IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
Invited Presentation SA-22-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

Large scale applications of HTS in New Zealand

Stuart C Wimbush
Robinson Research Institute
Victoria University of Wellington

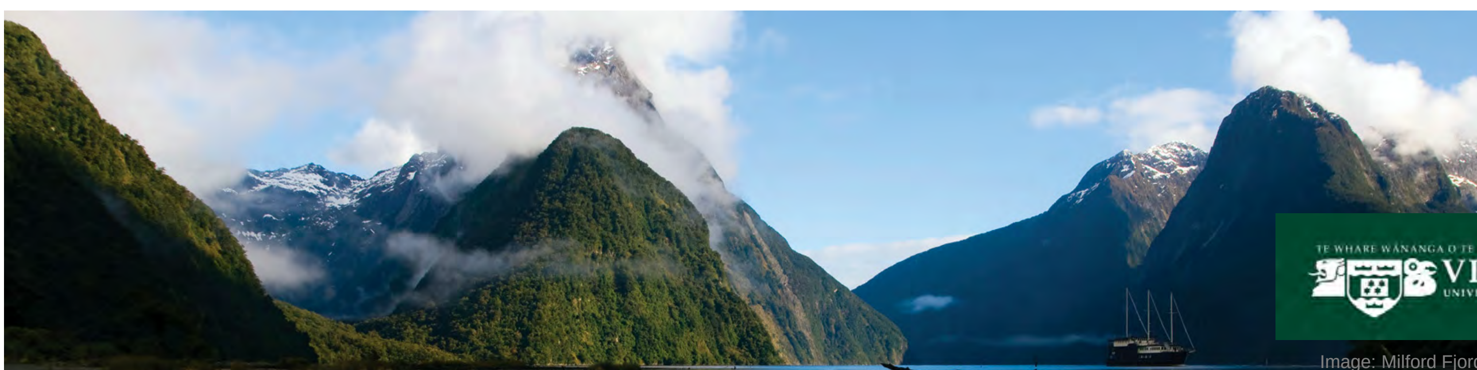
Large scale applications of HTS in New Zealand

- Coil-based
  - HTS MRI
  - Bench-top NMR
  - High-field (20 T) magnets
  - Flux pump (rotating machines)
  - Superconductor wire characterisation

HTS-110

- Cable-based
  - Commercial Roebel cabling
  - HTS transformer

General Cable SUPERCONDUCTORS Limited



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

Image: Milford Fjord, New Zealand

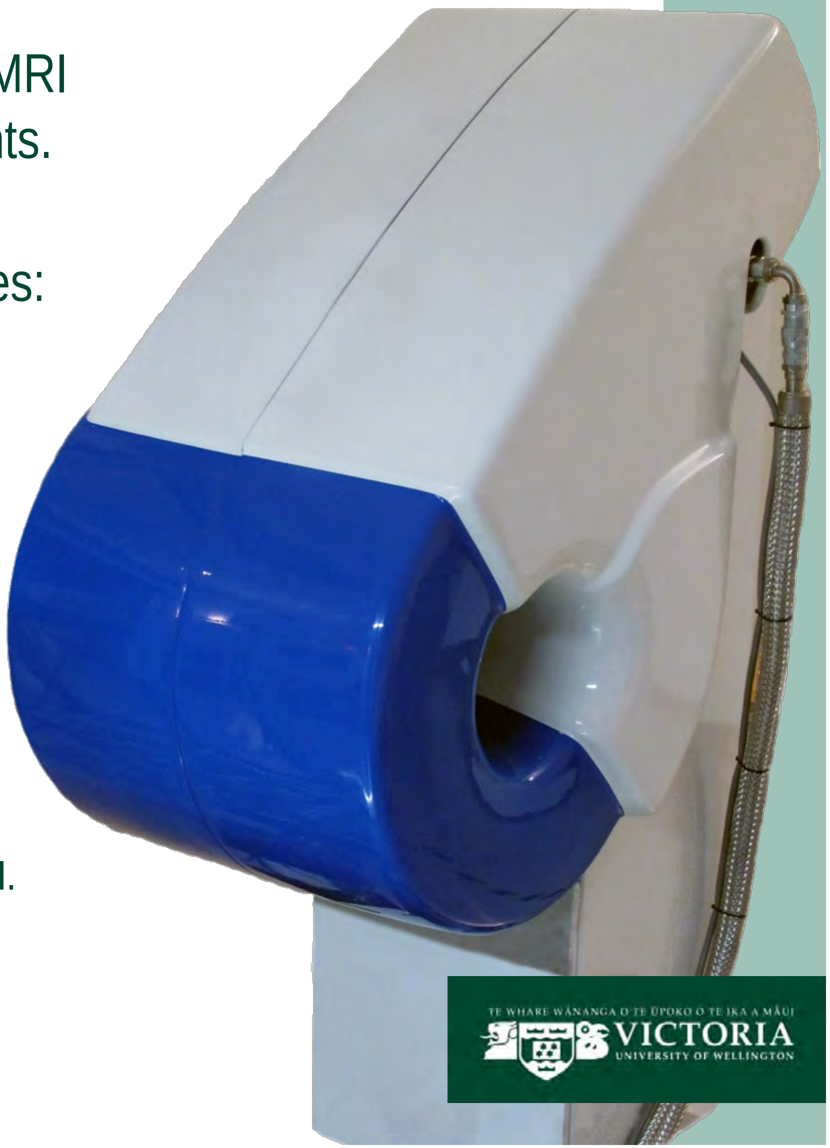
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
Invited Presentation SA-22-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

HTS MRI project

- Demonstration that a YBCO-based MRI system can meet clinical requirements.

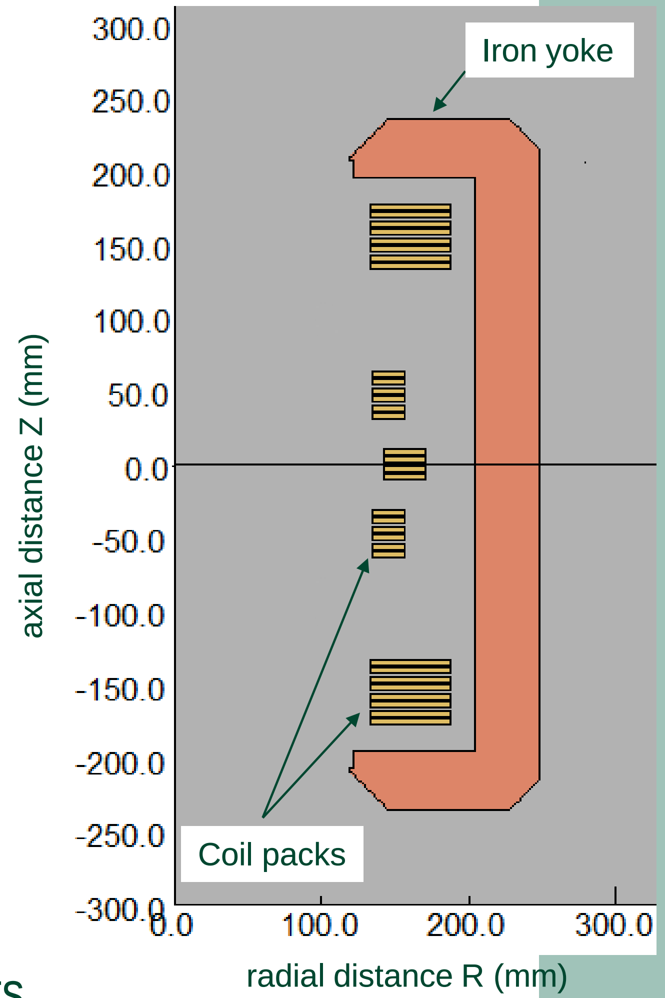
- HTS magnets have attractive features:
  - Cryogen-free operation.
  - Push-button ramping.
  - Fast recovery from power outages.
  - Mobile deployment.

- Short-term applications:
  - Human extremity MRI at 1.5 T.
  - Bench-top pre-clinical MRI at 3 T.
  - Research into low-field (hyperpolarized) MRI.



1.5 T HTS MRI magnet design

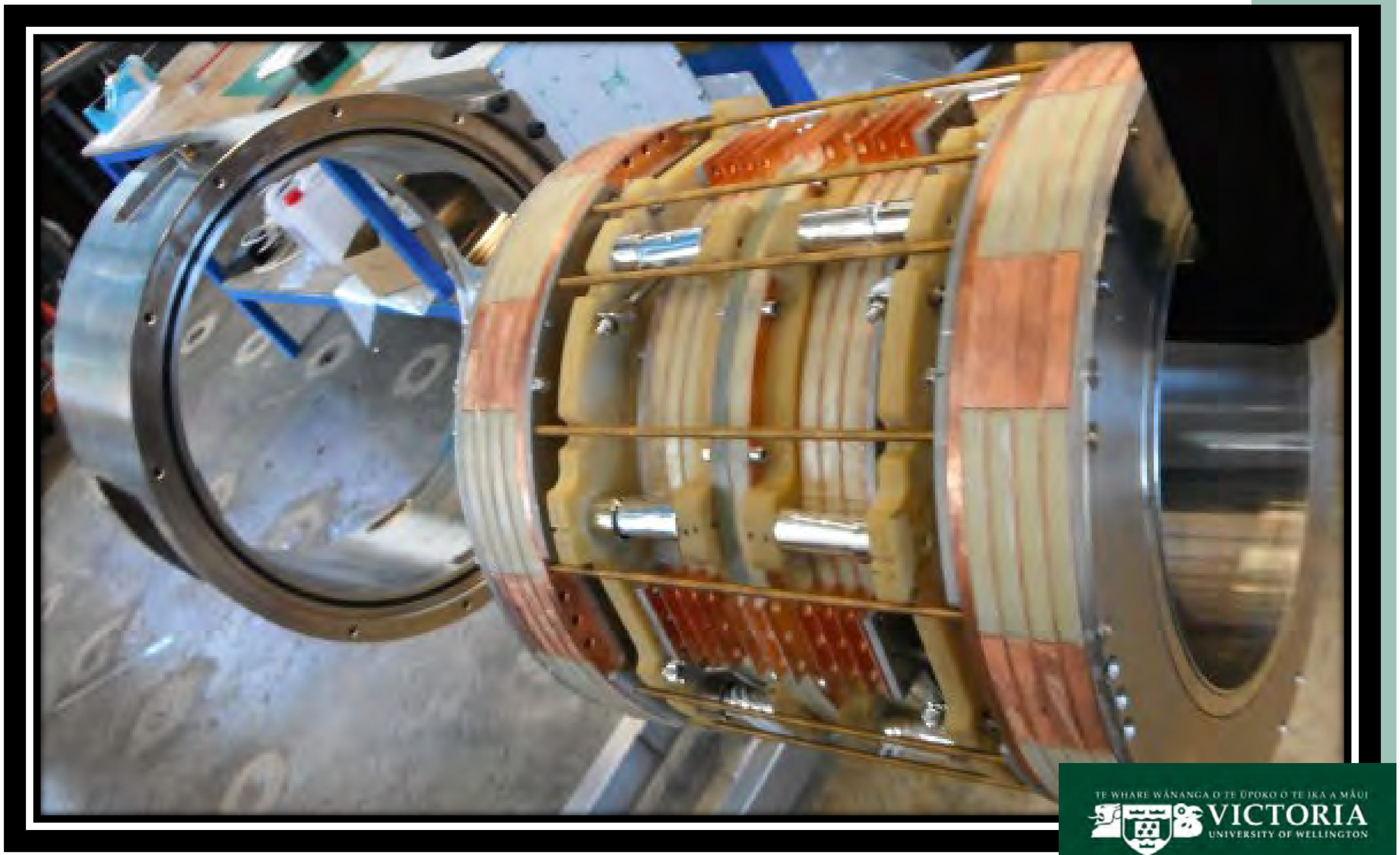
- Dimensions:
  - OD 500 mm x 470 mm long.
  - ∅ 240 mm bore.
  - 120 mm DSV (50 ppm pk-pk).
  - 5 G line: 1.8 m axial × 1.5 m radial.
- Superconductor:
  - Design optimised using measured $I_c(T,B,\theta)$.
  - 4.8 km AMSC Amperium® YBCO tape.
  - 1.5 T at 125 A coil current.
- Cooling:
  - Conduction cooled by pulse tube refrigerator.
  - Coil temperature 20 K.
  - ΔT < 0.2 K over all coils.
- Magnet designed to minimize eddy currents.



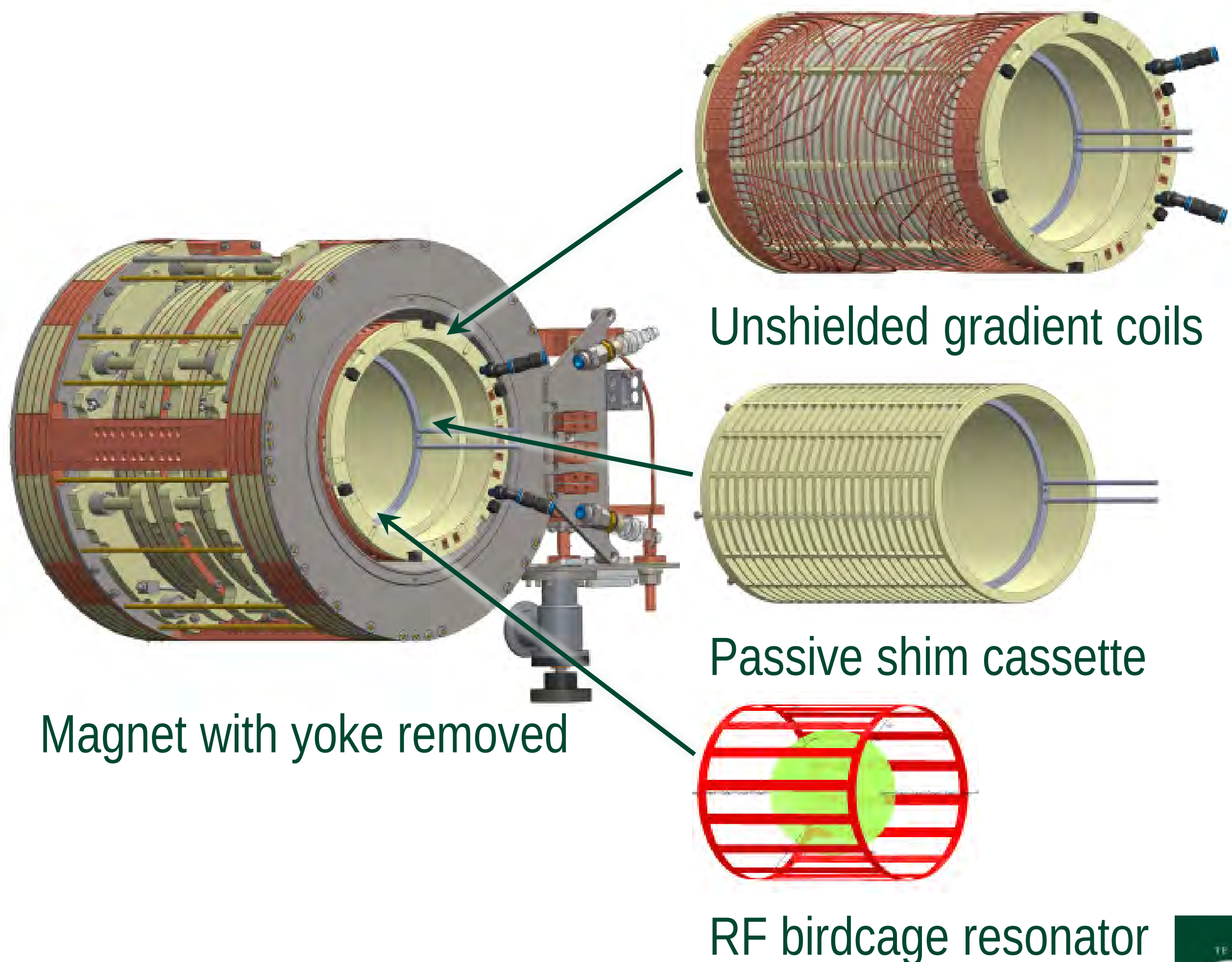
B J Parkinson, R Slade, M J D Mallett, and V Chamritski
Development of a cryogen free 1.5 T YBCO HTS magnet for MRI
IEEE Transactions on Applied Superconductivity 23, 4400405 (2013).

1.5 T HTS MRI magnet assembly

- Prior to wrapping with multilayer insulation.



1.5 T HTS MRI system components



R A Slade, B J Parkinson, and R M Walsh
Test results for a 1.5 T MRI system utilizing a cryogen-free YBCO magnet
IEEE Transactions on Applied Superconductivity 24, 4400705 (2014).

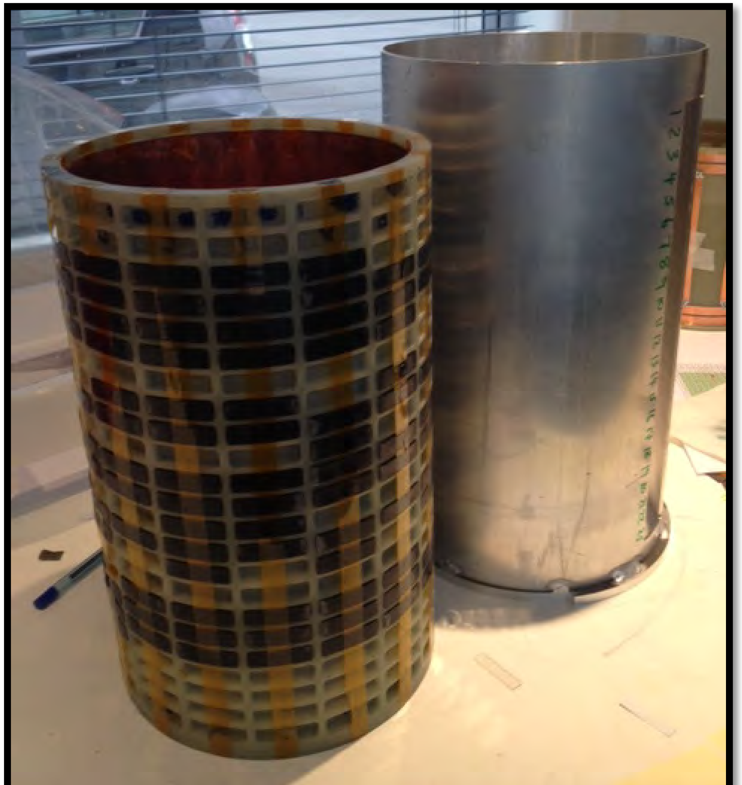
1.5 T HTS MRI unshielded gradient coils

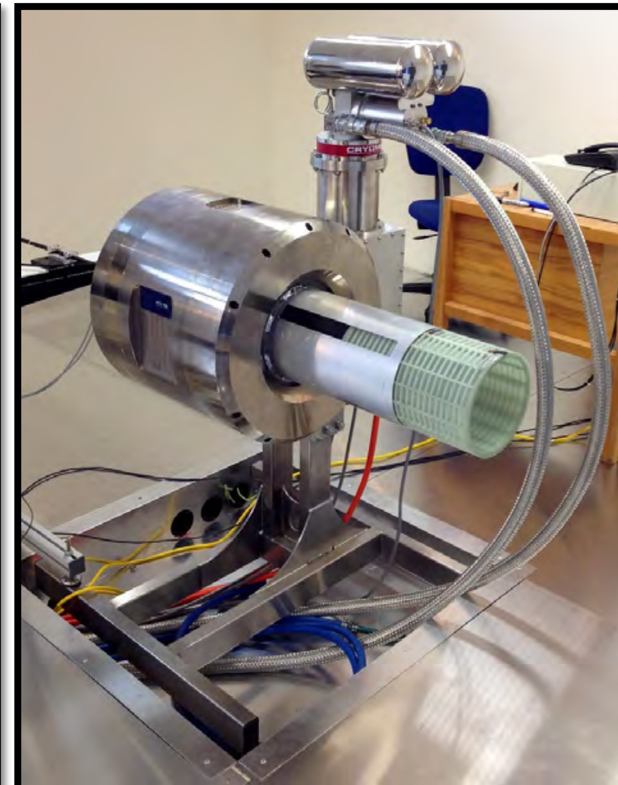
- Gradient coils provide spatial resolution and are typically shielded to prevent interaction with the magnet during pulsing.
- Potential benefits of unshielded gradient coils:
  - Greatly reduced power consumption.
  - Reduced gradient coil and shim heating.
  - Simpler construction.
  - Reduced magnet bore / reduction in HTS wire cost.
- Increase in heat load to 20 K cold mass
  - < 1 K increase in magnet coil temperature during full day of routine imaging.
- Variations in MR signal phase due to eddy currents in the magnet
  - Correct with standard pulse pre-emphasis techniques.

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

1.5 T HTS MRI passive shim cassette

- Passive shimming using up to 368 iron plates of varying thickness.





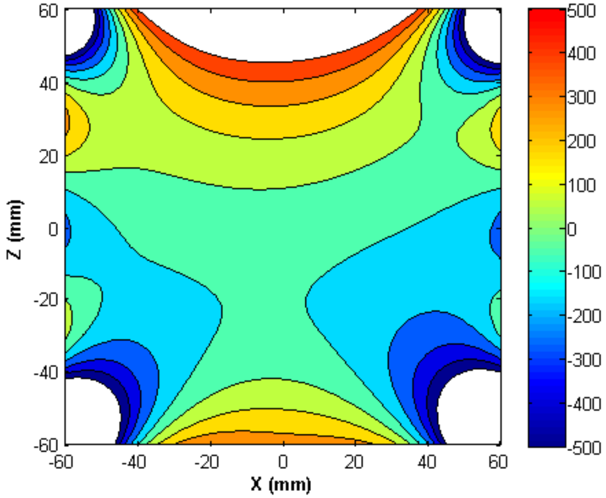
  - Measurement – decompose into spherical harmonics – shim calculation – construction.
    - Automated using custom software.
- Question over impact of screening currents in YBCO tape.

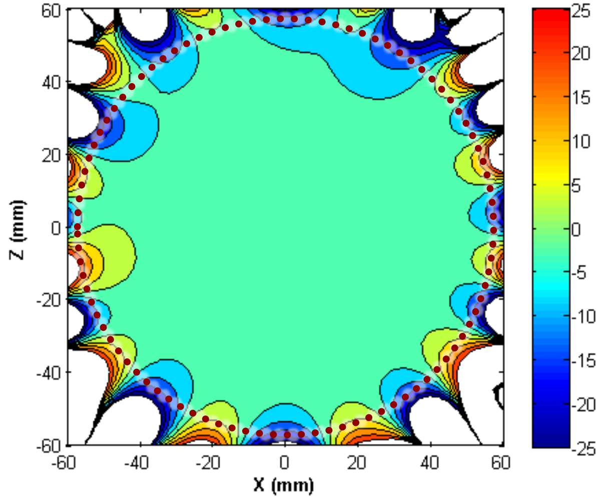
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

1.5 T HTS MRI shimming and homogeneity

Field map prior to shimming

Field map after three passive shim iterations with full set of active shims applied



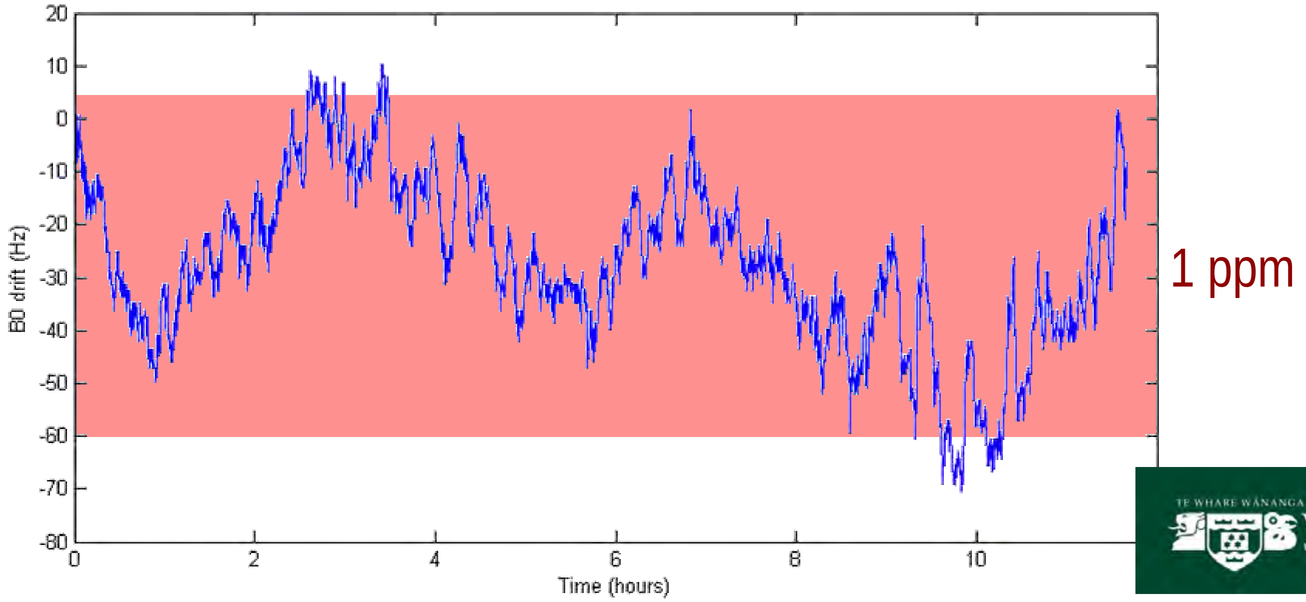


Note 20× reduction in scale

- Scale in ppm relative to 1.5 T. Contours 100 ppm / 5 ppm.
- Successfully shimmed to 49 ppm pk-pk over ∅115 mm sphere.
- Changes in homogeneity immediately following magnet ramp or thermal cycles are within the correction range of the active shims.

1.5 T HTS MRI field stability – NMR measurement

- HTS magnet operates in **driven mode.**
  - Magnet current stabilised to <1 ppm by Danfysik 854 power supply.
- Iron yoke temperature stabilised to within 0.1°C.
- Observed long term change in resonant frequency ≈1 ppm.
  - Could be further improved by feeding back NMR signal to power supply.
- Short term oscillations ~40 nT assessed by MR pulse sequences.



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

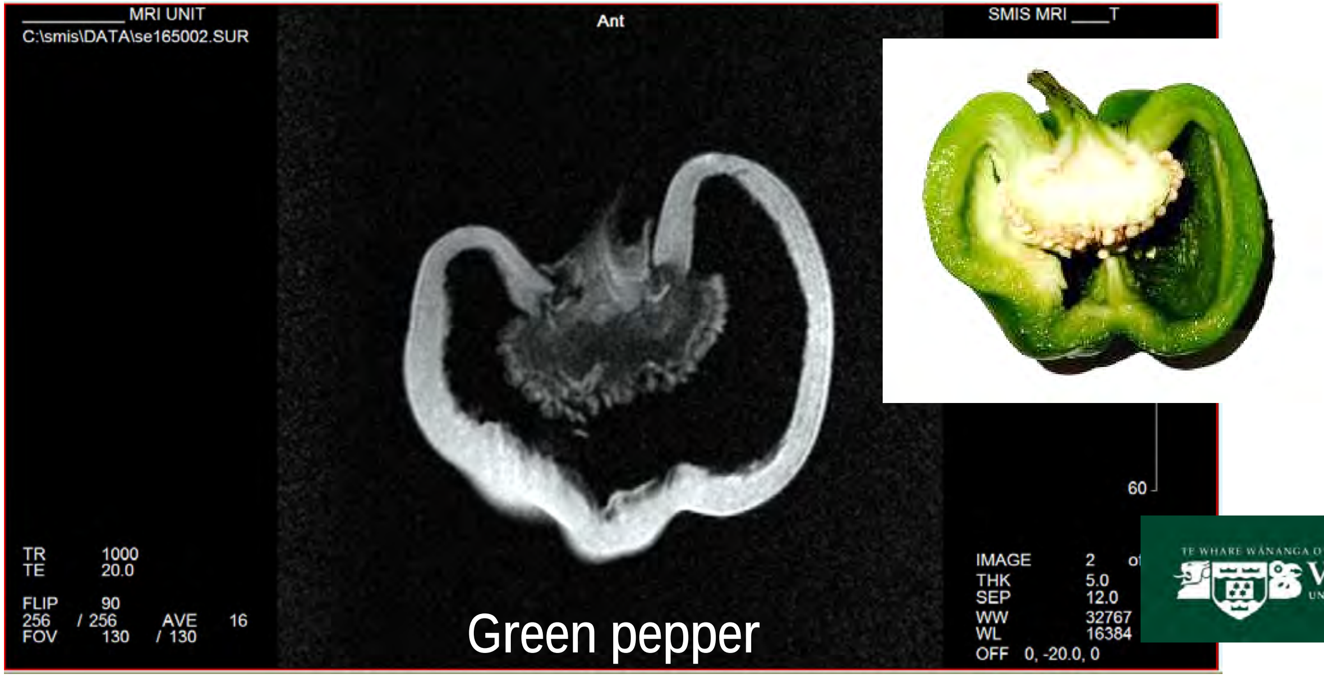
1.5 T HTS MRI imaging gallery

- 5 mm slice thickness offset 8 mm from magnet centre.
- Spin-echo sequence with TR = 300 ms, TE = 20 ms.
- Quadrature driven birdcage resonator for Tx & Rx (∅ 165 mm).
- No Faraday cage.

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

1.5 T HTS MRI imaging gallery

- 5 mm slice thickness.
- Spin-echo sequence with TR = 1000 ms, TE = 20 ms.
- Quadrature driven birdcage resonator for Tx & Rx (∅ 165 mm).
- No Faraday cage.



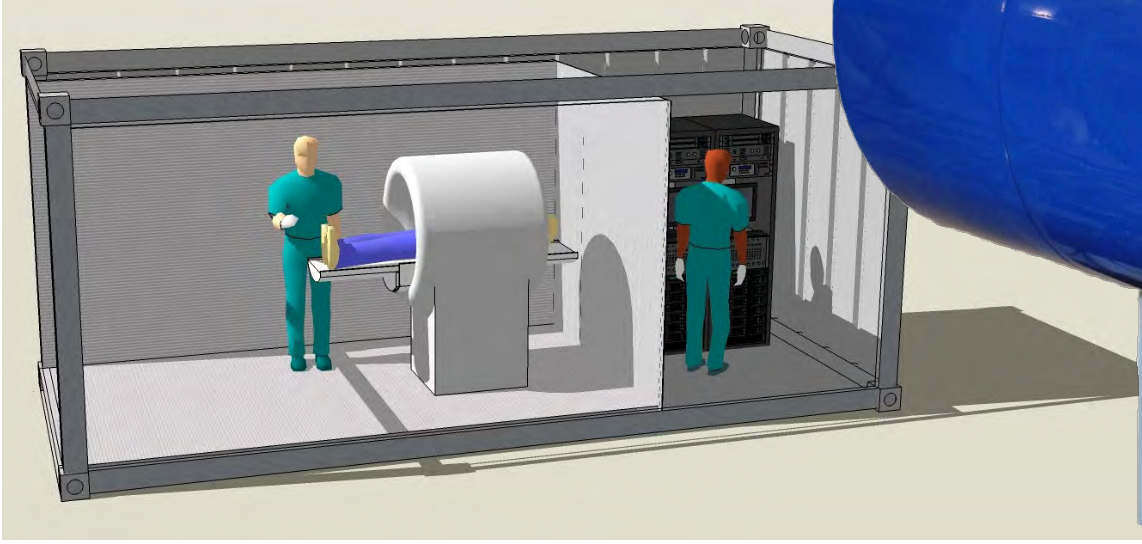
1.5 T HTS MRI imaging gallery

- 8 mm slice thickness offset 24 mm from magnet centre.
- Spin-echo sequence with TR = 500 ms, TE = 16 ms.
- Quadrature driven birdcage resonator for Tx & Rx (∅ 165 mm).

HTS MRI project summary

- Clinical-grade MRI is possible using a YBCO HTS magnet operating in driven mode.

- Future developments:
  - NMR field lock to improve field stability.
  - "Instant on" ramp and image capability.
  - Variable field imaging.
  - Transportable whole-body MRI (MgB_2).



Flux pump excitation of HTS coils

- No technology presently exists for making an HTS persistent joint.
  - HTS magnets need to be operated in driven mode.
- Current leads: Q_{lead} = 40 mW/A for each lead. 125 A = 10 W.
  - Usually the largest single heat load on the cryocooler.
- Cooling cost increases with current and stability requirements.

Magnet power supply

Cryocooler compressor

0.5 × 0.5 × 0.5 m^3

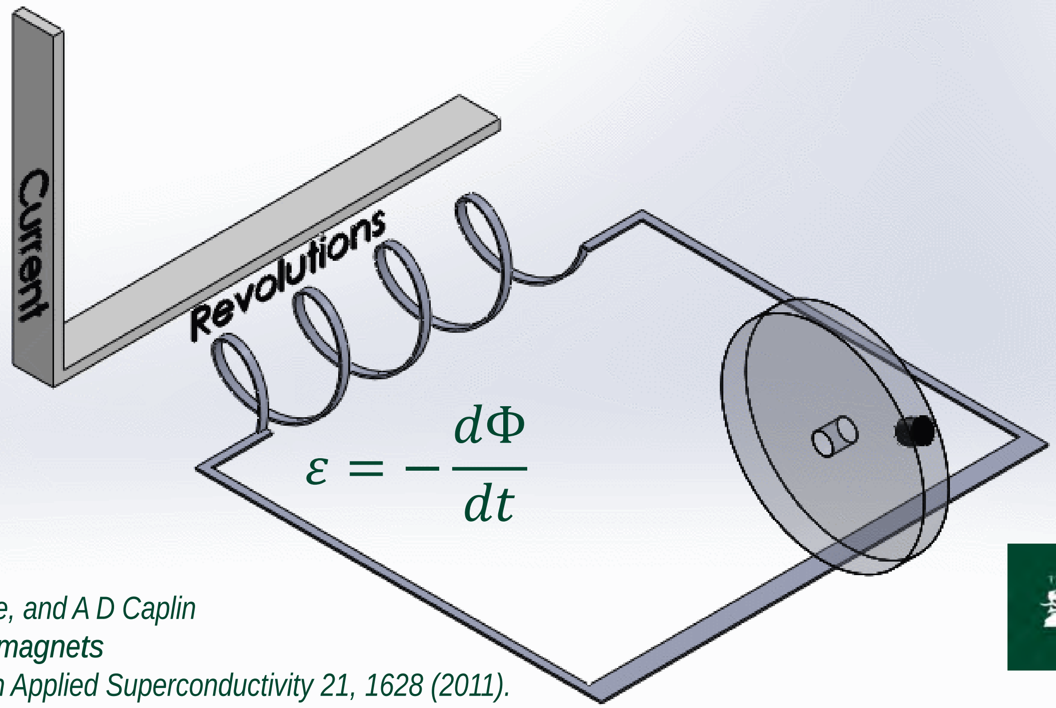
Example heat loads (W) on cooling system

Heat load	Description	100 A 77 K	100 A 30 K	500 A 30 K
Q_{lead}	Current lead conduction and resistance	8	8	40
Q_{wall}	Cryostat wall conduction and radiation	8	10	10
Q_{joint}	Ohmic dissipation at joints	0.1	0.1	2.0
	Total heat load	16.1	18.1	52.0
	Specific cooling factor	14.5	81.8	81.8
	Required cryocooler power	233	1480	4250

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

Flux pump principle of operation

- Inductively excite the coil without the need for current leads.
- Current accumulator – zero resistance of a superconductor.
- Increasing current results from Faraday's law of induction.

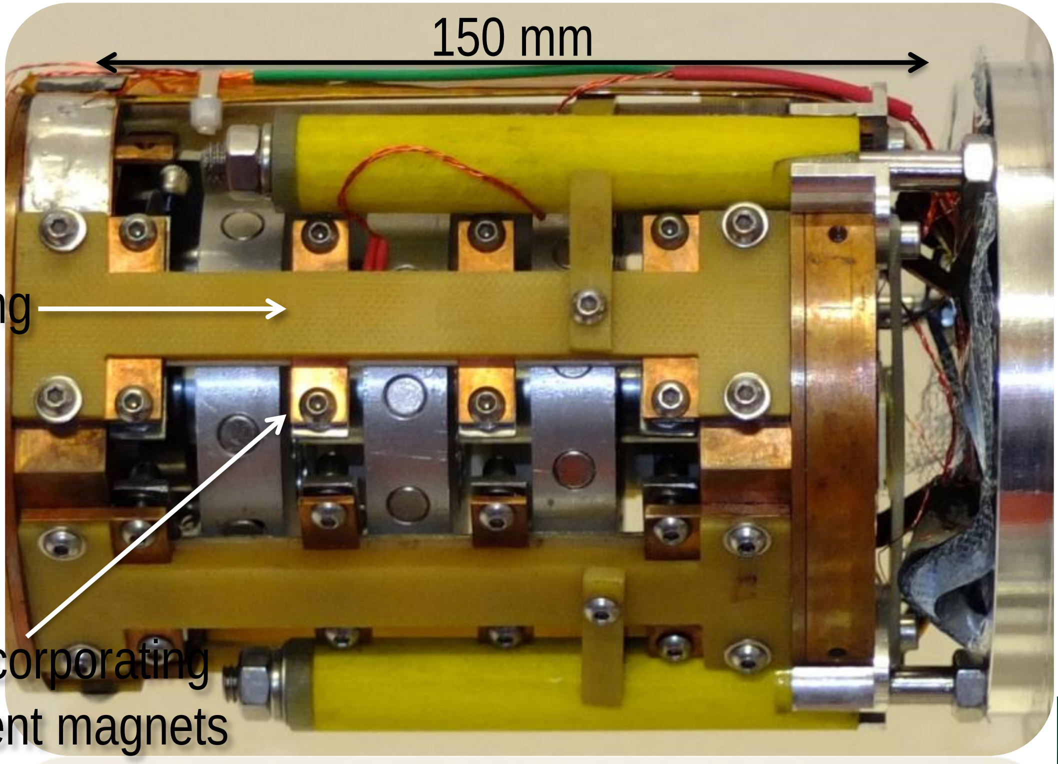


$$\varepsilon = -\frac{d\Phi}{dt}$$

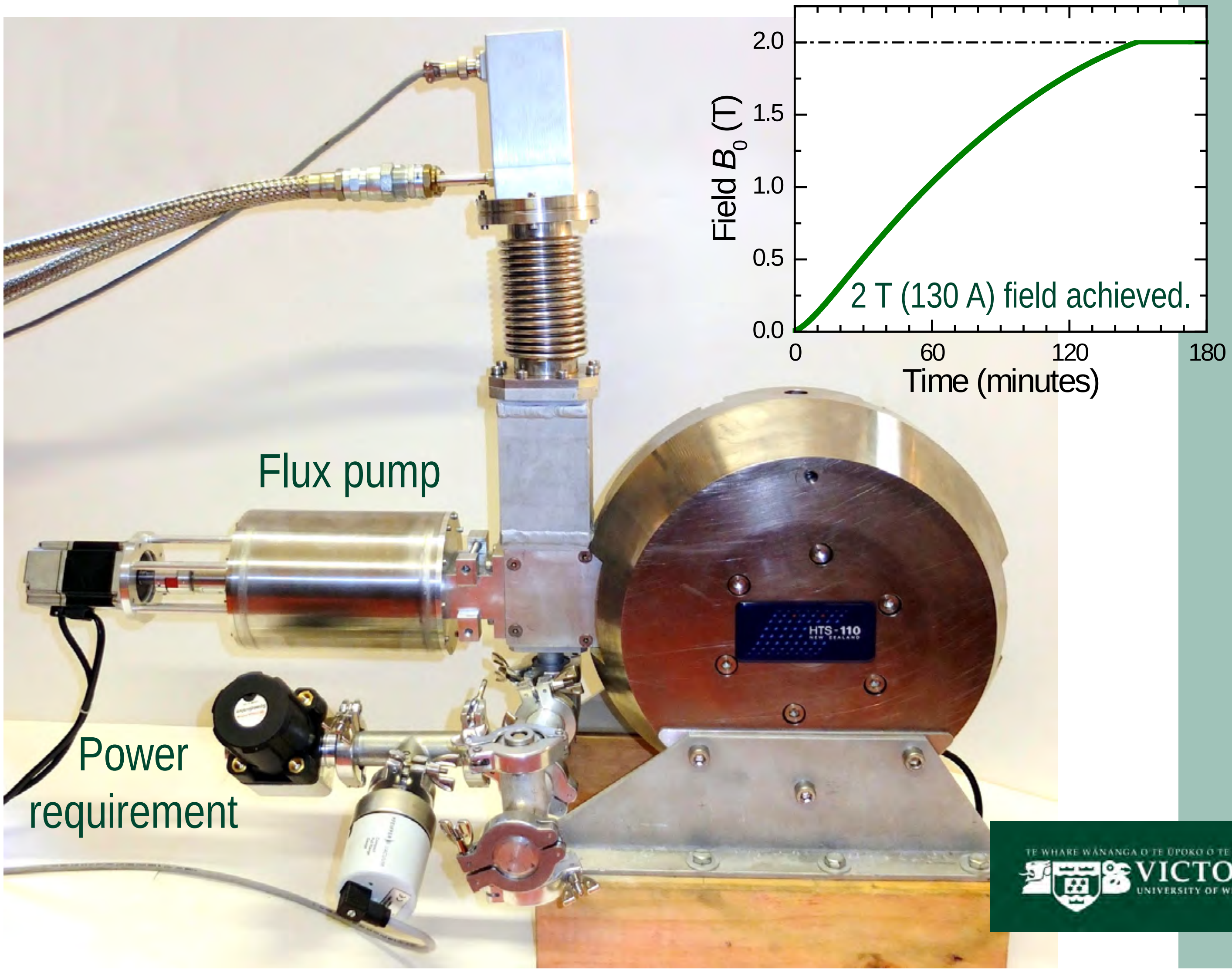
C Hoffmann, D Pooke, and A D Caplin
Flux pump for HTS magnets
IEEE Transactions on Applied Superconductivity 21, 1628 (2011).

HTS flux pump construction

- $Q < 2$ W total heat load at full field (130 A) – factor 4.5 reduction.
  - Residual heat load due to "dynamic resistance" and magnetisation losses.
- Much reduced size, weight and power requirement.

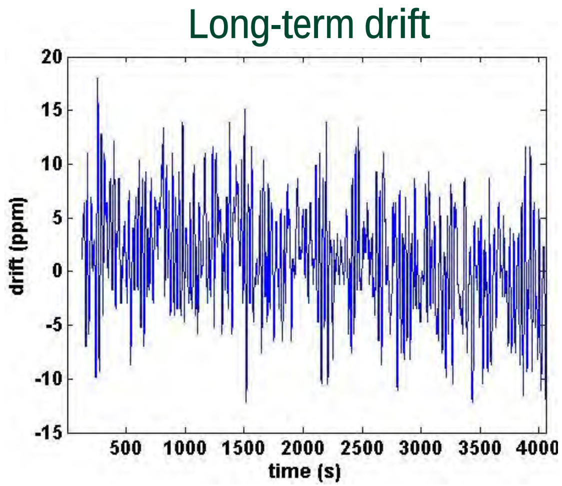


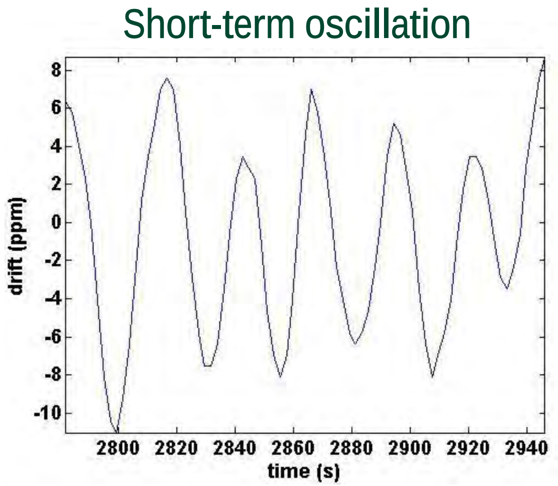
HTS flux pump retrofitted to a 2 T HTS NMR magnet



HTS flux pump NMR field stability

- Free induction decay (FID) used to track the B_0 field change.
- Total variation over 1 hour: 30 ppm (60 μT) peak-to-peak.
- Short-term oscillation period ~25 s.
- Result of the available feedback resolution of the Hall probe.
- Improve with additional feedback such as a ^{2}H lock channel.



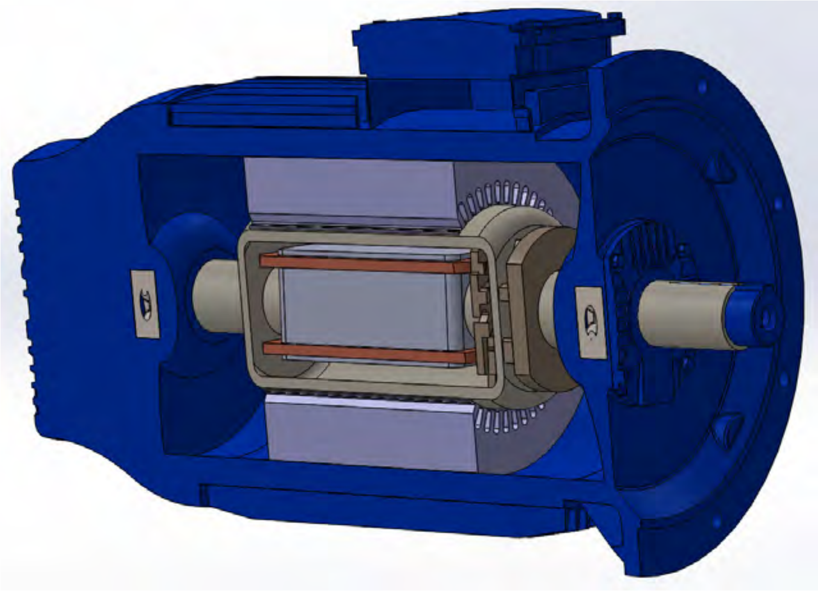


R M Walsh, R Slade, D Pooke, and C Hoffmann
Characterization of current stability in an HTS NMR system energized by an HTS flux pump
IEEE Transactions on Applied Superconductivity 24, 4600805 (2014).

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

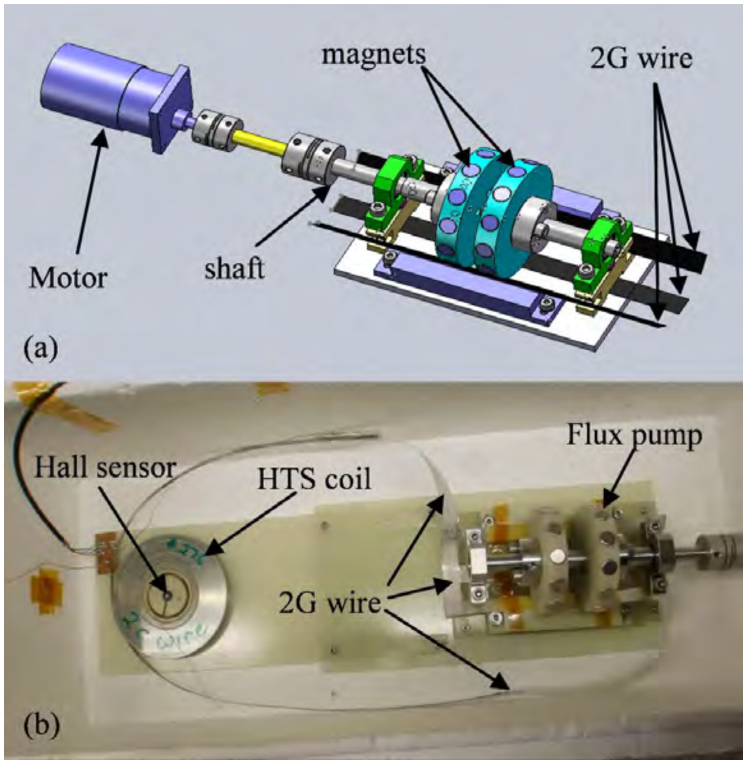
Axial flux pump exciter for a 55 kW HTS generator

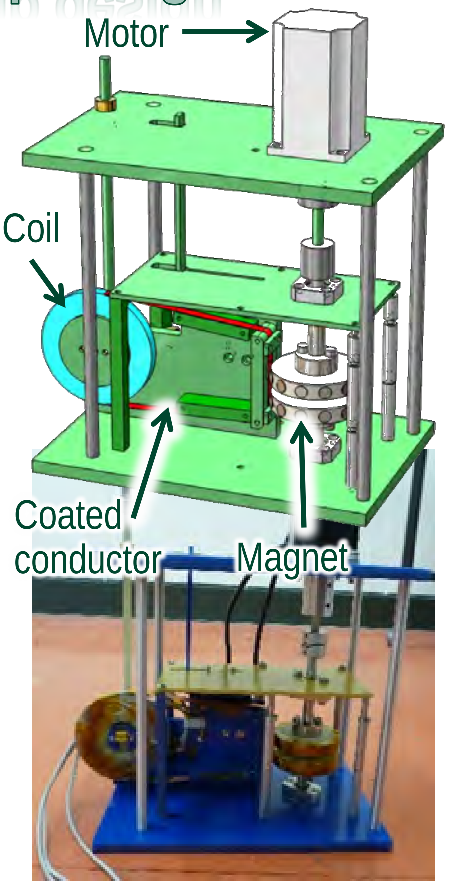
- Project aims:
  - Develop the knowledge necessary to build a prototype HTS rotor, and demonstrate current excitation at 77 K and 1500 rpm.
  - Demonstrate a novel (axial) flux-pump current excitation concept.
  - Design a flux-pump exciter suitable for rotating machine implementation.
    - Requires effective operation across practical cryogenic gaps.
  - Design and test integrated rotating cryostat, exciter and coils.
    - Rotating cryostat and torque tube being built by Fabrum Solutions.



FABRUM SOLUTIONS
AUT UNIVERSITY AUCKLAND, NEW ZEALAND
WelTec Wellington Institute of Technology Te Whare Wānanga o te Awakairangi
HTS-110
posco
창원대학교 CHANGWON NATIONAL UNIVERSITY
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI VICTORIA UNIVERSITY OF WELLINGTON

Four generations of flux pump design





Under construction

Radial

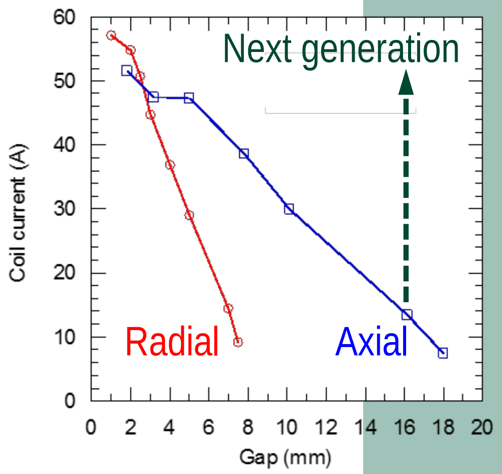
Axial

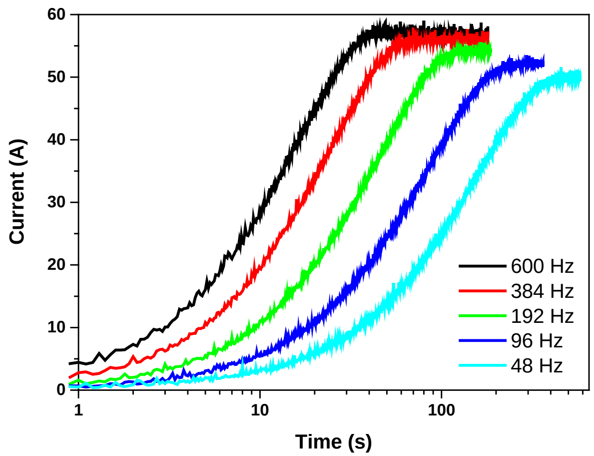
Z Jiang, K Hamilton, N Amemiya, R A Badcock, and C W Bumby
Dynamic resistance of a high-T_c superconducting flux pump
Applied Physics Letters 105, 112601 (2014).

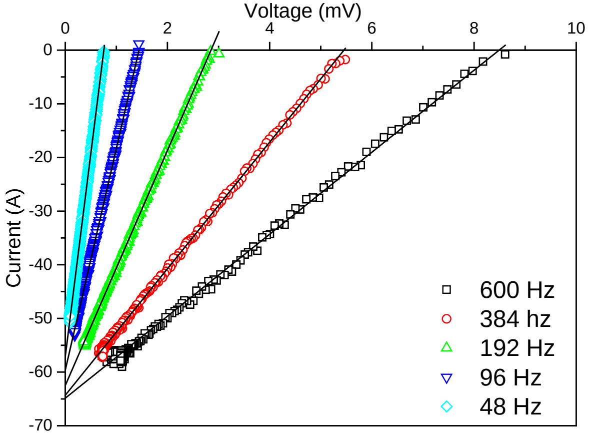
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Flux pump current status

- Improved performance (achievable coil current) across the gap from radial to axial design.
- Further optimised using finite element modelling.
- Newest design maximises gap through minimisation of magnetic reluctance (field shaping).
  - Magnetic field at 16 mm separation expected to be similar to that of previous design at 1 mm.
  - Sufficient to pump across the cryostat wall.
- Improved pumping speed by faster rotation.







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

NZ provisional patent applied for (628556).

Roebel cabling

- Started R&D (at IRL) in 2004.
- Commercialised through GCS Ltd.

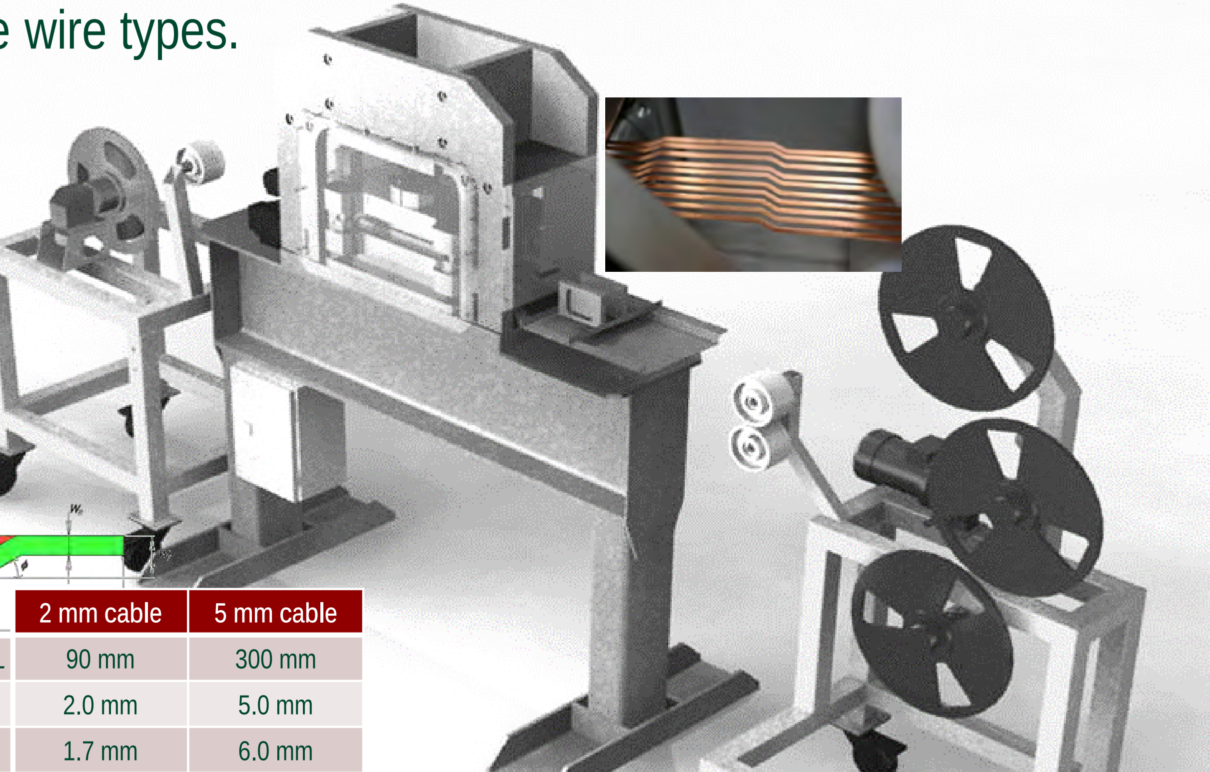
- Develop long-length automated Roebel cable manufacture from multiple wire suppliers (AMSC, SuperPower, Fujikura, STI).
- Characterise physical properties.
- Prove applications in high-current and/or ac machines:
  - 150 MW generator (Siemens).
  - 1 MVA **transformer** (Robinson Research Institute).
  - High-field magnets (CERN).

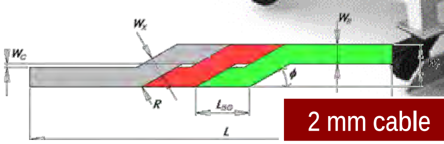
General Cable SUPERCONDUCTORS Limited

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

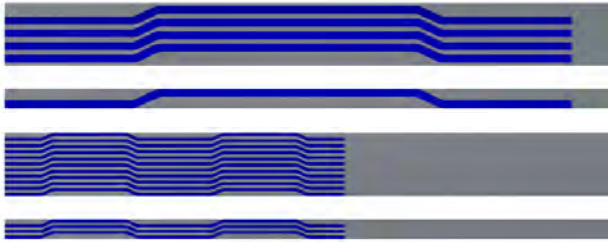
Roebel cabling – punching

- Present designs are a compromise reflecting the wide range of available wire types.





	2 mm cable	5 mm cable
Transposition length, $2L$	90 mm	300 mm
Strand width, W_R	2.0 mm	5.0 mm
Crossover width, W_X	1.7 mm	6.0 mm



4×5 mm in 40 mm

1×5 mm in 12 mm

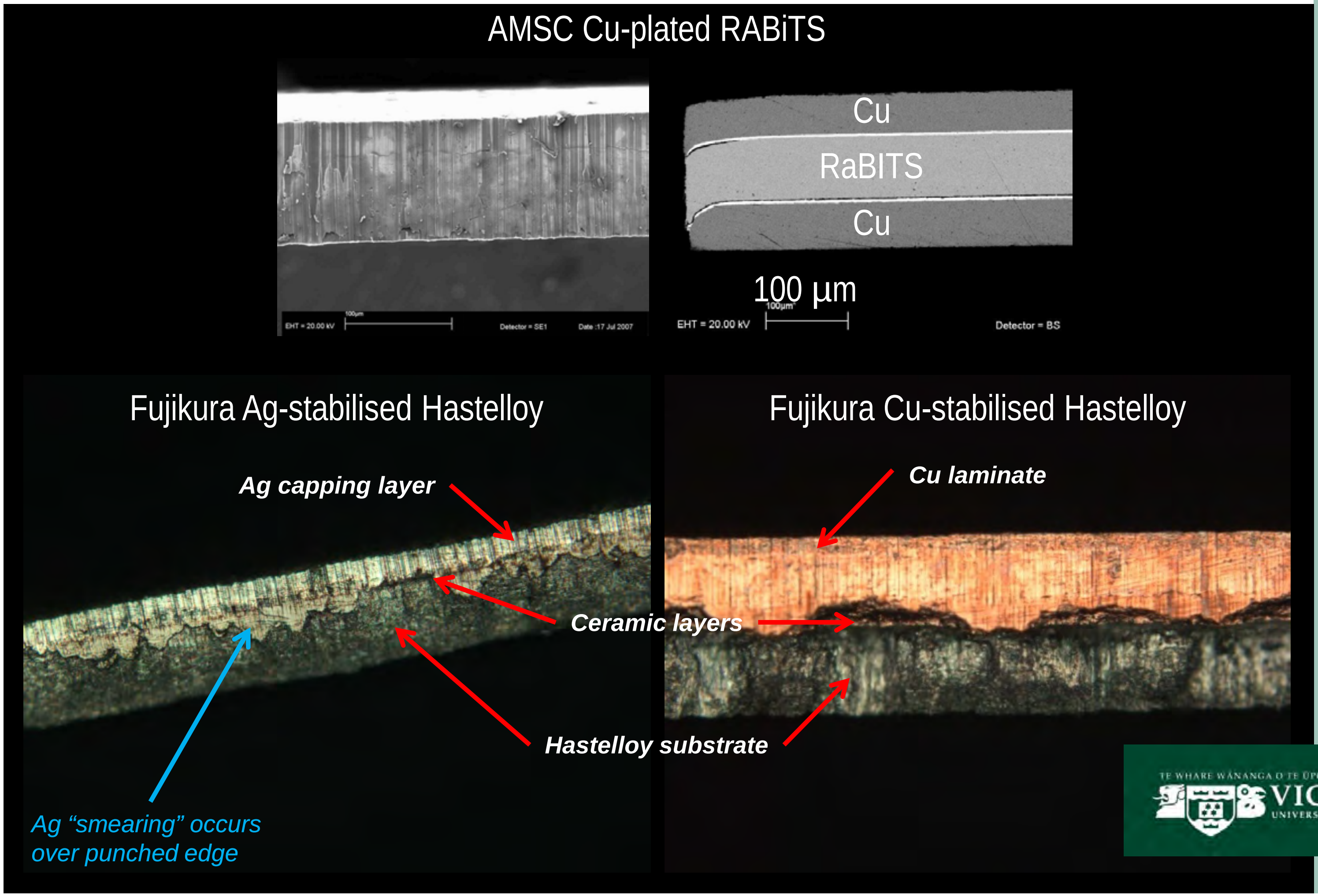
10×2 mm in 40 mm

3×2 mm in 12 mm

Automated multi-strand punching machine

Roebel cabling – quality of punched edges

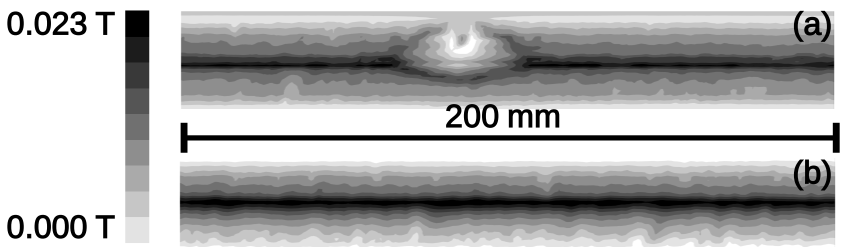
- Some smearing of soft coatings, minimal damage to edges (3–7%).

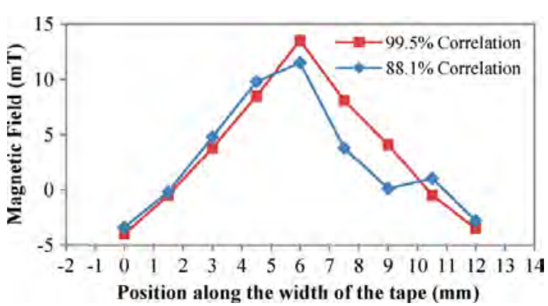


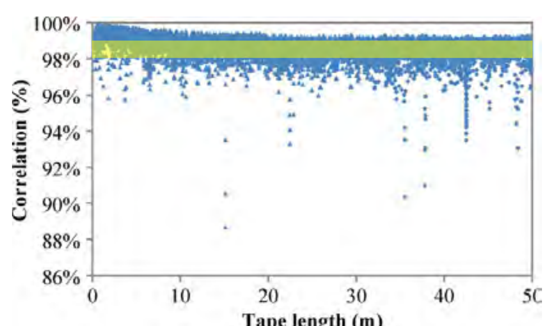
Roebel cabling – testing of punched strands

- Multiple approaches to testing:
  - Continuous scanning of remanent field.
  - Full wire transport measurement in liquid nitrogen bath.
    - Punched strands are moisture sensitive.
    - Heat in dry nitrogen only.
  - Short sample measurement (e.g. transposition section).

Spiral racetrack former for testing strands up to 30 m







N J Long, R A Badcock, K Hamilton, A Wright, Z Jiang, and L S Lakshmi
Development of YBCO Roebel cables for high current transport and low AC loss applications
Journal of Physics: Conference Series 234, 022021 (2010).

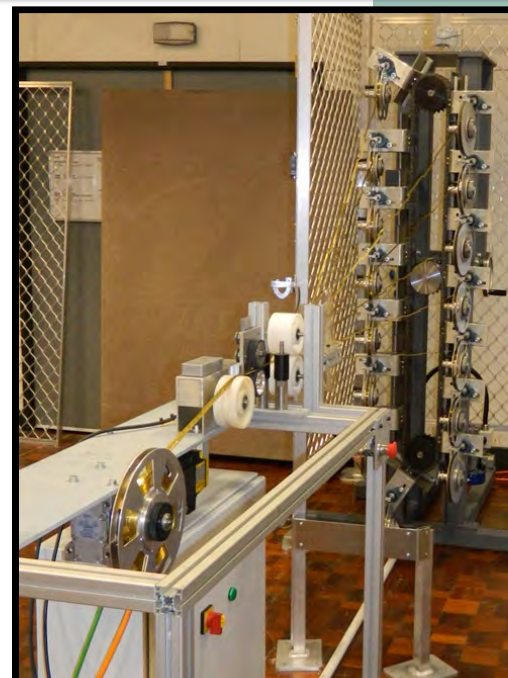
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Roebel cabling – winding

- Long length registration of crossovers.
  - Need high precision for each transposition length in the punching process.
  - Need tension control on strands in winding.
- Measured I_c is close to expected I_c.
  - For short length cables accurate I_c measurement is difficult.
  - There are strong self-field effects that must be accounted for.

Example I_c measurement of assembled cables at 77 K

Cable architecture	Cable I_c (A)		
	Σ Strands	Calculated	Measured
5/2	252	220	203
9/2	426	339	319
9/2	426	359	342
15/5	1454	1033	1100
15/5	1616	1109	1010
15/5	2093	1372	1410



Automated planetary winding machines

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

Roebel cabling – perspectives

- Manufacturing process in place for long lengths, supplier neutral.
  - Cabling demonstrated with wire from AMSC, SuperPower, Fujikura, STI.
- kA-class conductors (at 77 K) available.
  - Cables preserve tape I_c performance (~90%).
- Quality control is in hand.
  - Measuring magnetic correlation is relatively easy.
  - Measuring strand I_c is time consuming and adds risk.
- Cables up to 25 metres (15/5) delivered to customers.
  - Cables up to 40 metres wound successfully.
- Cost ultimately dominated by wire cost.
- AC loss well characterised (not discussed here).
- Demonstration in applications underway.

Roebel cable ready for testing at Siemens Corporate Technology

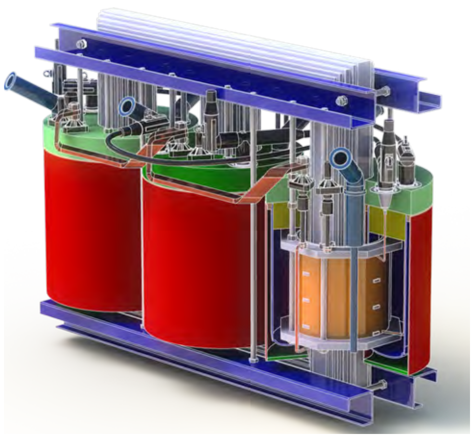
General Cable SUPERCONDUCTORS Limited

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

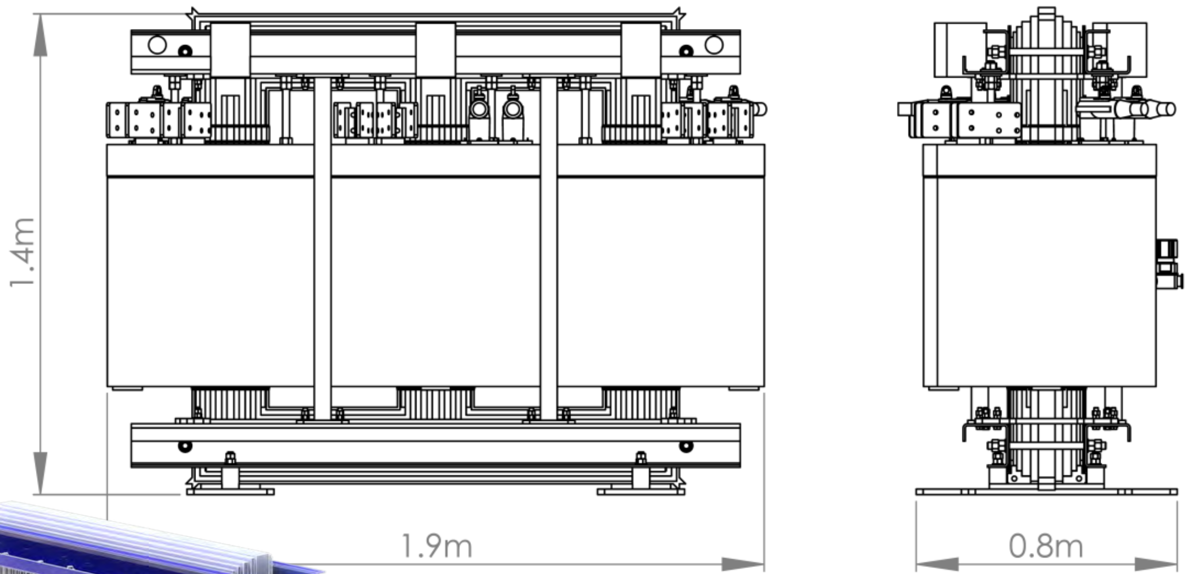
1 MVA grid-connected HTS transformer

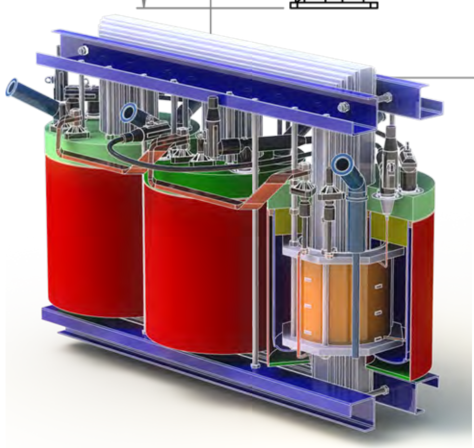
- Project partners
  - Robinson Research Institute (development)
  - PB Power (project management)
  - Vector & North Power (network owners)
  - ETEL & Wilson Transformer (manufacturers)
  - HTS-110 (coil winding)
  - Fabrum Solutions (cryostats)
  - Absolut System (cryogenics)

- Project goals
  - Apply Roebel cable in ac power systems.
  - Design a robust cooling system for HTS transformers.
  - Demonstrate behaviour of a grid-connected HTS system.



1 MVA HTS transformer – dimensions





	Approx. Mass (kg)
Core	2000
Windings + Cryostats	600
Liquid Nitrogen	200
TOTAL	2800

N Glasson, M Staines, R Buckley, M Pannu, and S Kalsi
Development of a 1 MVA 3-phase superconducting transformer using Roebel cable
IEEE Transactions on Applied Superconductivity 21, 1393 (2011).

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

HTS transformer – design parameters

- 3-phase, 1 MVA rating, 70 K (LN_2).
- LV winding (Star connection):
  - 415 V, 1389 A rms (1964 A peak).
  - 19.6 m (20 turns) of GCS 15/5 Roebel cable single layer solenoid coil, strands not insulated.
  - Glass fibre reinforced polymer former.
  - Direct liquid nitrogen contact with the cable.
- HV winding (Delta connection):
  - 11 kV, 30.3 A rms.
  - 980 m (918 turns) of SuperPower 4 mm 2G tape in 24 double pancake coils, kapton wrap.
  - No encapsulation:
    - Maximise heat transfer.
    - Maintain HV withstand voltage.

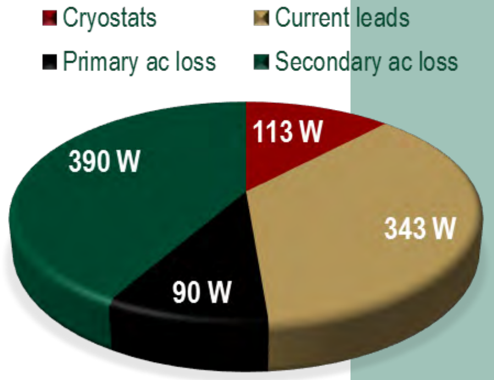
M Staines, N Glasson, M Pannu, K P Thakur, R Badcock, N Allpress, P D'Souza, and E Talantsev
The development of a Roebel cable based 1 MVA HTS transformer
Superconductor Science and Technology 25, 014002 (2012).

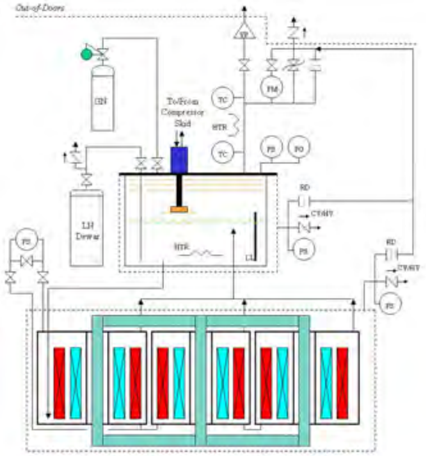
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA UNIVERSITY OF WELLINGTON

1 MVA HTS transformer cooling system

- Sized to provide 1100 W cooling power, with maximum return temperature from the transformer of 70 K.
- Two systems run in parallel:
  - Subcooler using vacuum-pumped bulk nitrogen
    - Confirmed by experiment to provide 1200 W at 70 K.
  - Cryocoolers
    - Up to three GM cryocoolers each providing 500 W at 70 K.
    - Allows for removal for servicing without system warmup.

Heat load (W) on cooling system
Total = 936 W





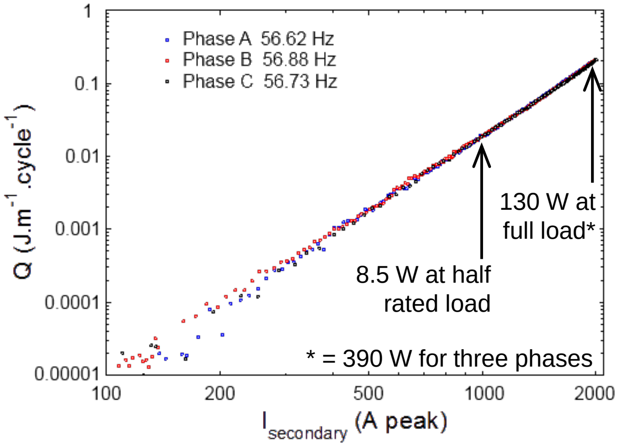
N D Glasson, M Staines, Z Jiang, and N Allpress
Verification testing for a 1 MVA 3-phase demonstration transformer using 2G-HTS Roebel cable
IEEE Transactions on Applied Superconductivity 23, 5500206 (2013).

INNOVATIVE SOLUTIONS
ABSOLUT SYSTEM

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

HTS transformer efficiency

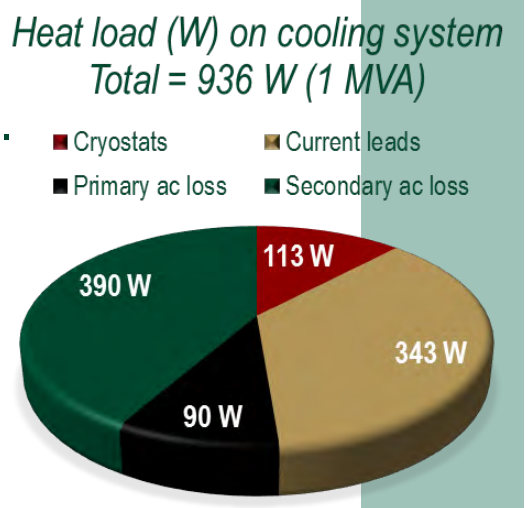
- 1 MVA transformer Minimum Energy Performance Standard
  - 99.27% efficient at half rated load (equates to 3.6 kW loss).
- To match this loss a 1 MVA HTS transformer can have no more than 120 W dissipation in the cryogenic environment.
- **Electrical** efficiency: 99.95% at full load; 99.997% at half load.
- Accounting for cooling (30:1): 98.6% at full load; 99.91% at half load.
- Cost: ~$40,000.



N D Glasson, M Staines, Z Jiang, and N Allpress
Verification testing for a 1 MVA 3-phase demonstration transformer using 2G-HTS Roebel cable
IEEE Transactions on Applied Superconductivity 23, 5500206 (2013).

HTS transformer – scale-up to 40 MVA?

- Conventional 40 MVA transformer losses: 150 kW.
  - 99.6% efficient at full load.
- Translates to a 5 kW dissipation limit in the cryostat.
- Cryostat and current lead losses are little changed.
- We expect a sub-proportional increase in ac loss:
  - Current in the low voltage winding increases by only 50%.
  - Conductor length per turn increases by 260%, but most of the loss is concentrated in the end turns of the windings.
  - ac loss can be further reduced by lowering the operating temperature to 65 K.
- ac loss modelling, validated on the 1 MVA transformer, is underway to quantify the projected loss.
- Using Roebel cable, ac loss is not a fundamental obstacle to HTS transformer commercialisation.



Summary

- Clinical-grade MRI is possible using an HTS magnet in driven mode.
- The flux pump can provide low heat leak excitation of HTS coils.
- High-current, low ac-loss Roebel cable is commercially viable.
- ac loss is no impediment to HTS transformer commercialisation.
- **Biggest issue affecting all projects is the cost of the wire.**

We look forward to working with you on your HTS challenges!

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