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

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Abstract. The increasing commercial availability of High-T_c Superconducting (HTS) wire in the decade following the discovery of this amazing class of materials opened the door to a range of unique application opportunities. The early international focus was on the power industry with a promise of a significant transformation in efficiency and supply security; however the realities of funding large and technically demanding prototypes and the lengthy timelines involved in realistic commercialisation pathways, meant that for a small business nearer-term opportunities would need to be explored. From a background in materials research and wire development activities, HTS-110 was established over 13 years ago to design and manufacture HTS magnets for a wide range of scientific and industrial applications; over the last decade significant progress has been made in the commercialisation of HTS magnets, both by HTS-110 and other manufacturers, paralleling the improvements in wire performance and quality. In this paper we review the developments of HTS magnet technology and applications leading to a range of niche application areas, from sample environments for synchrotron and neutron beamlines and other materials analysis applications, through to developments for the demanding realm of magnetic resonance, all of which leverage the benefits of high current density relative to copper and a relatively high operating temperature compared to the low-temperature superconductors. New future application areas promise to extend these developments and greatly expand the role of HTS magnets in our industrial society.

1. Background

Following the discovery of the High-T_c superconducting materials, New Zealand, like many countries around the globe, invested heavily in research and development of these remarkable superconductors since it was easily argued that this represented an opportunity to radically alter the generation, distribution and use of energy around the world. The leap in efficiency and security would drive widespread deployment, associated with rapidly falling wire prices due to the large scale of manufacture that would be required to meet this market demand. For almost two decades then, there ensued a programme first of materials discovery and characterisation followed rapidly with the development efforts targeting wire production in order to enable the promised revolution in the electricity industry. On the basis of materials and processes that had been identified by the team in New Zealand, a patent licensing agreement was reached with what was then the pre-eminent producer of first generation (“BSCCO”) wire in the world. From this relationship a core body of local knowledge developed regarding the properties and performance of this wire, extending to the understanding that it seemed unlikely that wire manufacturing itself would be a viable option in the New Zealand environment. However establishing a manufacturing business to build devices using the
wire seemed attractive; the initial target would be for industrial, scientific and medical applications rather than directly for the expected large markets in the electricity sector. This suited the type and scale of industry in New Zealand, and did not preclude partnerships in the electricity industry for components as the demand arose. Importantly it would also demonstrate a commercial outcome from the public funding of HTS research, even if extensive growth of such a business would likely rest on other industries to drive volume manufacturing of the wire.

On this basis, HTS-110 was formed in 2004. Initially with just three employees and no firm customers such was in the interest in the HTS machine development that we soon were manufacturing coils for several organisations, extending then into magnet assemblies. We benefitted from early adopters in the move to fully integrated magnet systems, and with partners in meeting the needs of niche industrial users. Sitting behind the magnet development were research and development programmes, first to establish robust coil manufacturing technologies for the HTS wire, then continual efforts to extract higher performance for the magnet systems. Given the size and resources of the company these developments were necessarily targeted at near-term commercial outcomes rather than very future-focussed efforts. An underpinning HTS research and development team continued within the government-funded research environment, that team reformed as the Robinson Research Institute and through which HTS-110 has also benefitted from the wider R&D activity.

2. Technology development for coils and components

The basic information required for magnet design centred on wire performance which was a rapidly moving target in the early years. This incorporated knowledge of the anisotropic field dependence of critical current as a function of temperature, the development of reliable design tools for electromagnetic and thermal integration, plus the more practically focussed matters underpinning a reliable coil manufacturing process such as turn-to-turn insulation selection and resin selection for vacuum-pressure impregnation. Ultimately these selections would need to be tailored to both the application requirements (for example turn-to-turn or coil-to-ground dielectric strength), or even in responding to the properties of the particular wire chosen. For example, in the manufacture of the first REBCO wire coils it was quickly discovered that a re-evaluation coil manufacturing and handling processes was needed due to coil performance failures; these resulted from damage to the wire during thermal contraction on cool-down of the coil. Resin selection was an important factor and HTS-110 successfully demonstrated paraffin wax as an interim alternative while other resins were identified.

2.1. Non-contact I_c wire qualification

Especially in the early years of HTS wire manufacture, wire performance was usually very inconsistent on a length basis and given the high cost it was necessary to provide a quality assurance measure that would enable reliable coil performance. A non-contact I_c measurement system was developed to give high-resolution long-length I_c data on incoming wire.

![Image](image-url)

**Figure 1.** In-line non-contact I_c measurement system for wire qualification (left) with graph (right) showing correspondence between the induced signal and transport data measured on the same sample.
This was based on a small AC magnet inducing local supercurrents in the wire the effect of which could be detected through a differential Hall sensor setup operated with a lock-in detector. Calibration against wire with known transport current data provided a system with excellent correlation to the transport data yet able to give rapid scanning of wire at 77 K (figure 1). This became an essential tool in the manufacturing process.

2.2. Wire characterisation $I_c (B, \theta, T)$
Capability development towards routine characterisation of transport properties of HTS wires ultimately led to the development, though our research partners in Robinson Research Institute, of an automated test instrument capable of $I_c (B, \theta, T)$ measurements to approximately 1 kA on HTS samples over the temperature range of 15-100K and with fields of 0-8 T applied at any desired angle to the tape plane [1]. The magnetic field is generated by an HTS 8 T dipole magnet constructed by HTS-110 and is integrated with a sample cryogenic system based on forced helium gas flow through the sample chamber, employing a separate cryocooler to that used by the magnet. This system, named “SuperCurrent” has been of particular value in characterising the transport properties of second-generation wire types.

![Image of SuperCurrent system](image-url)

Figure 2. The “SuperCurrent” wire critical current measurement system showing the 8 T magnet and sample cryogenic manifold (left) and example data from a REBCO sample at 8 T applied field.

3. Magnets
3.1. The first large HTS magnets
The first large-scale physics magnet built with HTS wire was a ion-beam steering magnet installed in 1997 into a radio-carbon dating facility at the Institute of Geological and Nuclear Sciences in New Zealand [2]. This magnet was important in demonstrating the robustness of HTS magnets and the longevity of the wire and coil performance over many years of operation (which had not previously been demonstrated). Ultimately the magnet was decommissioned due to failure of the compressor for the cryocooler. This magnet led on to the development of a general-purpose H-frame 3 T laboratory electromagnet [3] with HTS coils operating at a temperature of around 30K, cooled by a single stage GM cryocooler; this system is still employed today for some transport measurements on HTS samples.
3.2. Higher-field – magnets for synchrotron x-ray and neutron scattering sample environments

We were fortunate in having “early adopter” push for high fields in a compact envelope for the Hahn Meitner Institut at their high resolution x-ray diffraction and resonant magnetic scattering beamline MAGS at the Berlin Electron Synchrotron facility BESSY [4]. This resulted in a 5.4 T split-pair magnet with system mass sufficiently low that it could be mounted in a commercial goniometer and was able to be rotated by 90° with respect to the beam axis and scattering plane. The magnet was cooled with a pulse-tube refrigerator set at an angle of 45° to the vertical; this allowed operation of the magnet in the two orientations without suffering from the large cooling performance drop associated with pulse-tube coolers when tipped towards the horizontal orientation. An aluminium cryostat helped to ensure an overall low system mass, again for compatibility with the goniometer. This design has been replicated for other synchrotron facilities.

At about the same time a much larger 5 T split pair magnet was designed and manufactured for the Australian Nuclear Science and Technology Organisation [4]; this unit had large optical access angles, was designed to be compatible with the user’s existing sample cryo-furnace, and was also to sit on a rotating stage but with limited range of motion. 12km of HTS wire was used and when running, almost 60 tonnes of internal compressive forces had to be managed, requiring a carefully designed combination of titanium, carbon fibre and other composite components. Whereas the x-ray diffraction magnet was protected with a cold-diode bank the neutron scattering magnet, with a stored energy of order 0.5 MJ, required a room-temperature energy dump circuit to be designed; this unit provided a rapid switched-resistance discharge of the magnet, with the switching control powered by the magnet stored energy itself. Following these two magnets the management of stored energy has remained with room-temperature dump resistors, either actively engaged or always connected. More recently the quench protection heaters have also been employed successfully by other groups [5].

Since these two magnets, several more systems have been designed for neutron and synchrotron beamline sample environments, many of which has been of modest field strength (2-3 T), but offering compact physical envelopes combined with large optical and sample access. An interesting possibility with the soft-iron yoke is the control of zero-field points in the magnetic circuit, which is of particular concern for experiments with polarised neutrons [6]. Magnets for UHV applications have also been delivered, either with the UHV chamber embedded inside the HTS magnet, or with the HTS magnet mounted inside a UHV chamber [7,8]. In the latter case the magnet vacuum system is kept separate from the UHV system, and in both cases attention had to be paid to maintaining the HTS coils at resin-compatible temperatures during vacuum “bake-out”.

One of the largest magnets to date, with 8.6 T in a room temperature bore of 110 mm, was manufactured for LARIAT II (Large Area Rapid Imaging and Analysis Tool, Synchrotron Research Inc., USA), used for imaging and chemical analysis with soft x-rays. Imaging is achieved with a CCD detector housed in a separate HTS detector magnet, the strength of which determines the image

![Figure 3. Examples of sample environment magnets for synchrotron and neutron endstations. Left: a 5 T split-pair magnet for resonant magnetic scattering and high-resolution X-ray diffraction. Middle: The pair of magnets for the LARIAT II imaging spectrometer. Right: a 3 T magnet for polarized neutron scattering.](image-url)
magnification [9]. Another novel system is a compact cylindrical-bodied magnet (diameter 150 mm) of modified H-frame design offering in-plane field which can be rotated around a fixed sample, providing a mechanical vector field control with in-plane optical access of 180° for all field angles and an out-of-plane opening angle of over 8° [10].

4. Fast ramping magnets, beam scanning
Responding to a need for rapid high-throughput characterisation of magnetic materials, for example in the data-storage industry or in the development of permanent magnets, a series of fast ramping magnets has been developed. This has entailed the careful characterisation of AC losses in the HTS coil systems at ramp rates which are low compared to loss studies performed near utility distribution frequencies (50/60 Hz) or higher. In this case, the in-cycle peak losses may be more important than average losses and may be observed as in-cycle coil-pack temperature deviations. It is difficult to calculate the thermal load in a complex magnet geometry as it depends on multiple factors including field magnitude, orientation, tape I_c, operating current, tape cross section, and other factors. The loss is also difficult to minimise mechanically since there are currently limited commercial options for reducing the aspect ratio of the HTS tapes. Further potential solutions may conflict – for example: higher I_c wire will operate safely at higher temperature so will be less sensitive to local heating caused by AC loss, but coils built with high I_c tape will have higher losses and coil pack temperature rises. Nevertheless, good progress has been made, with the latest generation of magnets designed for measurement via MOKE (Magneto-optical Kerr Effect) able to perform 7 T four-quadrant ramp cycles in 60 s on a continuous basis (figure 4).

Figure 4. Split-coil (dipole) magnets for high throughput MOKE measurements; the optical access is through the magnet poles (iron), while the sample is inserted in the slots between the split coil pairs. Left: 5 T model, Middle: 7 T model (capable of 8 T at slower ramp rate), Right: Ramp cycles to 7 T with 62 s four-quadrant cycle time; non-linearity is due to the iron circuit.

5. Magnetic resonance
A significant research and development effort at HTS-110 has been directed towards magnetic resonance applications, particularly NMR for chemical analysis in industrial applications. While much international effort focusses on extending the available realm of NMR fields above the limit of LTS conductors (for NMR above 1 GHz, which is of interest especially for the analysis of large organic molecules), the effort at HTS-110 has been to leverage the mechanical robustness of HTS magnets, and the absence of liquid cryogens, to enable chemical spectroscopy in industrial locations. The first NMR magnet was a small 2 T split pair magnet designed initially for petrochemical applications; this has progressed through 4.7 T solenoids (200 MHz NMR) to, most recently, the first 400 MHz instrument to be installed directly in a fume hood of a chemistry laboratory for reaction monitoring in
the pharmaceutical industry (figure 5). These magnets are all actively driven with high-stability power supplies of sufficient quality for standard NMR field-locking systems to operate. The field homogeneity requirements, which approach the part-per-billion level for high-resolution NMR, cannot be addressed with superconducting shims as in LTS magnets due to the lack of persistent joint technology for the BSCCO wire employed. Instead a passive ferromagnetic shimming approach, similar to that of MRI, has been adapted which brings field uniformity over the sample volume to the level of 1 ppm scale, then conventional room-temperature shims are employed for the finer scale field correction.

With the wide HTS conductors, screening currents induced during the ramp to field can have a significant impact on the field uniformity and also on the temporal stability, with the combined effect of screening currents being to reduce the central field in a solenoid. If ramped directly to field then long-term drift is observed yielding an increasing field, and of drift strength that would be problematic both in mapping and NMR operation of the magnet; moreover the field uniformity may change with time. Understanding and mitigation of screening currents is an on-going research activity internationally [11,12], but a sufficient control strategy has been to employ multi-stage ramp cycles which depress the effect of screening currents.

In addition to NMR systems, MRI magnets using both BSCCO and REBCO conductors have been successfully demonstrated [13].

Figure 5. Left: A 400 MHz HTS NMR magnet with standard 54 mm room temperature bore. Right: comparison of magnet drift suppression with a multi-stage ramp cycle.

6. The future

Wire cost, engineering current density, anisotropy, mechanical strength, all remain issues requiring further development for wider uptake of HTS technology. Reducing overall facility requirements is also desirable for magnet systems, which then require improvements in efficiency and reliability of power supplies and crycoolers. As much as higher field strengths are a research focus in many national laboratories, widespread practical applications do not necessarily need the generation of such high fields but nevertheless would benefit from any improvements in conductor and coil manufacturing technologies. Of equal importance is the development of architectures better suited to AC-type applications, even in the realm of magnets for materials analysis where high-throughput is demanded. These modified architectures may also make a useful contribution to the limitation and control of magnetisation currents which is important for both particle accelerators and other applications requiring high field uniformity such as NMR. Beyond these wire developments, successful uptake in industry requires extensive system-wide integration and optimisation. With that, the industry is moving forward; several commercial niche areas for HTS magnets now exist (though requiring limited volumes of wire) and application areas are developing that promise to lead to significantly increased wire manufacturing volume, such as compact fusion systems.
7. Conclusions
In parallel with improvements in conductor performance, a wide range of HTS magnets have been produced of increasing performance and sophistication. As a small company, HTS-110 has concentrated on development of magnets for commercial applications and this has necessarily focused R&D effort into near-term issues. Out of this, niche scientific and industrial application using HTS conductors are a commercial reality. One relatively long-running development investment for the company has been in the area of magnetic resonance, culminating in the production of a 400 MHz NMR system with performance comparable to conventional LTS systems yet able to be sited directly in the users’ laboratory. Such systems demonstrate the advantages accruing to the high operation temperature, namely stability, mechanical robustness and a compact cryogenic envelope, in addition to the absence of liquid cryogens. The application horizons are expanding with further wire performance improvements and with the associated system-level integration necessary for commercial applications.

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