R&D of applied superconductivity by a small business: experiences and future perspective

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HTS Development – NZ history

1986
HTS Discovered

1988
DSIR Discovers Bi-2223

1990-2000
AMSC License

1992
HTS Wire Development

2004
HTS-110 Formed

2007
5.4 T magnet delivered by HTS-110

www.irl.cri.nz
Broad-based HTS research activity continued, now transferred to Robinson Research Institute at Victoria University of Wellington.

Activities span fundamental materials science to engineering applications.

HTS-110 focussed R&D on coil and magnet technology and selected near-term applications.

2013 HTS-110 fully owned by Scott Technology, a NZ public company.

Fabrum (composite cryostats and cryo-coolers).
First large scale physics magnet

Ion beam steering magnet installed 1997

- First large scale HTS physics magnet to operate in a commercial environment.
- Beam steering to one of three detector lines for a 6 MeV tandem Van de Graaf accelerator (mainly used for radiocarbon dating).
- Built consortium including AMSC, IRL, ISYS.

Magnetic field parameters

- Coil clear-bore dimensions 346 x 620 mm
- Pole gap field 0.72T across 30 mm gap
- Coil current 100A, coil voltage <10 V
- Routine operation at T=20K, but tested to T=50K.
Knowledge-base for HTS systems

The knowledge base of making HTS systems requires

- Coil winding
- Coil potting
- Ground insulation (cyclotron, current limiter)
- Terminal to terminal insulation (current limiter, transformer)
- AC coils (large power applications)
- Cryo-integrated systems (thermal behavior, quench, ramping, thermal transient)
- Large number of mechanical cycles (fatigue, aging)
- High field (lamination, fatigue, insulation)
- Large number of identical coils (reproducibility)
- Large coils (low cost/alternative winding techniques for power applications: layer winding, cabled winding, saddle coils, wet layer, alternative joining techniques)
- Radiation exposure (accelerator magnets)
- Industrial environment (robustness, longevity)
- Quench protection
- Energy dumping
TapeScope in-line non-contact $I_c$ characterisation
Transport $I_c$ system “SuperCurrent”

System for measuring transport $I_c$ of superconducting samples, $I_c(T, B, \theta)$

- $B$: +/- 8 or +/- 5T
- $T_s$: > 15K
- Sample: 12mm x 40 mm max

Grade wire performance – or width - to optimise wire length required for the magnet

https://www.victoria.ac.nz/robinson/hts-wire-database
3.5 tesla electromagnet

- Iron yoke
- φ13cm pole; 5cm pole gap, open access.
- 1.6km HTS wire.
- Conduction cooled design, $T_{op}=35K$ with a commercial G-M cryocooler consuming 3kW power.
- For application with a vibrating sample magnetometer.

HTS-110’s first integrated HTS magnet, 2004
HTS current leads

Probably the first significant commercial application of HTS

- An enabling technology for cryogen-free LTS magnets based on mechanical cryocoolers
- Low heat leak compared to optimised normal-conducting leads (~1 W/100 A per pair of leads)
- Based on HTS wire (Ag-Au alloy BSCCO and 2G), also bulks
- Wire based leads are:
  - Tolerant of external fields
  - Mechanically robust
- Typical capacities 150 A – 2000 A

Connection to LTS
HTS module
LN2 or He-cooled Cu stage
RT connection flange

LN2 or He-cooled Cu stage
RT connection flange

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HTS-110

SCOTT
Eliminating the current leads – Dynamo-type HTS flux pumps

- Rotating permanent (Nd-Fe-B) magnets move across a coated conductor
- PMs mounted in homo-polar orientation
- Flux penetrates YBCO film and induces a DC current to flow in series connected superconducting coil

Liquid nitrogen, 1 T HTS electromagnet

Quantum Design (USA)

1 T short solenoid
- 38 mm RT bore
- 57 mm height
- Cool down < 4h
- LN2 consumption ~0.5 lph

Bath-cooled
LN2 circulation-cooled
First magnet for synchrotron endstation

Resonant magnetic scattering and high resolution XRD
- 5-6 tesla
- Tight user dimensional/weight constraints
- <100 kg
- Allows 90 degree rotation
- 40 mm RT bore for variable temperature insert
- Hahn Meitner Institute/BESSY (Germany)

- HTS coils conduction cooled to below 20 K with a pulse-tube refrigerator
- AMSC “High Strength Plus” 1G BSCCO wire (stainless steel laminated)
- Wire Ic performance over 160A (77K, s.f.) for demanding locations in the coil pack
Neutron beamline – small angle scattering

Features

- Small-angle neutron scattering at ANSTO
- 5 T at sample in variable temperature insert
- 80mm room temperature bore
- Ability to tilt in any direction
- Wide neutron beam accessibility angles
- Goniometer mounted for tilting up to 15 degrees
- Operating temperature: 20K
- Force on HTS coils: 5000 kg
- BSCCO wire
Cross-section of a typical HTS solenoid magnet (LM Optical Short Solenoid)

NOTE a very small gap between the cold mass and the room temperature structure.
Short solenoid magnets

3 T, 80 mm bore
- Low profile designs
- Operating temperature ~30K
- Optical applications

2 T, 53 mm bore

2 T “Projected field”

Device/wafer testing
Fast Ramping Magnets – AC loss

Literature often emphasises high frequency and low field apps (>10Hz, <100 mT) e.g. transformers, and calculate total loss per cycle.

Operation at much lower frequency and higher field (~0.01 Hz, 5-8 T): peak loss within a cycle is more important.

Solutions:

- AC loss prediction software: empirical, first principles (e.g. finite elements analysis) + phenomenological.
- Experience from performance of and measurement on first gen. fast ramp magnets.
Fast-ramping dipole magnets

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
Ion-beam implantation is a key manufacturing step in producing silicon chips. Increased circuit density requires more sophisticated magnets to deliver the uniformity and throughput needed.
Synchrotron beamline - UHV

- 2.2 T dipole magnet with 40mm axial bore and 90 mm pole gap
- For X-ray Magnetic Circular Dichroism (XMCD)
- National University of Singapore

- Resonant x-ray scattering end-station in a custom built UHV reflectometer
- 2.2 T, 50 mm pole gap
- Auxiliary RT coils for superimposed AC/DC fields
- ALBA-Cells (Spain)
LARIAT II (Large Area Rapid Imaging Analytical Tool)

Near Edge X-ray Absorption Fine Structure (NEXAFS) imaging spectrometer

- Sample magnet 8.6 T 110 mm RT bore
- Detector magnet 0.8 T 204 mm RT bore
- Brookhaven National Laboratory
### X-ray beamline vector (rotating) 2G magnet

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>YBCO</td>
</tr>
<tr>
<td>Critical current @ 77K</td>
<td>80 A</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>~35 K</td>
</tr>
<tr>
<td>Max. operating current</td>
<td>110 A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm bore</td>
<td>31 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>149 mm</td>
</tr>
<tr>
<td>Optical opening in x-y plane</td>
<td>270°</td>
</tr>
<tr>
<td>Optical opening in z-axis</td>
<td>+/- 4°</td>
</tr>
</tbody>
</table>
Synchrotron storage ring magnets can consume around 1 MW of power – resistive copper magnets.

Retrofit HTS magnets to give factor ~10 reduction in energy consumption.

Increased aperture for dipole after HTS retrofit.

NSRRC Taiwan dipole magnet

HTS-110 retrofit for Brookhaven National Lab.
Neutron beamline: 2.2 T magnet for neutron time-of-flight scattering

**Description** | **Specified value** | **Test value**
---|---|---
Maximum Field (T) | 2 | 2.2
Field homogeneity over 15mm DVS | <2.0% | 1.45%
Fringe field (mT) B(1.8m) | <0.5 | 0.4
Maximum operating current (A) | <260 | 208
Ramp time (min) | <30 | 6
Cool-down time (hour) | <36 | 22.5
Mass - magnet and cryocooler (kg) | <250 | 186

**Features**
- Neutron time-of-flight (TOF) scattering
- 80mm room temperature bore
- Ability to tilt in any direction
- Scattering angle up to 150° in-plane, 40° cones elsewhere
- Dimensions: 596 X 363 X 794 mm
- Operating temperature: 20K
- Force on HTS coils: 1800 kg
- Commissioned 2014 at the Heinz Maier-Leibnitz research neutron source (FRM II), Technische Universität München

**HTS-110**
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
HTS-NMR – Major focus

- Reaction monitoring
- Process & yield optimisation
- Mobility, ease of siting, no liquid cryogens, oxygen sensors etc.
- Robust – no anti-vibration legs etc.

NMR spectroscopy requires:
- PPB field uniformity and stability
- In LTS this is provided by superconducting shim coils and persistent mode operation
- In HTS – persistent mode operation still not fully developed
- So use passive (ferromagnetic) shimming and high stability power supply
- Both HTS and LTS require RT electric shims and NMR field-lock
The measured magnetic field is used to calculate the shim distribution necessary to create a correction field. Linear superposition of the two fields produces a resultant field with reduced magnetic inhomogeneity.
Temporal stability – screening currents

- Radial field component at solenoid ends induces strong and slow-decaying screening currents
- Negative contribution to central field
- Harmonics shift with time

Magnet ramp algorithm to reduce impact of magnetisation currents.

- Temporal stability: sufficient for standard lock circuit
Cryogen-free high-field NMR – 400 MHz

2D $^1$H-$^{13}$C HMBC experiment (HMBC=heteronuclear multiple bond correlation, gives H-C correlations through 2-4 bonds but optimized to 3 bonds based on average H-C coupling constant for 3 bonds. Acquisition time ~1hr: a test of magnet uniformity and stability.
NMR relaxometry

Stelar srl (Italy) instrumentation for NMR relaxometry
to study the molecular dynamics in various fields including:
- MRI contrast agents
- Pharma and biochemical research
- Polymers
- Liquid crystals
- Solid-liquid interfaces
- Porous materials
- Food science

0-3T variable field HTS magnet
- 25 mm pole gap
- 50 ppm uniformity over excitation range, suitable for NMR relaxometry
HTS MRI systems

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

Compared with permanent magnet systems
• Higher field
• Larger bore

Compared with LTS magnet systems
• Liquid He-Free
• Thermally robust

Field map prior to shimming

Field map after passive shimming

Note 20x reduction in scale

Magnet with yoke removed

Unshielded gradient coils

Passive shim cassette

RF birdcage resonator

Robinson Research Institute
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

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

3.0 T BSCCO Preclinical MRI system (2015/16)
Benefits
- Relatively high operating temperature
  - High thermal stability → robust, simple operation
  - Modest-sized cryocoolers (potentially more energy efficient)
  - The magnet system benefits enormously from the possibility of magnets operating at elevated temperature (20-40 K instead of conventional ~4K)
  - HTS can tolerate a large local increase in temperature in superconducting coils caused by the decay particles
  - “Moreover, the temperature need not be controlled precisely. The temperature control can be relaxed by over an order of magnitude as compared to that for present superconducting accelerator magnets” (Dr. Ramesh Gupta BNL).
- Compact, with large sample/optical access
- Low fringe field with iron yoke
- Fast ramping
- Power supply doesn’t have to be specialised for superconducting loads
- Opportunity for generation of very high fields

Drawbacks
- Anisotropic properties need to be considered
- Generally lower engineering current density than LTS
- Usual form is a wide flat conductor – AC loss, magnetisation currents, field accuracy
- No persistent mode (power supply always connected) – not always a drawback
- Conductor strength
- Cost of wire (still!)
Concluding remarks

• HTS magnets and current leads are in commercial production
• Broad range of applications
• “BSCCO” conductor currently the “workhorse”
• 2G looks more future-proof (high Je, strength)
• Higher J_e desirable for future magnet technology
  • Promise of lower-powered cryocoolers
  • Smaller overall system size, lower cost
• Lower AC loss for faster ramping magnets
  • Ability to subdivide the tape
  • Of benefit also to field quality
• Very high fields
• Persistent joints

But
• Price/markets
• Need for high level of system integration for market acceptance
Thank you

Happy Birthday
HTS-110

10 years, 2014