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Presentation AT-5 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.

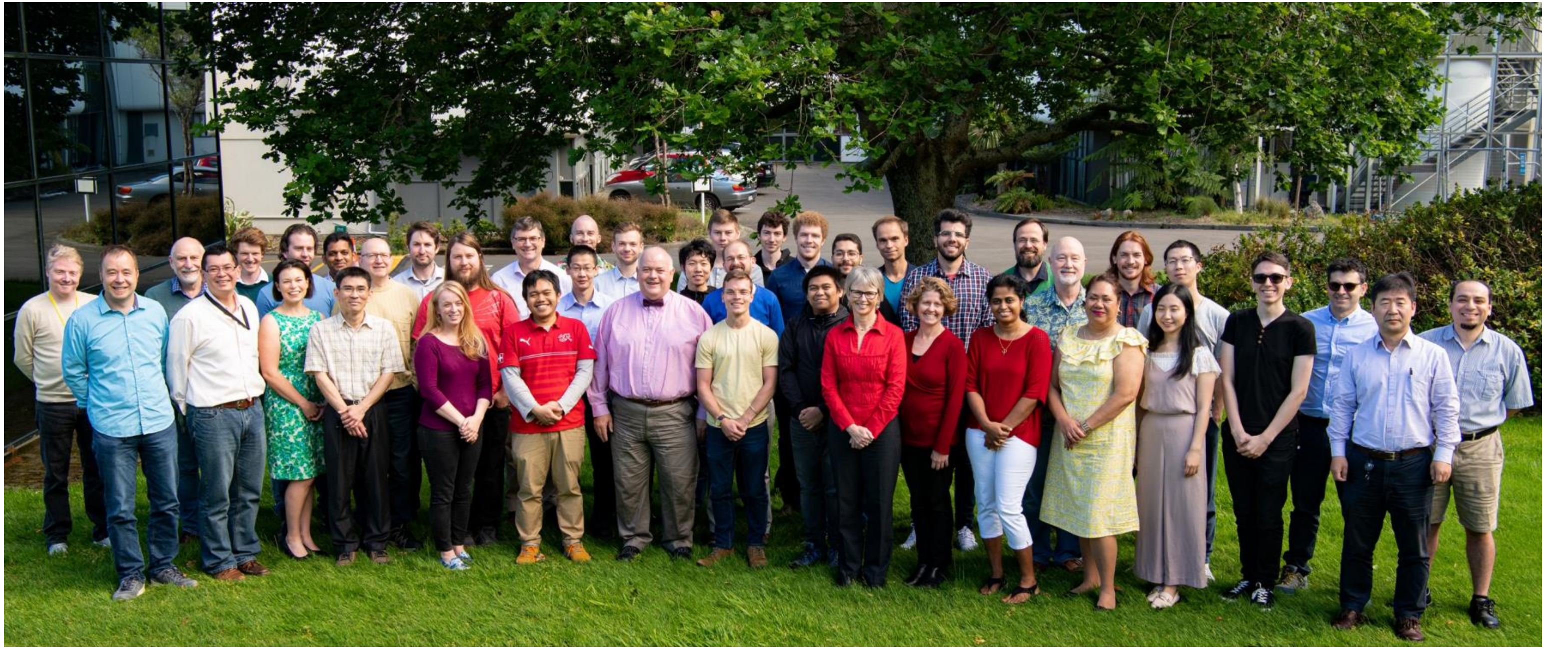
Current superconductivity and cryogenics research in New Zealand

Joint Conference
10th ACASC
2nd Asian-ICMC
CSSJ

Nick Long

Robinson Research Institute, Victoria University of Wellington, New Zealand

Robinson Research Institute

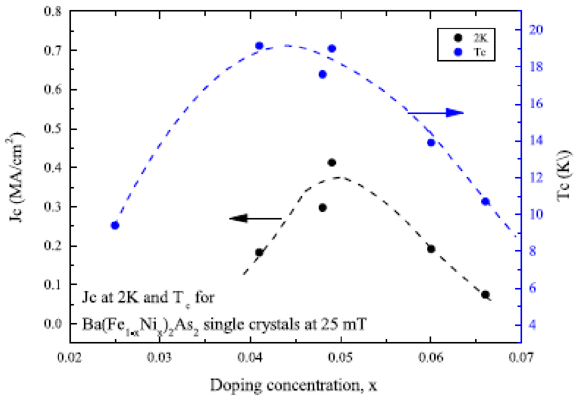


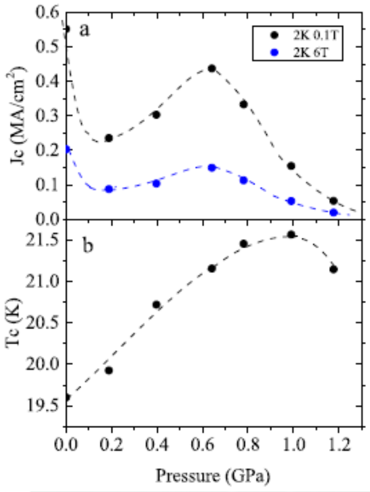
Contents

- Materials science
- HTS cables
- Critical current (SuperCurrent) measurement system
- MRI
- Rotating machines
- NZ companies and HTS
- Superconductors for space applications
- ISS 2020

Fe based superconductors

- Led by Dr Shen Chong
- Ba 122 family a promising candidate for high-field applications
- Recent study: effect of pressure and doping on T_c , J_c in $Ba(Fe_{1-x}Ni_x)_2As_2$
- T_c pressure dependence is typical of HTSC
- Maximum in J_c associated with a possible QCP
- J_c shows anomalous pressure dependent behaviour. Peak in J_c around 0.65 GPa.





G Bioletti *et al.* Supercond. Sci. Technol. 32 (2019) 064001

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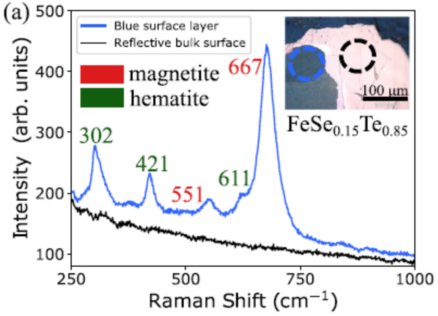
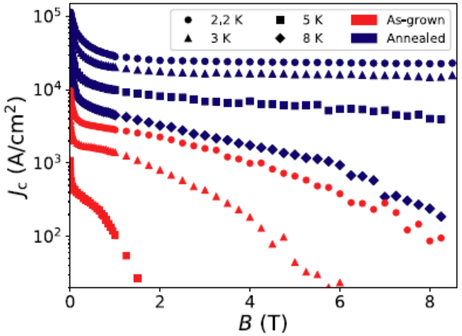
Thermal post processing of $FeSe_{1-x}Te_x$

- $FeSe_{1-x}Te_x$ of interest for high Bc_2 and high J_c properties
- Air annealing leads to the formation of hematite (α-Fe2O3) and magnetite (Fe3O4) on the surface of $FeSe_{1-x}Te_x$
  - Observe an increase in T_c, from 7 to 14 K, and in the critical current density, J_c, by one order of magnitude
- Annealing is more effective in improving the superconducting properties in this family of superconductors than elaborate synthesis procedures
- Optimal annealing conditions depend on the size of the sample.
  - Reduction of excess interstitial Fe is thought to be main factor

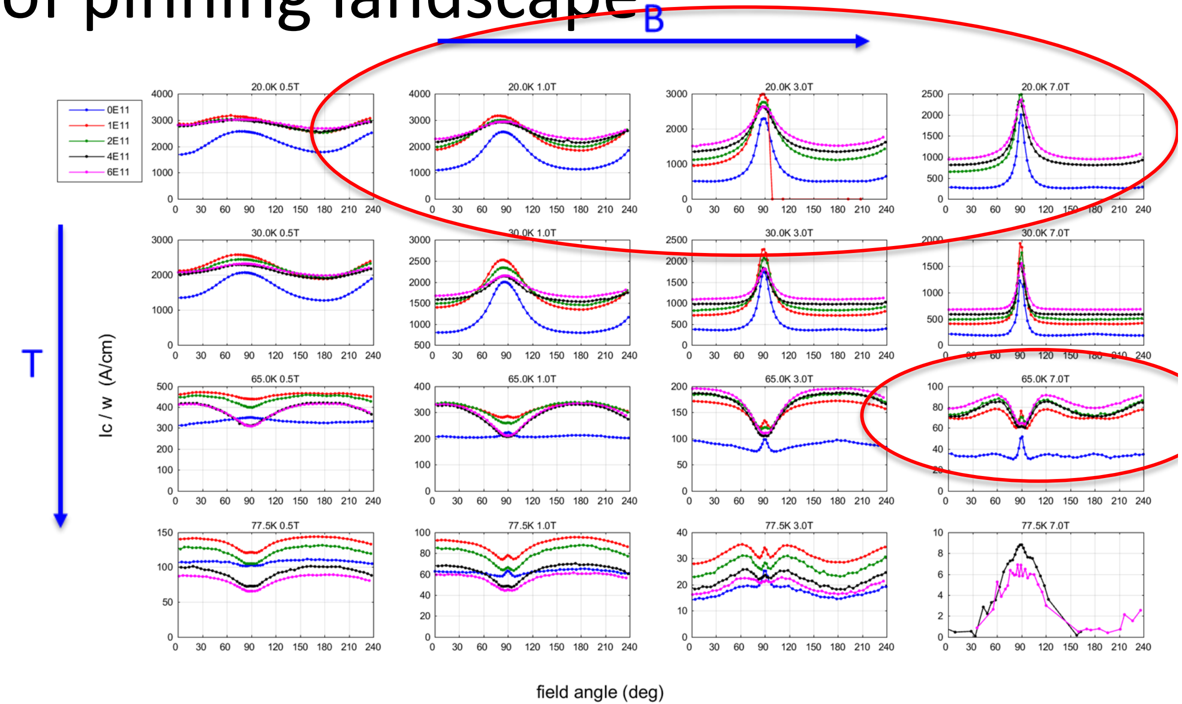




D M Uhrig et al. Supercond. Sci. Technol. 32 (2019) 074002

Rational design of pinning landscape

- Controlled introduction of defects using ion beam irradiation
- AMSC production samples (Ag capped)
- Normal incident Au irradiation of MOD REBCO at 16-18 MeV
- Strong c-axis peaks at higher temperatures but not at low temperature



N Strickland, S. Wimbush, N. Long

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Analysis of $J_c(\theta)$: Maximum entropy distributions

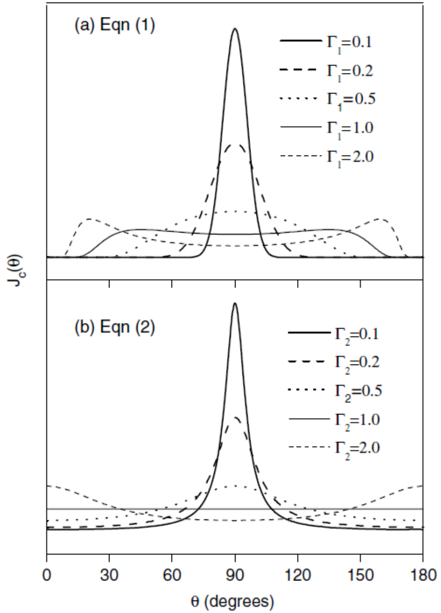
- Angular-Gaussian

$$J_c(\theta) = \frac{J_0}{\sqrt{2\pi}\Gamma \sin^2\theta} \exp\left(-\frac{1}{2\Gamma^2 \tan^2\theta}\right)$$

- Angular-Lorentzian

$$J_c(\theta) = \frac{1}{\pi} \frac{J_0 \Gamma}{\cos^2\theta + \Gamma^2 \sin^2\theta}$$

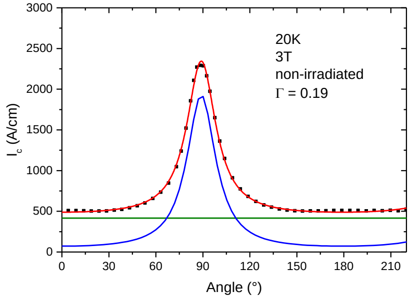
- Derived from the effect of central limit theorem, or from information entropy



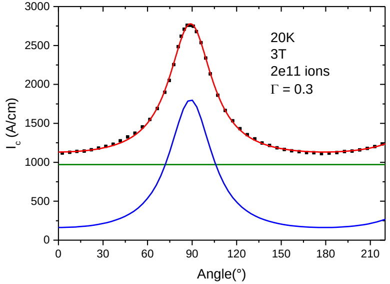
NJ Long, Supercond. Sci. Technol. 21 (2008) 025007

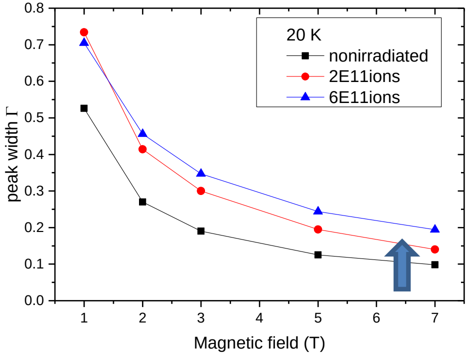
Analysis: Peak broadening at low T

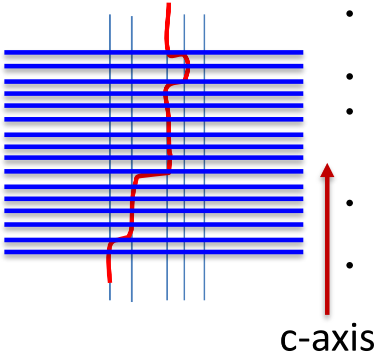
At 20 K data fits a single angular-Lorentzian + constant term



irradiation







- Vortices are interacting with c-axis aligned radiation tracks
- Interact at all angles
- Increase in uniform component is a measure of increased pinning at all angles
- Increase in Γ is a measure of increased pinning at all angles
- Lack of a c-axis peak can mislead you into thinking there is no interaction

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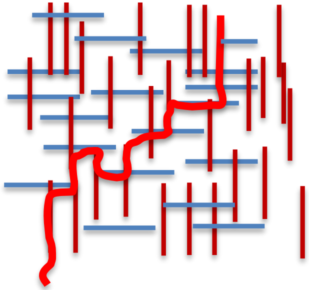
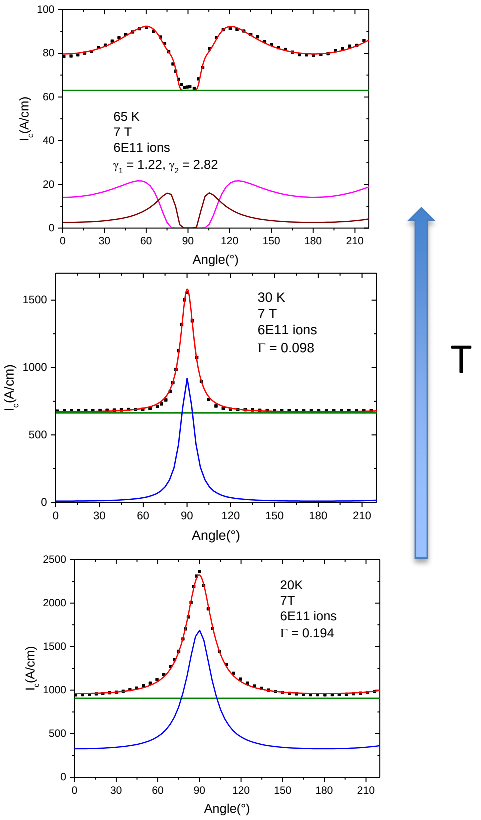
Analysis: $J_c(\theta)$ at 7 T

- How to explain and predict the behaviour with temperature?
- At higher temperature (65K) we have a large uniform component and 2 c-axis components
  - Must be 2 defect populations broadening the c-axis pinning
    - Stacking faults
    - Intrinsic ab-plane pinning? Point defects?
  - No ab-plane peak as stacking faults density not high enough
  - Always have a large isotropic averaging (green component)
- At low T – dominant intrinsic ab-plane pinning gives a peaked distribution
- For prediction of J_c need a map of components in (B,T) space
  - R Knibbe et al, SuST 29 (6), 065006

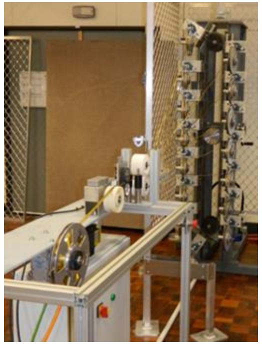


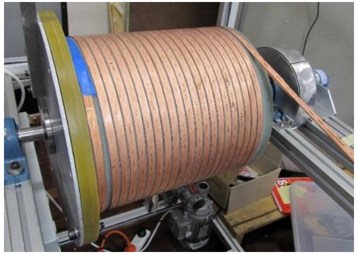


Roebel cable

- High-current or AC applications – need transposed cable
- Roebel is the nearest form-fit-function replacement for LTS Rutherford cable
- Long-length winding Roebel manufacturing at Robinson
  - 15/5 cable (15 x 5 mm strands)
  - 10/2 cable (10 x 2 mm strands)
- Lengths up to 30 m delivered to customers

HTS Roebel cable





HTS Roebel cable wound for transformer

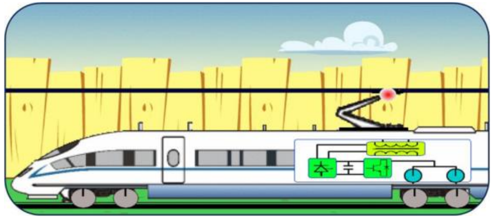
1 MVA Transformer

- AC loss
  - ~120 W loss per phase at rated current of 1.4 kA RMS at 70 K
  - Load loss due to AC loss ~1% - matching conventional 1 MVA performance assuming 30x cooling penalty
  - Good agreement with modelling results
- Total current lead loss ~ 345 W
- Heat leak loss ~ 180 W
- Stability of continuously operated sub-cooled nitrogen system – patent pending system developed
- High voltage withstand – some materials issues identified

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

Traction transformer

- Project lead: Beijing Jiaotong University
- Development of high-capacity superconducting transformers for high-speed trains
- Traction transformer – source of power for core functions, traction and braking
- Others: Innost, Zhuzhou Times New Material Technology Co, Ltd., Zhuzhou Liancheng Group Co., Ltd, Beijing University of Aeronautics and Astronautics
- Robinson role
  - Superconducting transformer design
  - Dewar technology
  - Roebel cable
  - AC loss prediction, measurement and management

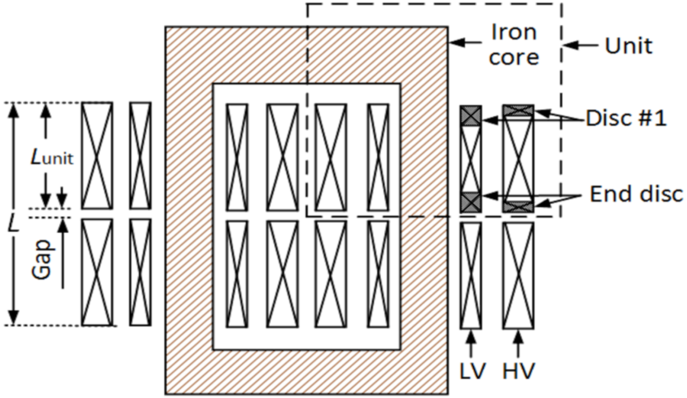


Goals of traction transformer project

Achieve high-capacity, high efficiency, long life, lightweight and manufacturable

	conventional	HTS	comparison
capacity/MVA	6.4	6.6	
efficiency	~95%	~99%	Increase efficiency by 4%
weight/t	6.7	~3	Reduce weight by 30% or more
size/mm	4300×3050×850	~2609×2295×834	Reduce the volume by more than 30%
Cooling medium	Insulating oil	Liquid N2 (77K)	No fire hazards, environmental adaptability

AC loss for traction transformer

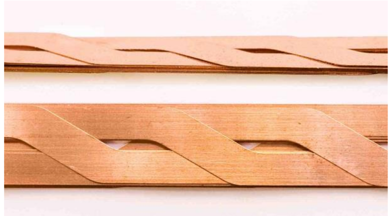


Items	Value
Winding length L (m)	1
Number of turns in each HV winding disc	14
Number of discs stacked to make the HV winding per unit	116
Number of layers of 8-strand Roebel cable in LV winding	3
Number of turns in one layer in LV winding	40
Number of total turns per unit in HV winding	1624
Number of total turns per unit in LV winding	120
Inner diameter of HV winding (mm)	437
Inner diameter of LV winding (mm)	285
Axial gap between the two units on each leg of the core (mm)	20
Short-circuit impedance (%)	43

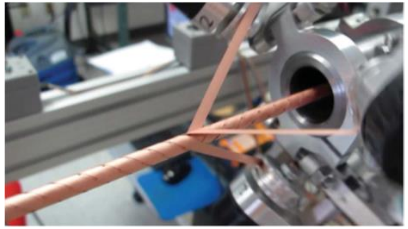
- Compromise between dimensions and AC loss
- Use a hybrid winding with different J_c wires
- With flux diverters we can get AC loss to 1.859 kW, which meets AC loss target for the project.

Alternative cable solution

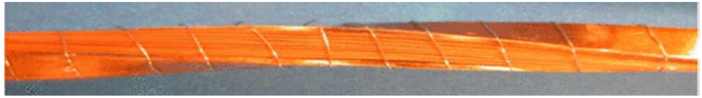
Some existing cables



Roebel cable

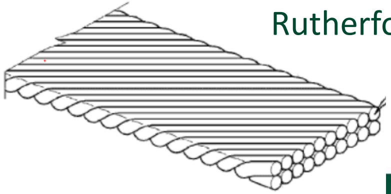


Corc™ cable



Twisted-Stack

Rutherford

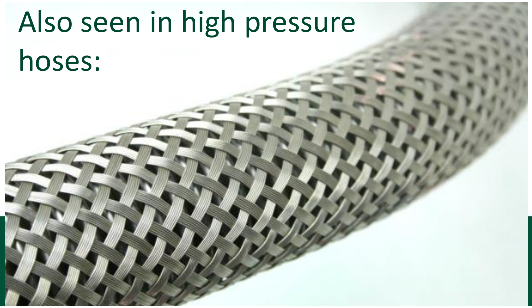


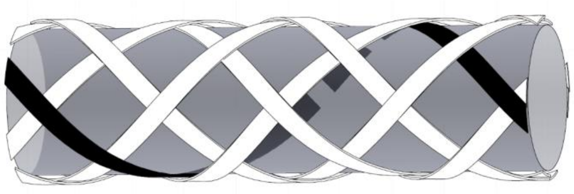
Sock woven cable

Inspired by the change in rope technology,
from:

to:

Also seen in high pressure hoses:





A sock weaving of HTS tapes.
Features
- Flexible
- Electromagnetically fully transposed
- Torque neutral under tension
- Possibly self supported
- Zero magnetic field in center

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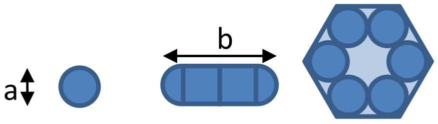
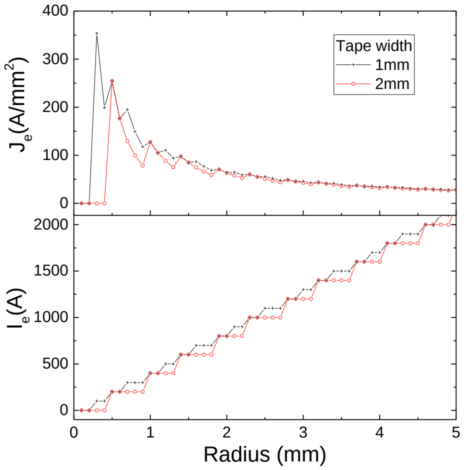
Effect of cable cross-section shape



	Cable	Rutherford	Bundle of 6 cables
a (mm)	4	4	12
b (mm)	4	12	12
I_e (A)	800	2000	4800
J_e (A/mm²)	63	45	46

Hypothesis:
Tape with I_e = 500A/cm



Circular cross-section, effect of tape width and cable radius on engineering current and current density. 45° pitch angle, maximum number of strands

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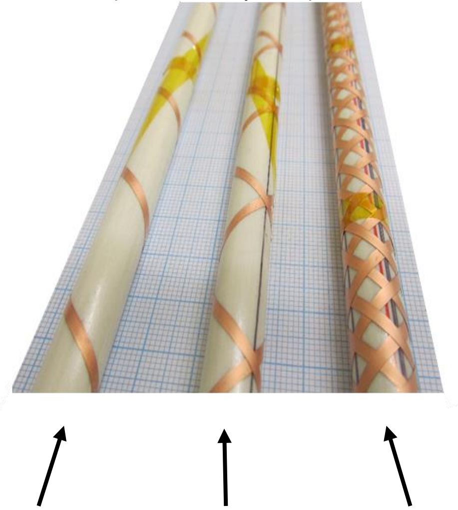
Woven cable construction

10 mm diameter on polymer rod
45° (31.4 mm pitch)



1 strand   2 strand   8 strand

4 mm diameter, air core, 8 strands
I_c > 300 A independent of bending angle

Critical current measurement system

– Fully automated $I_c(T,B,\theta)$ measurement:

0.1 A	≤	$\boldsymbol{I_c}$	≤	1600 A
10 K	≤	$\boldsymbol{T}$		
		$\boldsymbol{B}$	≤	12 T
−360°	≤	$\boldsymbol{\vartheta}$	≤	360°

- HTS (cryocooled) magnet.
- Closed-cycle cryocooled helium gas circulation system to cool the sample and current leads.

– Quality control characterisation of incoming wire:

- 100 full *IV* curve measurements per hour with automated analysis and I_c determination.
- Comprehensive wire characterisation in 24 hours
  – 2400 discrete I_c data points.

SuperCurrent I_c Measurement System

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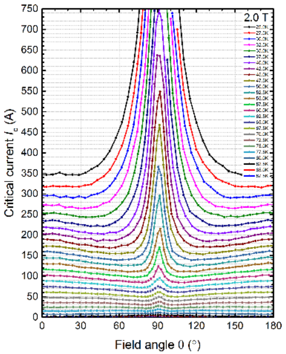
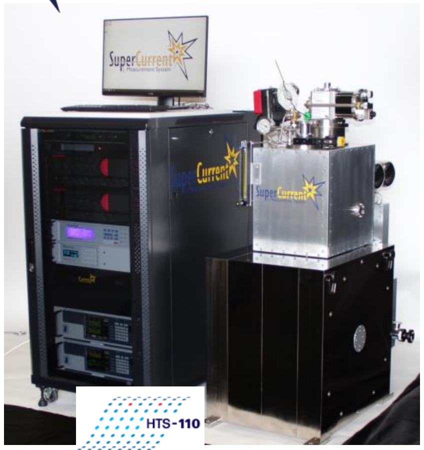


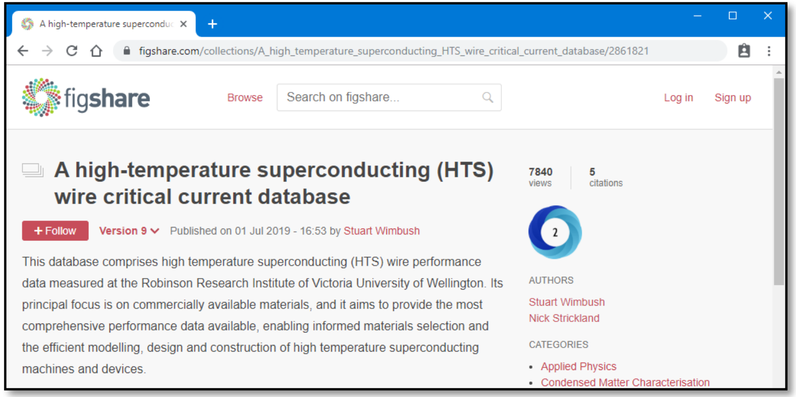


Strickland, Hoffmann, Wimbush,
Rev. Sci. Instr. 85 (2014) 113907.

Public HTS wire critical current database

- As high temperature superconducting technologies edge closer and closer to industrial breakthrough, the need for *detailed* wire critical current characterisation becomes greater and greater.

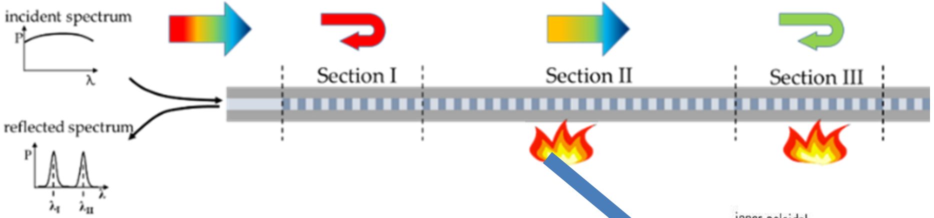
http://www.victoria.ac.nz/robinson/hts-wire-database

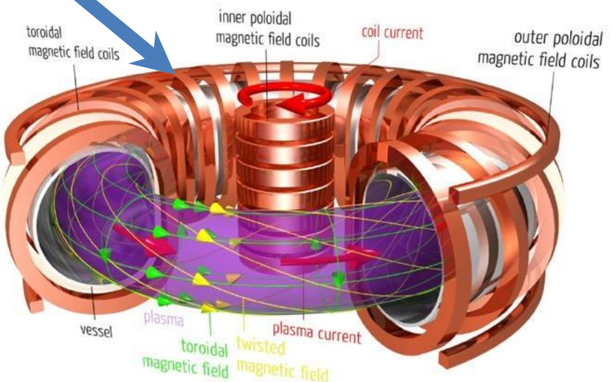


Wimbush and Strickland, *IEEE Trans. Appl. Supercond.* 27 (2017) 8000105.

amsc
SuperPower Inc. A Furukawa Company
Fujikura
STI Superconductor Technologies Inc.
SUMITOMO
THEVA
Nexans
SuperOx
SuNAM
上海上创超导科技有限公司 Shanghai Creative Superconductor Technologies Co. Ltd.
上海超导 SHANGHAI SUPERCONDUCTOR

Fibre optic quench detection

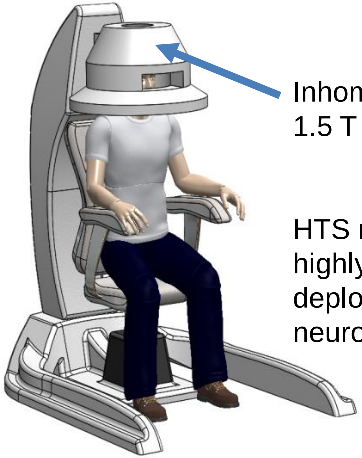




Matthias W Hirsch/Wikimedia

- Fusion coils…
  - Extreme electrical and magnetic noisy environment
  - Challenging super-cold cryogenic environment
  - Continuous sensing detection length required
- Robinson Research Institute
  - Using small diameter ultra long optical fiber Bragg gratings
  - Insensitive to interference
  - Low-cost, good temperature resolution and response time
- Simple interrogation technique and tested under simulated fusion conditions alongside MIT researchers

HTS magnets for brain-only MRI



Inhomogeneous (~200 kHz)
1.5 T HTS MRI magnet

HTS magnet proposed for highly compact, easily deployed system allowing neuro-imaging anywhere.

Advantages

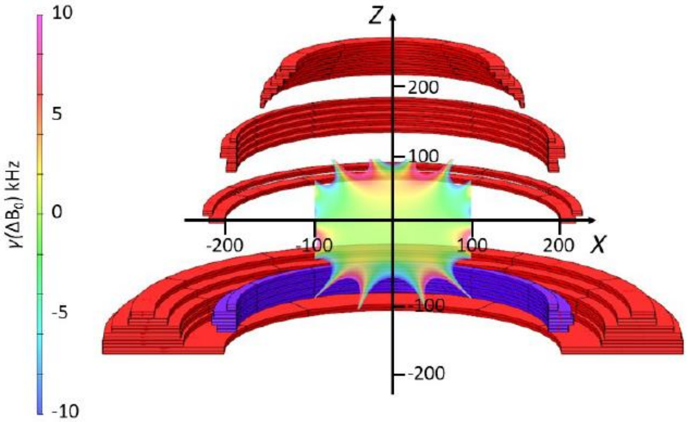
- **Cryogen free**
- **Wall socket power**
- **Rapid cool down (~ 1 day)**
- **Rapid ramp to field (~5 mins)**
- **Minimal space for insulation**

NIH U01
Imaging Human Brain Function with Minimal Mobility Restrictions
PI: Michael Garwood, PhD
Center for Magnetic Resonance Research
University of Minnesota

Robinson lead – Ben Parkinson

Brain imaging magnet

- Brain imaging magnet for use with poor field uniformity pulse sequences
- 15 km REBCO conductor
- 5.1 T peak field for 1.5 T centre field
- Inductance ~25 H
- 23 coils
- Coils with negative hoop stress
- Quench tolerance desired
- Reasonable ramping times
- Uniform turn density in the coils



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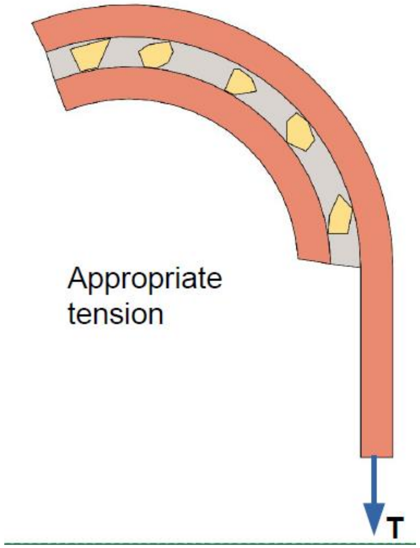
Hybrid winding approach

- Epoxy impregnation
- Conductive powder to achieve conductivity between turns
- Shrinkage inhibitor to match expansion coefficient
- Addition of a third filler or dual purpose filler with a narrow size distribution used as a gauging material



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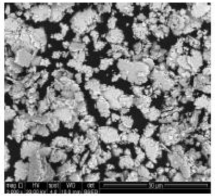
Impregnation recipe

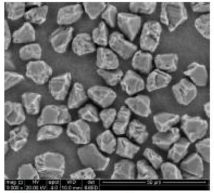
Resin

+



Copper

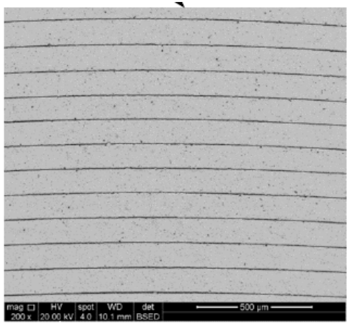
+



Diamonds

=

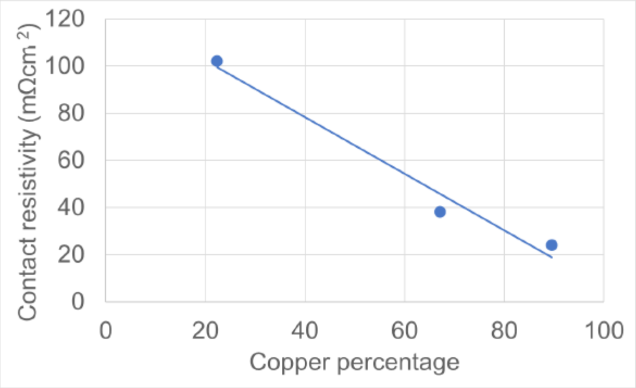
Coil test results



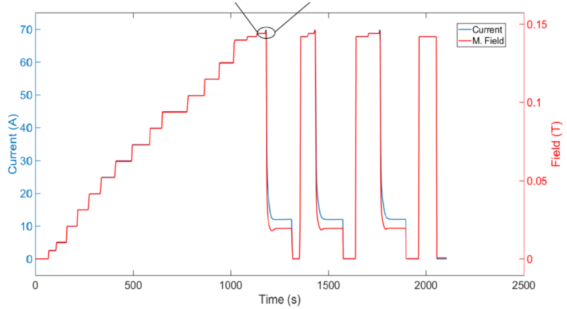
Example Coil

ID [mm]	24.5
OD [mm]	71.7
Turns	200
Conductor Thickness [mm]	0.1
Resin thickness [µm]	11.8

Uniform gauging successful



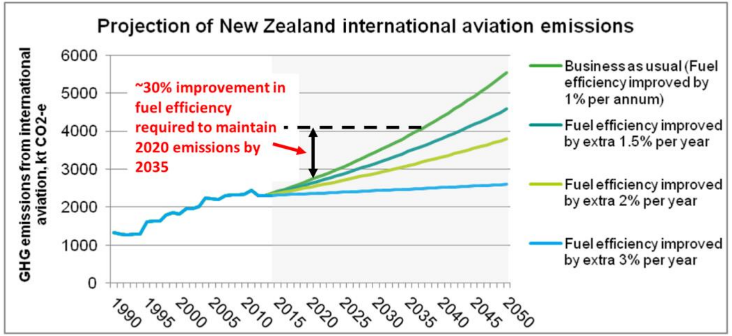
Tuneable electrical conductivity



Quench tolerance
- Multiple quenches without degradation

Electric aircraft – NZ context

- The demand for air travel continues to grow.
- NZ economy relies on air transport
  - $12B tourism and $20B exports
- To deliver our Paris agreement climate commitment a 30% improvement in fuel efficiency required by 2035.

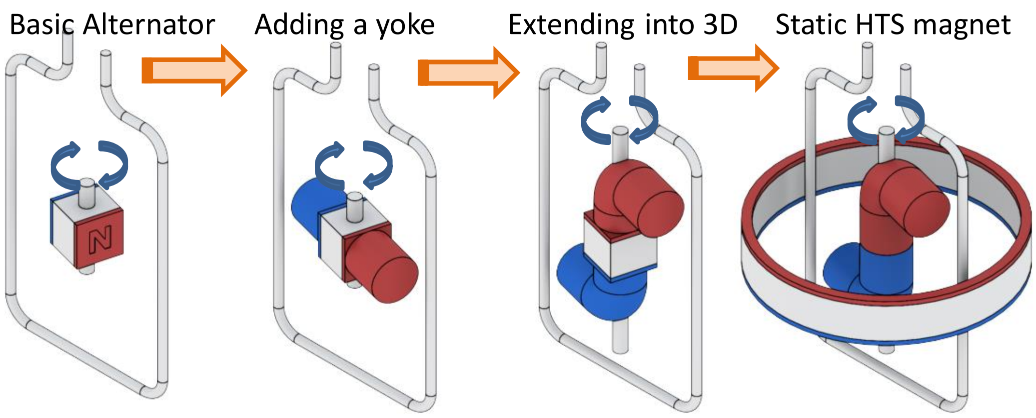


HTS machines programme

- New concept HTS machine designs including homopolar, induction and wound-rotor architectures
- Novel subsystem components to overcome challenges
  - **Flux pump exciters** and HTS bearings
- Computational tools to predict superconducting AC loss in ultra-high speed HTS machines
- Build a laboratory scale prototype HTS motor operating at > 20,000 rpm
  - Breaking the current world speed record

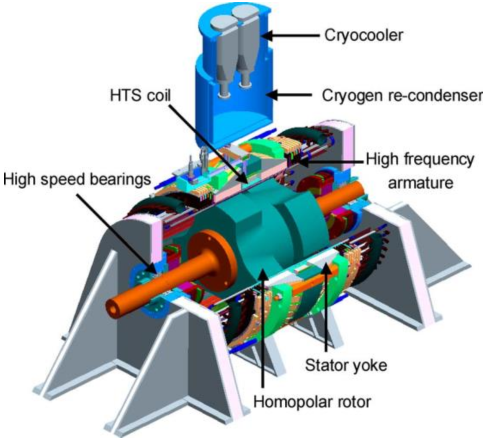
The HTS homopolar machine concept

- Use a static magnet to produce rotating rotor field
- Figure below shows concept



Why a homopolar alternator / motor?

- Field Coil (HTS) stationary
  - Does not experience the large centrifugal forces that a rotating coil would be subjected to.
- Commercially proven HTS coils - BSCCO or REBCO
- The cryostat of the coil is stationary.
  - There is no need for a transfer coupling to introduce a cooling medium into the rotating cooling circuit
- There is no need for a 'slip-ring' assembly to transfer current to the coil from a stationary exciter



Credit: GE / AFRL homopolar alternator (Kiruba Haran)
https://doi.org/10.1109/TASC.2009.2017758

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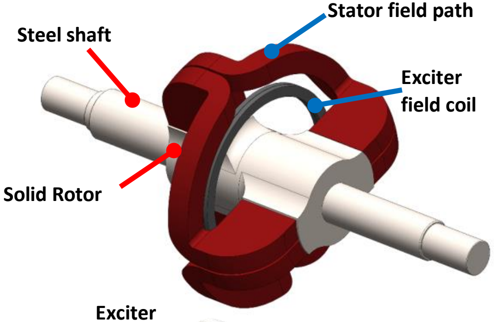
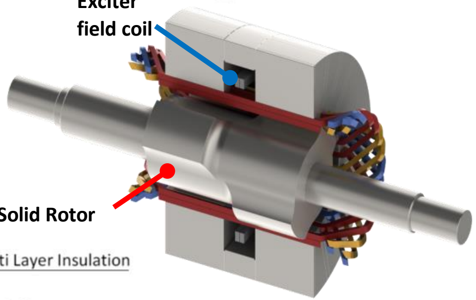
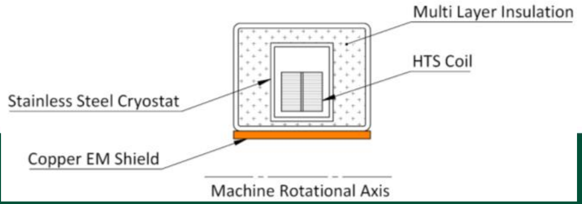
Rotor and exciter design

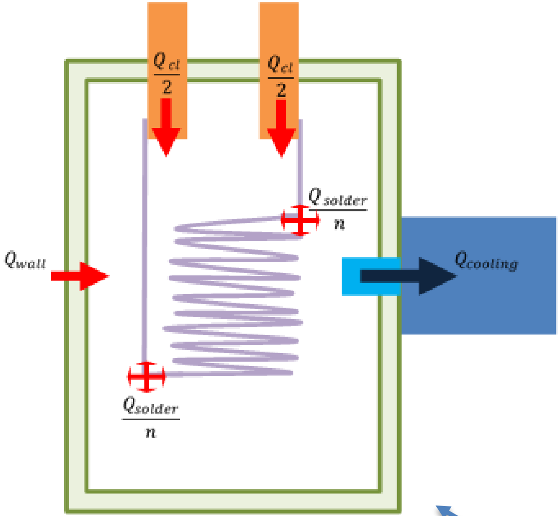
- Machined from single piece of magnetic iron
  - Shrunk onto steel shaft
- 4-pole field pattern
  - Shown in red in figure for field path in stator iron from rotor teeth
- Exciter coils
  - REBCO @ 50 K - stainless steel cryostat
    - Multi-layer-insulation (MLI) foil
    - Mounted to the vacuum chamber housing via insulated struts
  - Copper electromagnetic (EM) shield
    - Reduces AC loss in HTS
  - Designed for I_{op} / I_c of ~ 50 %

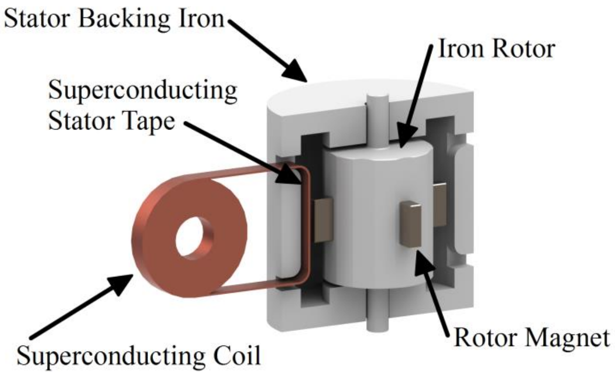


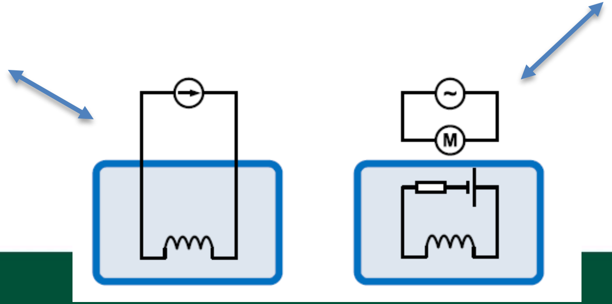




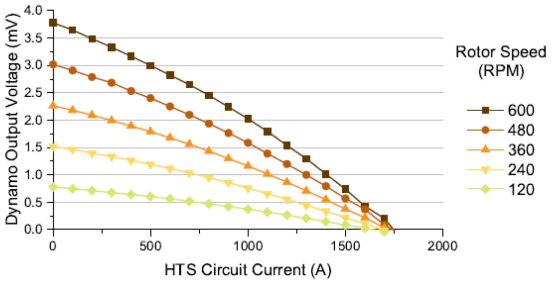
Current leads vs HTS flux pump







Flux pump performance



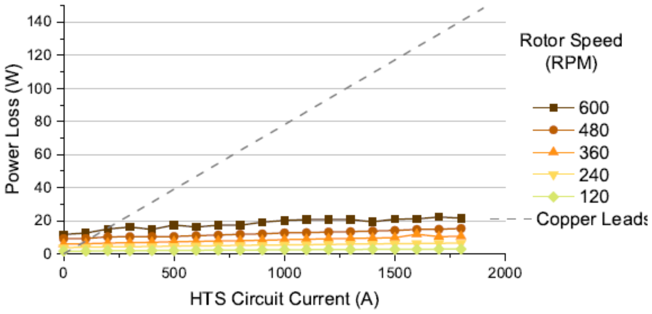


TABLE I
CONVENTIONAL COMPONENT EFFICIENCIES AND POWER

Component	Efficiency (%)	Power (W)
1000 A HTS Coil		2.00
Optimised Copper Leads		78.00
6680A Constant Current Supply	79.50	100.63
Required Cooling Power		80.00
Cryomech AL125 GM Cryocooler	3.08	2600.00
Total Power		2700.63

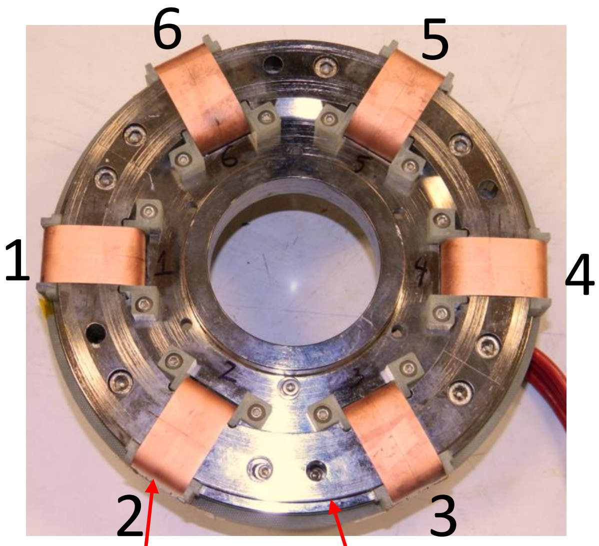
TABLE II
HTS DYNAMO COMPONENT EFFICIENCIES AND POWER

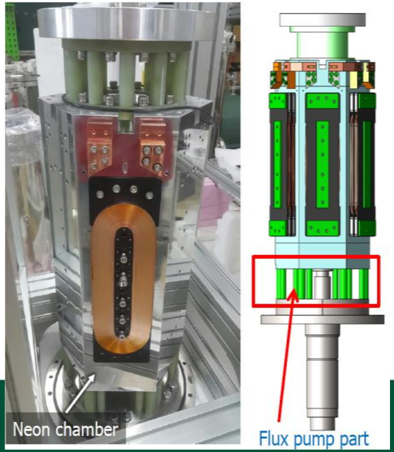
Component	Efficiency (%)	Power (W)
1000 A HTS Coil		2.00
HTS Dynamo	10.00	20.00
Maxxon GP32 Planetary Gearbox	75.00	26.67
Maxxon EC-max 30 Brushless Motor	75.00	35.56
Maxxon DEC 50/5 Speed Controller	95.00	37.43
Required Cooling Power		20.00
Cryomech AL125 GM Cryocooler	3.08	650.00
Total Power		687.43

Hamilton et al. IEEE Trans Appl Supercon 2019

Flux pump for CWNU 10 kW generator

- 6 magnet poles on rotor
- High current coils ~ 100 A
- 37 mH inductance per coil.
- Double width 12 mm CC wire (equiv. to 24 mm stator width)



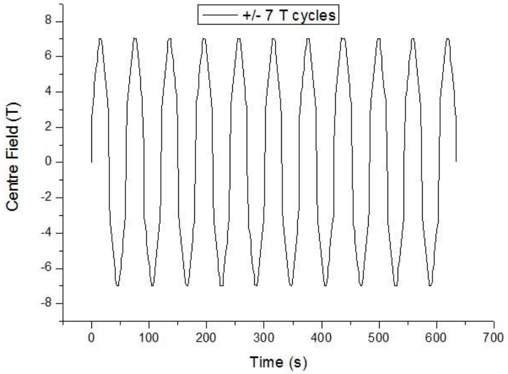


HTS-110 Ltd

- Founded in 2004
- Owned by engineering company Scott Automation Ltd

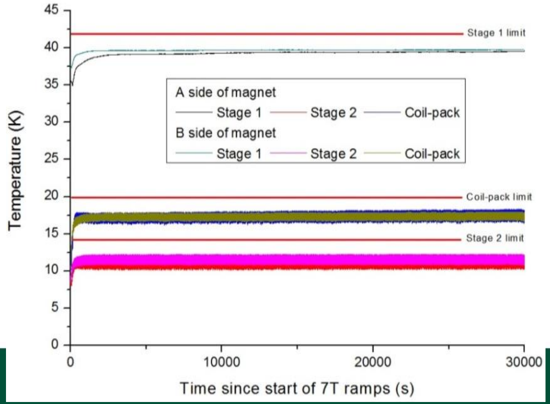
Fast-ramping dipole magnets

HTS-110



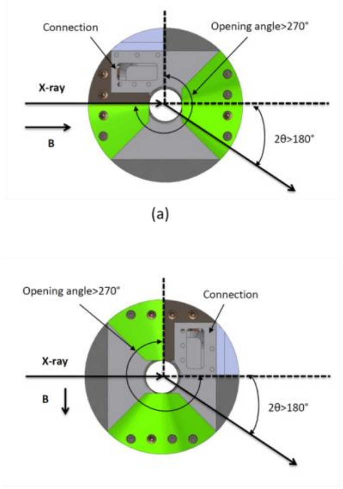
Significant improvements in performance

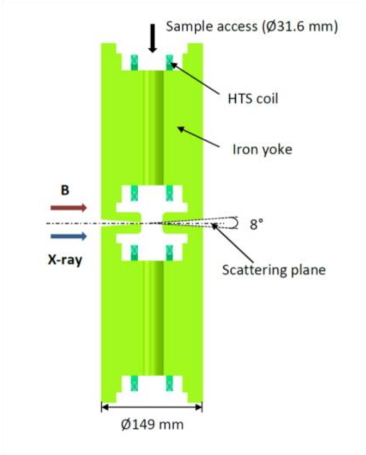
- First commercial high-field fast-ramp
  - +/-7T ~50 mT/sec. (plus 25% dwell time)
- Current fast-ramp systems
  - +/-7T @ >100 mT/sec. continuous
  - +/-6T @ 250 mT/sec. continuous
- Now manufacturing
  - +/-7T @ 450 mT/sec. continuous



X-ray beamline vector (rotating) magnet

HTS-110





Description	Value
Conductor	YBCO
Critical current @ 77K	80 A
Operating temperature	~35 K
Max. operating current	110 A

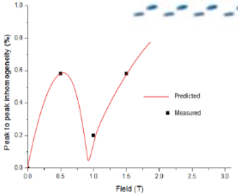
Description	Value
Warm bore	31 mm
Outer diameter	149 mm
Optical opening in x-y plane	270º
Optical opening in z-axis	+/- 4º

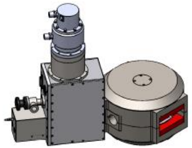
VICTORIA UNIVERSITY OF WELLINGTON

3 T dipole magnets for neutron scattering

Ideal compact 3 T dipole magnet for polarised neutron reflectometry

- 52 mm room temperature pole gap
- Large 160 x 52 mm through slot for neutron beam
- Additional ϕ52 mm orthogonal access bore
- Field homogeneity over 20 x 20 mm sample area at magnet iso-centre better than 1% throughout field range
- Magnet mass <180 kg, compatible with rotating stage
- Commissioned for NIST



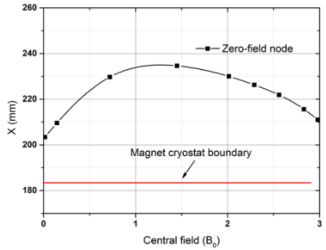


3T neutron scattering magnet

- Neutron diffraction
- Polarized neutron reflectometry

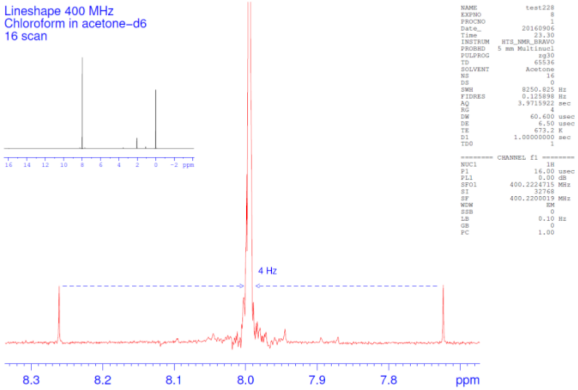
Features:

- Horizontal field up to 3.0 T
- 80 mm pole gap, Ø80 mm vertical RT bore
- Sample volume: 25 mm DSV
- 4 X Ø60 mm horizontal RT bore
- 32° horizontal opening angle
- Zero-field nodes outside the magnet cryostat
- Fringe field: < 1 Gauss (at 1 m) in radial direction, <10 Gauss (at 0.5 m) in axial direction
- Dimensions: 471 x 504 x 998 mm, Weight: 340 kg



Cryogen-free high-field NMR – 400 MHz

HTS-110



First system recently installed in a pharmaceutical company, directly in a fume hood for reaction monitoring and general-purpose spectroscopy.

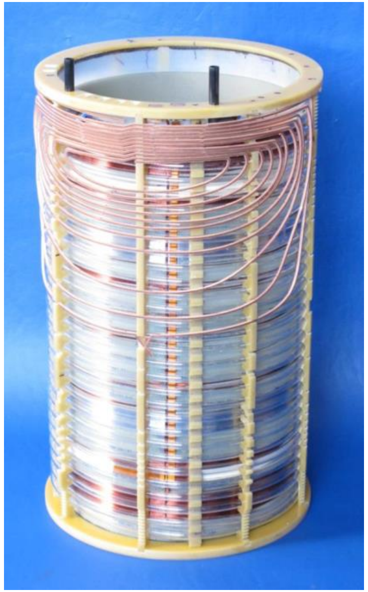
Fabrum Solutions Ltd

- Formed in 2004, based in Christchurch, NZ
- **Cryocooler technology** originally from Robinson team.
- Cryocoolers are 470 watts and 1250 watts cooling output at 77K
- Use patented diaphragm pressure wave generator technology (DPWG) and linear pulse tubes

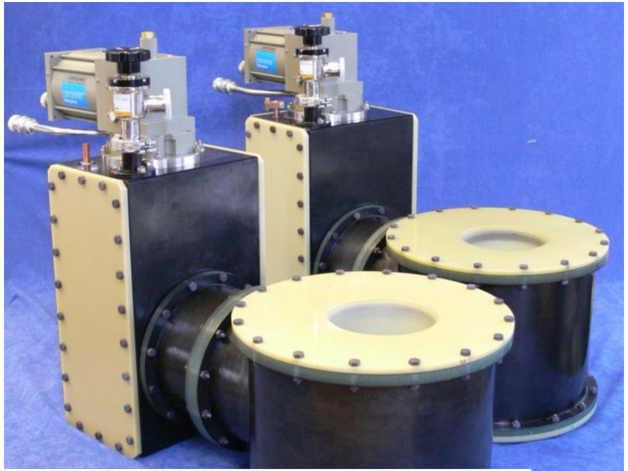
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Presentation AT-5 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.

Components and cryostats

FABRUMSOLUTIONS
skilfully engineered with style



MRI gradient coil



Cryostats for AC magnets
Carbon fibre and glass fibre
-No eddy currents
-Low weight
-Custom Segmented MLI
-High Vacuum Integrity

Cryostat development programme
- Improved vacuum and thermal performance
-Microsphere insulation
-Hybrid Insulation

Next step: superconductors in space

- Potential applications
  - Radiation shields
  - Electromagnetic Re-Entry Shielding
  - Magnetorquers
  - Electric propulsion/ thruster technology
  - Energy storage
  - Fuel burn modification
  - Re-entry plasma communication windows
  - Electromagnetic space craft interactions (docking, formations)

Electric propulsion: Applied field MPD

- Proposed collaboration with Nagoya University
- High thrust density
- Compact design
  - Applicability to **kW-level systems** with discharge currents < 100 A
  - Decrease in power requirements
- Benefits of higher fields
  - Efficiency, thrust and specific impulse dependent on magnetic flux density
  - Exploitation of Tesla-level fields dependent on the development of low-weight electromagnet

Prototype space coil

Summary

- Continuing efforts in materials science
- Roebel cable is preferred option for transformers
  - Can meet AC loss targets
- MRI programme looking at niche applications, head MRI
  - Where is HTS competitive?
  - REBCO can meet required stability targets
- Aircraft motors/generators have strong government support
- HTS for space has strong government support
- NZ companies with niche capability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Rob Suisted