Cryogen-free 1kA-class $I_c$ measurement system featuring an 8 T HTS magnet

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Abstract. We have developed a cryogen-free critical-current ($I_c$) measuring system comprising a conduction-cooled 8 T HTS magnet and convection-cooled sample, both cooled by commercial cryocoolers. The sample can be rotated and transport currents of up to 800 A delivered with less than 0.5 K temperature rise during the $I_c$ measurement. The system is automated with respect to variations in temperature (30–90 K), field (0–8 T), and field angle (0–360°). We have used this system to measure HTS wire samples, concentrating on metal-organic deposited YBCO on RABiTS substrates. Particular emphasis is given to the evolution of $I_c$ anisotropy with temperature, and the dangers of extrapolating from 77 K to 30 K.

1. Introduction

The critical current, $I_c$, is one of the principal metrics for the quality of high-temperature superconducting (HTS) wires. For convenience, $I_c$ values are often specified only at liquid-nitrogen temperature, 77 K, however this simple metric ignores the fact that $I_c$ is a complex function of external parameters temperature, $T$, magnetic field, $B$, and magnetic-field angle, $\theta$. This $I_c(T,B,\theta)$ variation arises from a combination of intrinsic and extrinsic properties and can therefore vary significantly for wires produced by different fabrication methods. Even quite similarly fabricated wires can have different behaviors and the implication of this for applications is that $I_c(T,B,\theta)$ should be measured over the parameter space that will be encountered in an application. The paucity of such data in the literature for $T<77$ K is testament to the challenge that arises in performing these measurements. Magnetic fields beyond 2 T and sample temperatures below 65 K are typically obtained in specialized systems in which both sample and magnet are cooled with liquid-helium [1]–[3], an inconvenient, expensive and non-renewable resource. For this reason, cryogen-free systems for cooling both the sample and the magnet are of interest [4],[5]. The transport measurements themselves are also difficult, particularly when a commercial conductor is to be measured in which case currents of several hundred amps must be delivered to the sample.

With these demands and difficulties in mind, we have developed a bespoke short-sample $I_c$ measurement system incorporating a conduction-cooled HTS magnet and gas convection-cooled variable-temperature sample insert both cooled by cryocoolers. Sample temperatures down to 30 K, magnetic fields up to 8 T, full field-angle dependence and transport currents up to 800 A have been measured.

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achieved. In this paper we give a brief description of the principal parts of the system and illustrate its performance with some example data obtained on commercial HTS wire.

2. $I_c$ measurement system

A photograph of the $I_c$ measurement system is shown in figure 1. The sample loading and cooling subsystem is contained within the vacuum chamber mounted on top of the magnet, while the magnet conduction cooling system is partially obstructed from view behind the magnet. The HTS sample is mounted on a top-loading cold-swappable sample rod and is typically 10–40 mm long.

![Figure 1. Photograph of the $I_c$ measurement system, including 8 T HTS magnet (diameter 525 mm) and cryogenic vacuum chamber.](image1)

The 8 T magnet at the heart of this system was designed and constructed by HTS-110 Ltd, New Zealand. This magnet is a horizontal-field split-pair dipole with a vertical, rectangular 30 mm × 80 mm room temperature bore. With this configuration the sample rod can be conveniently rotated by a computer-controlled rotation stage to explore field-angle dependences. The coils are wound from BSCCO HTS wire and are conduction cooled to below 20 K by a SHI Cryogenics CH-208 cryocooler. The full field of 8 T is achieved with a current of 200 A. The ramp time from 0 to 8 T is 9 minutes.

Gas convection cooling of a variable-temperature insert was chosen to ensure a consistent sample temperature as well as to provide direct cooling of the sample current leads; a schematic of the cooling cycle is shown in figure 2. Helium gas flows in a closed cycle transferring heat from the sample to a cryocooler (SHI Cryogenics CH-204) via heat exchangers mounted on both the first and second stages of the cold head, shown in place within the vacuum chamber in figure 3(a). The first-stage heat exchanger has a helical path while the second-stage heat exchanger has a serpentine path. Circulation pressure is provided by a room-temperature diaphragm pump with a counter-flow heat recuperator used to pre-cool the gas to about 100 K before returning to the cold head. The design of heat recuperator chosen is a tube-in-tube counter-flow type formed into a helix to minimise space, and is shown in figure 3(b). A gas over-pressure of about 300 mbar is maintained, with about 100 mbar differential across the pump, and with a flow rate of 5–10 L/min. A heater and heat exchanger on the variable-temperature insert provides temperature control of the gas stream.

Temperature control is provided by two feedback loops: one controlling the temperature of the gas stream and one controlling a heater on the sample mount. A cernox temperature sensor soldered directly onto the sample provides the sample temperature and feedback to the sample-mount heater.

To measure HTS wires over a wide range of conditions, high currents must be delivered to the sample without unacceptable heating. We have demonstrated up to 800 A as in the $E(I)$ curve shown in figure 4(a). $E(I)$ measurements are made in a ramp mode with current ramped quasi-continuously under computer control to above $I_c$ while the current and voltage are monitored. A standard 4-terminal
configuration is used with voltage taps spaced 5–10 mm apart and an electric-field criterion for $I_c$ of 1 µV/cm.

The current leads are a composite of stainless steel, copper and HTS wire. The stainless steel provides strength and thermal stability, the HTS wire carries high currents at the cold end and the copper carries current at the warm end of the current lead or whenever the local $I_c$ of the HTS is exceeded. The HTS wire terminates before the sample to avoid distorting the applied field.

Heating originates from three sources: the sample itself when currents exceed $I_c$, contact resistances, and more remotely in the current leads. Heating on and adjacent to the sample is of greatest concern as this can rapidly raise the sample temperature. Remote heating can manifest as slower temperature excursions coming well after the measurement. Both of these types of temperature rise are illustrated in figure 4(b), where the sample temperature was monitored during a series of $I_c$ measurements. In this series the $I_c$ increased as the field angle approached the ab-peak up to the 800 A measurement shown in figure 4(a). Measurements up to 400 A could be made with less than 0.2 K immediate temperature rise, and up to 800 A with less than 0.5 K. The maximum current was limited by the available power supply; currents up to and above 1000 A would otherwise be manageable with no further changes provided temperature rises of 0.5–1.0 K were deemed acceptable. Both immediate and delayed temperature rises can be reduced by limiting the duration of the current ramp; in a typical measurement the ramp time is limited to 5–10 seconds. The delayed temperature rises can also build up if many measurements are made in rapid succession, as in the example here. This effect can be minimised by allowing time between measurements for heat to be removed.

![Figure 3](image)

**Figure 3.** Vacuum chamber housing sample-cooling cryogenics: (a) the variable-temperature insert on the left and heat exchangers on the cryocooler on the right, and (b) the helical counter-flow heat recuperator, with other components now wrapped in super-insulation.

![Figure 4](image)

**Figure 4.** Example $I_c$ measurement: (a) $E(I)$ curve with current ramp up to 800 A with power-law fit giving an $I_c$ of 690 A and (b) temperature excursions measured on the sample during a sequence of $I_c$ measurements. The temperature spikes arise from heating on or near the sample, while slower excursions arise from heat diffusion to the sample from further up the current leads.
3. $I_c$ measurements of HTS wires

With temperature, magnetic field, sample orientation, current ramping and current–voltage measurements under computer control, $I_c(T,B,\theta)$ data collection is readily automated. In figure 5 we compare $I_c$ data for two wire samples fabricated by the MOD-TFA method on RABiTS substrates by AMSC [6]. The processing conditions were modified slightly to impact on the pinning landscape. This is evident in comparing the traditional 77 K, 1 T angle dependences in figure 5(a) and 5(b), where a flat background and prominent $ab$-peak in sample 1 contrasts with a broad $c$-axis peak and negligible $ab$-peak in sample 2. However when we compare the temperature series of angle dependences taken at $B = 6$ T in figure 5(c) and 5(d) we find that contrasting shapes at 60–70 K give way to similar shapes at lower temperatures. We draw the conclusion that extrapolations of $I_c$ from 77 K to 30 K, or vice versa, are not robust and that conductor characterisation should therefore routinely cover the parameter space relevant to the application of interest. The data is fitted here with maximum-entropy functions [7] which describe how $I_c(\theta)$ arises from averaging over defect populations; the details will be described in a future report.

Figure 5. The angle dependence of $I_c$ in different temperature and field regimes. (a) Sample 1 at 77 K, 1 T, (b) Sample 2 at 77 K, 1 T, (c) Sample 1 temperature variation at 6 T, (d) Sample 2 temperature variation at 6 T.

4. Conclusions

We have constructed and demonstrated a cryogen-free critical-current measurement system covering a parameter space of 30–90 K, 0–8 T, and full field-angle dependence, automated with respect to these parameters and $E(I)$ data collection. Critical currents up to 800 A can be measured with an immediate temperature rise of less than 0.5 K, allowing for extensive measurements of commercial HTS wires. Extension to higher currents would be possible with an appropriate power supply.

With this instrument under computer control, a large amount of data can be conveniently collected covering the stated parameter space. We have illustrated this with examples showing that $I_c(\theta)$ curves can evolve differently as functions of temperature and field even in quite similarly fabricated samples.

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