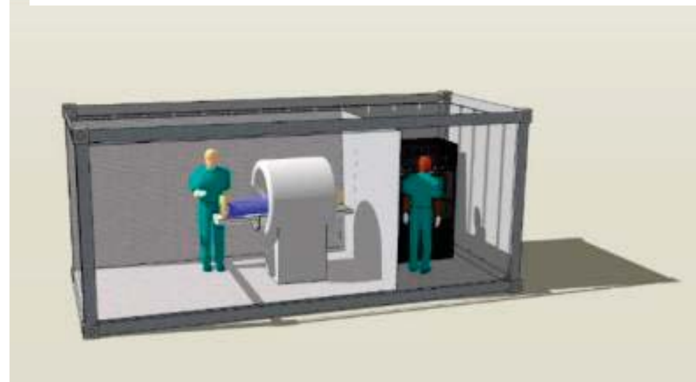
WHY HTS MRI?

- HTS MRI magnets promise attractive features:
  - Cryogen-free operation (eliminates He costs).
  - Thermally robust, Light-weight and rugged
    = Suitable for mobile and industrial environments
- But – HTS wire cost remains very high…
- Short-term HTS MRI applications:
  - Orthopaedic/Human extremity MRI
  - Bench-top pre-clinical MRI at 3 T.
  - pod-MRI – Mobile MRI for rural and emergency response.
- But HTS MRI introduces new challenges
  - No persistent current joint!
    = Driven current operation
  - Cryo-cooling design and balance of system
- Technology demonstration required.

*pod*MRI – mobile MRI in a shipping container.



*pod*MRI magnet (centre) to scale with standard LHe-cooled 3 T (left) and 1.5 T magnets (right)

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A major area of focus for the Robinson Institute team has been the development of cryogen-free MRI systems

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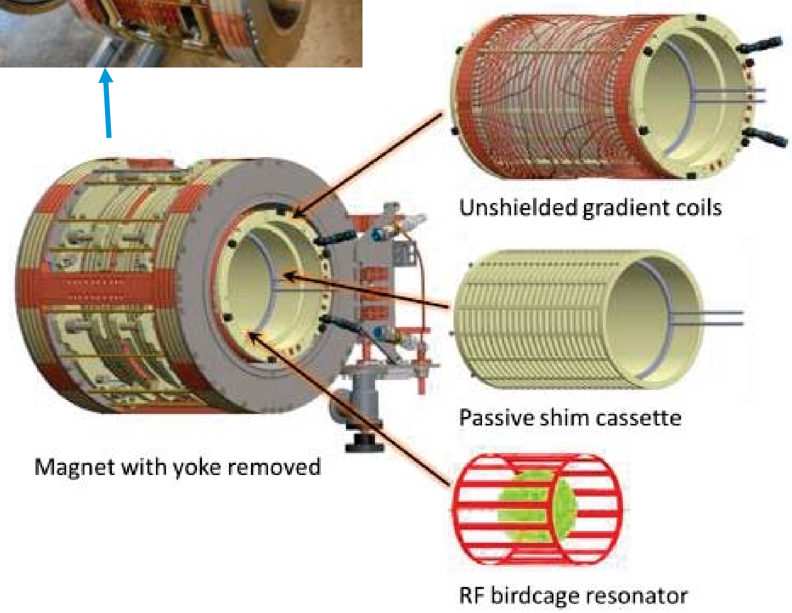
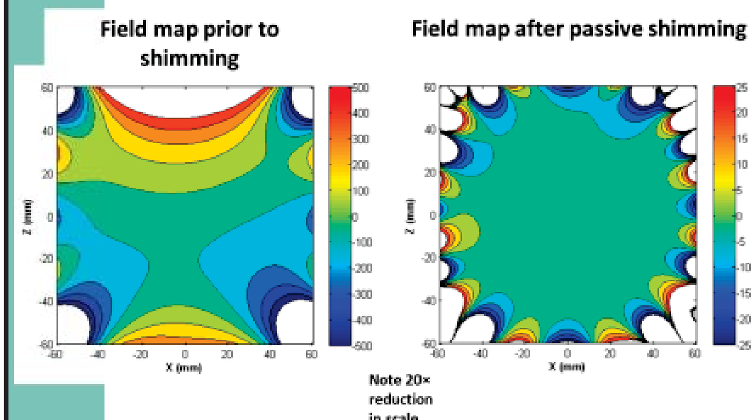
HTS MRI system components

HTS-MRI system development is complex and multi-faceted:

- HTS magnet design:
  - Field stability/homogeneity
  - Thermal design for conduction cryo-cooling
- Passive and active shimming
- Gradient and RF coil manufacture
- System integration and stability





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There are more components to an MRI system than just the magnet.
Building an HTS MRI system requires a team with multiple inter-dependent skills and expertise.

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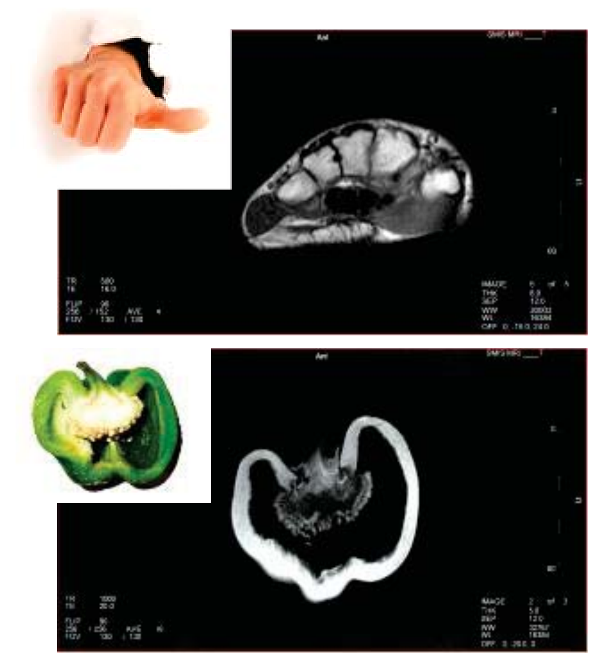
1.5 T YBCO Orthopaedic MRI system (2012/13)

- World-first YBCO MRI system (2012/13)
- 115 mm imaging volume, 240 mm bore
- Compact overall design
- *Unshielded gradient coil* demonstrated for spin-echo imaging.
- System analysis and optimisation tools developed during project.



Images obtained using robust imaging sequence (spin-echo)

YBCO MRI - it works.

R.A. Slade et al. IEEE Trans. Appl. Supercond. ***24****, 4400705 (2014)*

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Our first MRI system was developed and demonstrated in 2012/13 (Slade/Parkinson).
Many unique features – and it works rather well!

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3.0 T BSCCO Preclinical MRI system (2015/16)

- Higher field provides greater spatial resolution (Important if your subject is small…)

Features

- Shielded gradient coil
- Cryogen-free
- Entire system only requires a single electrical phase supply
- Compact magnet dimensions (*5 G line on or near magnet)*
- Cost competitive to LTS solutions
- 60 mm imaging volume, 160 mm bore

Now working with spectrometer partner to develop complete product

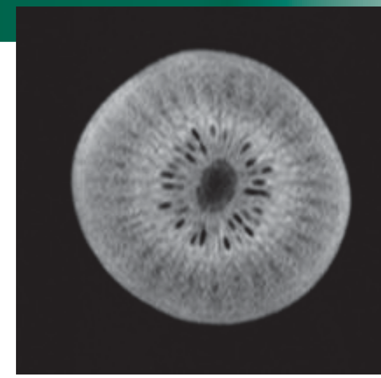

Image of kiwifruit obtained using spin-echo imaging sequence

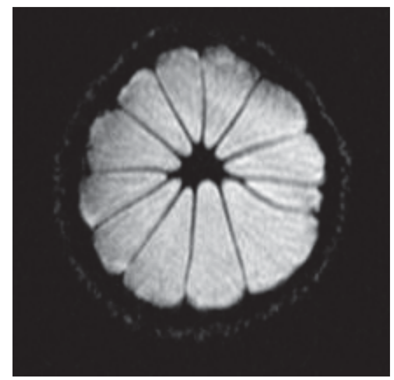

Image of lemon obtained using gradient echo imaging sequence

3T BSCCO MRI works too…

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Recently developed a higher field BSCCO system, this time with a shielded gradient coil.
This system also works very well!
See: *B. Parkinson Supercond. Sci. Technol. 30 014009 (2017)*

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HTS Roebel cable

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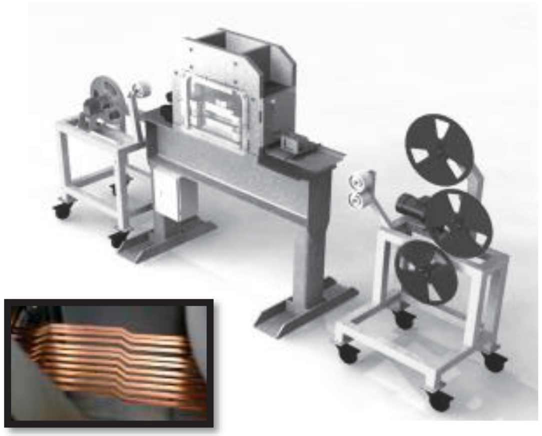
Roebel Cable for high current windings

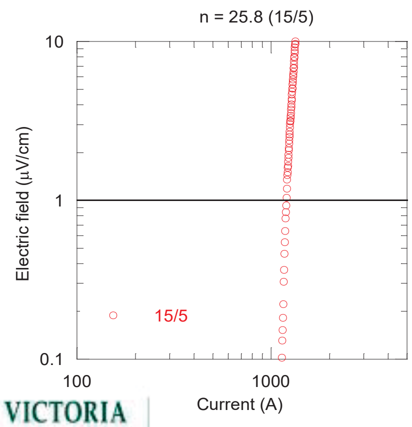
- Roebel cable is a fully transposed HTS cable
- Fully-transposed cables ensure current sharing in high current applications in:
  - AC power systems
    - Transfomers, AC machines etc.
  - Fast ramping/high field magnets
    - Beam-lines, Tokamaks etc.

RRI development in partnership with GCS Ltd.

- Automated pilot-plant manufacture of long-length HTS Roebel cable (100 m+).



HTS Roebel cable



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HTS Roebel cable is commercially manufactured at RRI under contract to GCS Ltd. This high current transposed cable has applications in ac machines and high field magnets.
Fabricated from ReBCO coated conductor wire.

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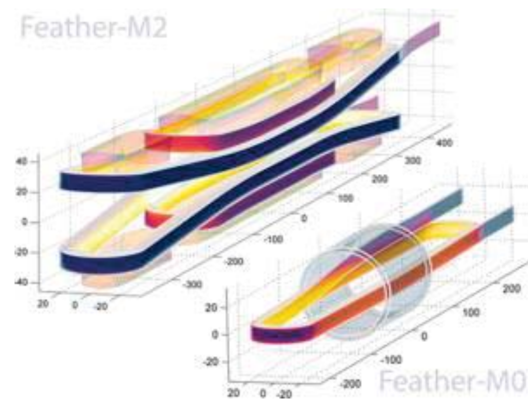
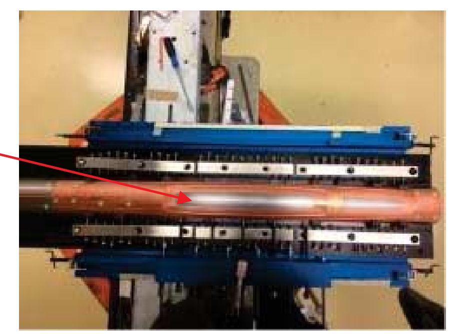
Example Application: EUCARD-Feather2 project (CERN)

- CERN-EU project targeting 'next-generation' accelerator magnets
- 'Aligned block' design to enable stand-alone field of 5T.
  - Insertion into dipole background to achieve 17T to 20T.
- Employing HTS Roebel cable for > 10 kA @ 4.2 K.



Images courtesy of Glyn Kirby, CERN

Roebel cable supplied by GCS



G. Kirby et al. IEEE Trans. Appl. Supercond. 26 (3) 4003307 (2016)

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GCS has supplied test cables to the CERN EUCARD project. (However, NZ is not an official partner in this project).

HTS Power systems: (i) Transformers

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Demonstration 1 MVA HTS transformer

Project goals

- Demonstrate utility of HTS Roebel Cable in an HTS Transformer
  - Can AC losses be overcome?
- Build capability and knowledge in component parts and systems
  - Windings, bushings, composites, cryostats, cooling

Parameter	Value
Primary Voltage	11,000 V
Secondary Voltage	415 V
Maximum Operating Temperature	70 K, liquid nitrogen cooling
Target Rating	1 MVA
Primary Connection	Delta
Secondary Connection	Wye
LV Winding	20 turns 15/5 Roebel cable per phase (20 turn single layer solenoid winding)
LV Rated current	1390 A rms (1964 A pk ≈ 90% of Ic (70 K)
HV Winding	918 turns of 4 mm YBCO wire per phase (24 double pancakes of 38.25 turns each)
HV Rated current	30 A rms (43 A pk = 25% of Ic (70K)

Vector ETEL AUT UNIVERSITY PB WelTec FABRUM SOLUTIONS WILSON TRANSFORMER General Cable SUPERCONDUCTORS HTS-110 Callaghan Innovation VICTORIA UNIVERSITY OF WELLINGTON Robinson Research Institute

RRI has led the development, design and demonstration of 1MVA transformer employing high current HTS Roebel cable

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Transformer installation

- Transformer installed in a 6m shipping container
- Cryo plant installed in a second container
  - Mounted above
  - Hybrid system rated for 1.1 kW heat load
  - Cryocooler + vacuum pumping to sub-cool liquid nitrogen to 70K
  - Allows thermo-syphon circulation of sub-cooled LN_2
- Easily separated for transportation

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Transformer has been built and tested.
See: *M. Staines et al. Transformers, 3(2) pp68-73 (2016); 3(3) pp90-95 (2016)*

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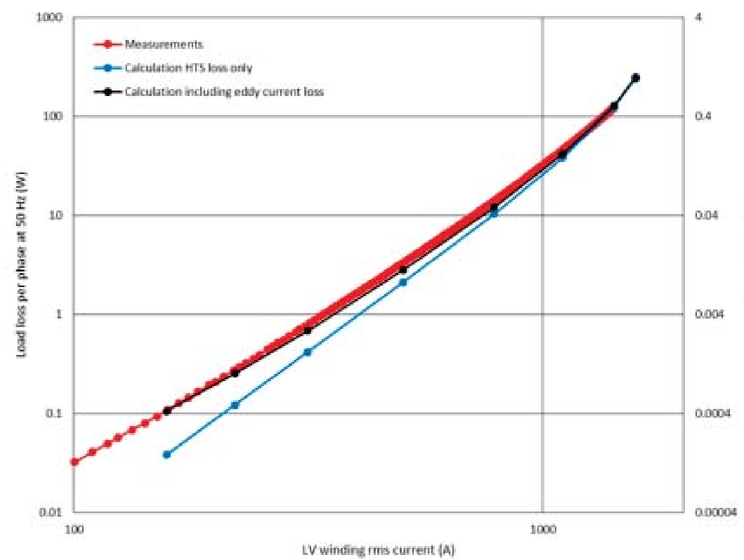
AC loss – model and measurements

- Measured hysteretic ac loss
  - Good agreement with modelling
- Eddy current loss in copper terminals significant at low current
- **~360 W AC loss** at rated current
- **< 0.5 % load loss**
  - (assuming cooling penalty 13.5)
  - Compared with 1% load loss for conventional Tx



"AC LOSS NOT A FUNDAMENTAL OBSTACLE IN HTS TRANSFORMER COMMERCIALISATION WHEN USING ROEBEL CABLE"

E. Pardo *et al., Supercond. Sci. Technol.* ***28*** *114008 (2015)*

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AC loss has been measured. Roebel cable overcomes this issue and is an enabling technology for HTS transformers.

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TX lessons - summary

- The transformer has been successfully loaded to 100% of rated current
  - 1390 A RMS: A **world record** for HTS Transformers
  - Load loss less than conventional 1 MVA transformer
- Demonstration of Robel cable for AC loss management
  - Modelling and design for commercial application **VALIDATED**
  - Roebel cable **VALIDATED**
- Development of non-metallic and cryogenic HTS management suitable for deployment
  - Nitrogen as a dielectric and cryogen for power systems **VALIDATED**
  - Composite cryostats **VALIDATED**
- Future focus:
  - Install in-grid!!

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HTS Power systems: (ii) Generators

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HTS Generators for electric aircraft

- Hybrid-electric aircraft offer substantial efficiency savings
  - Lower CO_2 emissions
  - Lower operating costs
- But will require very lightweight multi-megawatt on-board generators – cannot be achieved by conventional machines
- Power = Torque x speed
  - Torque ∝ rotor field
- High-speed HTS machine (>15,000 rpm) could enable very low weight machine (16 kW/kg)
  - Rotor only is HTS; conventional stator
- HTS windings could provide required field, but can they withstand inertial loads?

Concept hybrid electric aircraft designs (NASA)

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Q: Can HTS windings withstand inertial loads at > 14,000 rpm?
A: Yes – we've previously shown this with BSCCO!

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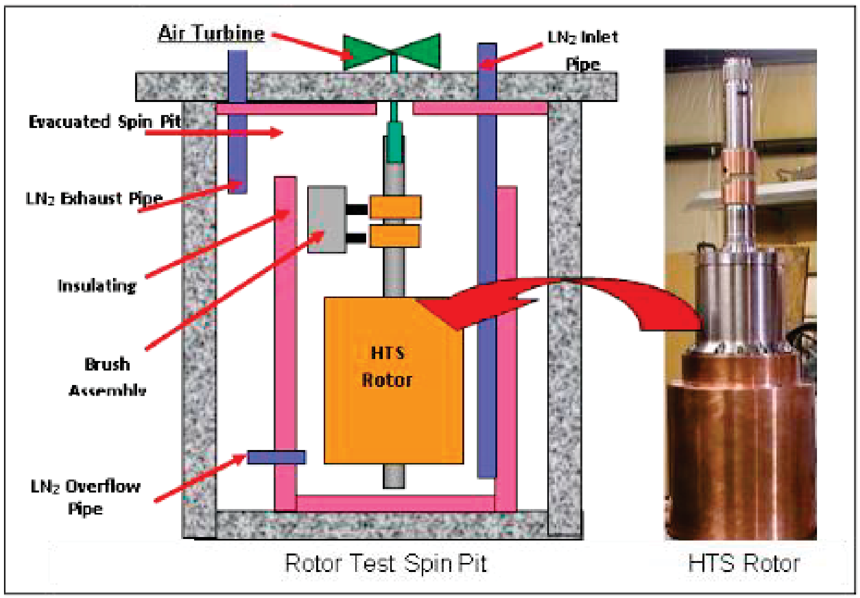
Demonstration HTS high-speed rotor

Test rotor

- LEI//USAF project
- BSCCO coils produced by HTS-110
- World first spin-test at 14,000 rpm, 77K
  - Coils survived just fine
  - Test rig failed first.....
- Further study now underway within new NASA/DoE programme.



HTS (BSCCO) rotor poles manufactured by HTS-110 for LEI

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New Zealand (HTS-110) has previously supplied a set of BSCCO coils to the LEI/USAF high speed generator programme. The coils performed beyond specifications. These coils are continuing to be studied within an ongoing NASA programme.

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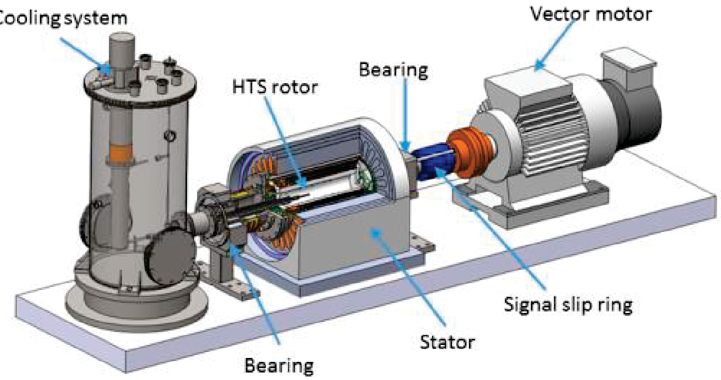
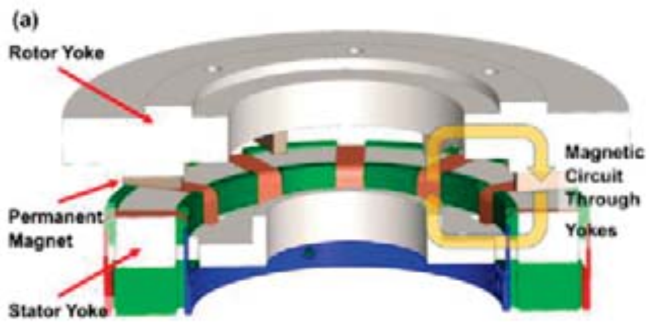
HTS Exciters for HTS Generators

Opportunity:

- Superconducting generators enable high power and torque densities
  = large reductions in weight and size for equivalent power density
- But, cryogenic rotor requires excitation from external current supply
  - Large parasitic heat leaks down current leads
  - High-current rotating brushes have very high wear rate = large maintenance costs.



Demonstration HTS generator under construction (Changwon University, Korea)



Solution:

- Flux Pump (FP) Exciter inductively excites magnet through cryostat wall

See *Bumby et al. IEEE Trans. Appl. Supercond.* ***26****(4), 0500505 (2016)*

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A key challenge with HTS rotating machines is injecting current into a rotating cryostat. RRI ahs been at the forefront of developing mechanically-rotating HTS flux pumps, which can be employed as brushless exciters for these machines.
The physics of these devices is not trivial – an ac magnetic field induces a DC current - but only in the superconducting state (the output in the normal-conducting state is zero). We have recently shown this is due to partial rectification effects which arise due to circulating currents in the HTS stator. See *C.W. Bumby et al. Appl. Phys. Lett. 108, 122601 (2016).*
A Flux pump 'brushless exciter' can be arranged such that all active excitation elements are outside the cryostat – and the HTS circuit is excited across the cryostat wall. This eliminates penetrations of the cryostat wall and accompanying parasitic heat loads.

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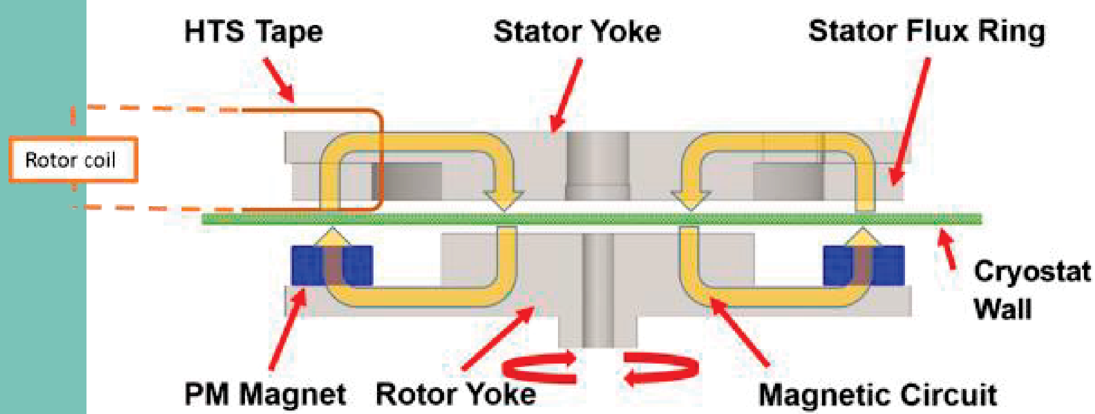
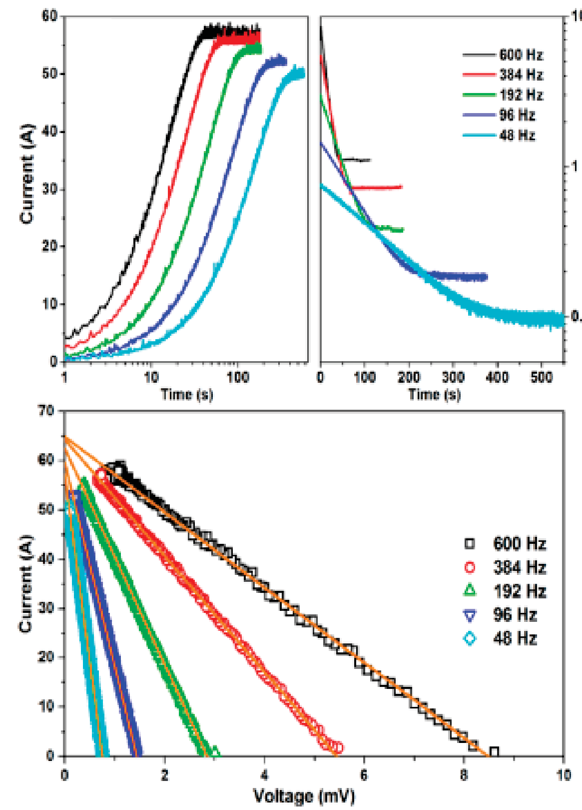
Brushless exciters – Simplifying HTS machines



Bumby et al. SUST ***29*** *(2), 024008 (2016)*



- Reduces complexity
  - No current lead / no penetration
  - Removes slip-rings
- Increases efficiency
  - Half the heat load
  - Smaller cryocooler / lower cost
  - All-superconducting circuit

A component that can be supplied to any manufacturer

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The resulting device forms a component that can be supplied to any manufacturer of rotating machines.

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Summary – HTS applications under development in NZ

- **Scientific magnets**
  - 800 A, 8 T, ≥20K wire characterisation magnet developed and commercially available
  - Multiple custom beam-line magnets delivered to international customers (HTS-110)
- **HTS MRI**
  - YBCO human-extremity MRI demonstrated at 1.5 T
  - BSCCO pre-clinical MRI demonstrated at 3 T - spin-echo and gradient echo imaging.
- **Roebel cable**
  - Fully-automated pilot plant production of high current, fully transposed cable (GCS/RRI)
- **HTS Transformers**
  - World first demonstration of 1MVA transformer
    - AC loss characterised – efficiency is not necessarily a problem!
- **Rotating machines**
  - High speed HTS rotors can be built, and survive to > 14,000 rpm….
  - **HTS brushless exciters** enable DC excitation of HTS rotor coils without current leads or brushes

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New Zealand is highly active in the development of HTS technologies for large-scale applications, across a broad range of topics.

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VICTORIA UNIVERSITY OF WELLINGTON TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI

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The End

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