Extended-Performance “SuperCurrent” Cryogen-Free Transport Critical-Current Measurement System

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Abstract—We have previously reported the development of a cryogen-free critical current characterization system able to measure field-angle dependences of voltage-current characteristics of short-length superconducting tapes to temperatures of 25 K, fields up to 8 T and currents up to 875 A. We have now extended the existing system and built a parallel system which further extends the parameter space to 10 K, 12 T, 1600 A. With a software suite that fully automates batch measurements we have been able to generate detailed coverage of the temperature-field-angle-current parameter space relevant to many of the applications proposed for high-temperature superconducting tapes. We describe the improvements to the system and present data from commercial tape samples that illustrates the utility of the instrument.

Index Terms—Critical current and flux pinning, critical current measurement, test facilities and instrumentation.

I. INTRODUCTION

There are a number of applications of high-temperature superconducting (HTS) wire that require high-current operation in high (several Tesla) magnetic fields and relatively low temperatures (below 25 K), currently led by compact-fusion power generation. This leads to a need to specify and qualify large quantities of wire from multiple manufacturers.

Much of the work in developing, optimizing and qualifying state-of-the-art HTS wires relies upon measurements of critical current ($I_c$) taken in a liquid nitrogen bath, due to the relative convenience and low cost. However, it is now widely recognized that there is often a poor correlation between critical currents in different temperature regimes [1]. A need therefore exists for high-throughput $I_c$ measurements over a wide range of temperatures, magnetic fields, magnetic field angles, and transport currents. These measurements inform the science of flux pinning [2], [3], electromagnetic modelling of superconducting magnets and machines [4], [5], and the optimization of manufacturing processes for conductor performance and uniformity. A small number of specialized facilities for measurements of this type exist worldwide [5]–[11]. We have previously described a completely cryogen-free system covering temperatures down to 20 K, magnetic fields up to 8 T, field rotation throughout the plane perpendicular to the current and currents up to 875 A [12]. In the present paper we describe improvements to the original system at Victoria University of Wellington (VUW) that expand the parameter space to 12 K, 8 T, 1200 A and introduce a newly-constructed system installed at Commonwealth Fusion Systems (CFS) expanding further to 10 K, 12 T, 1600 A (Fig. 1).

Fig. 1. SuperCurrent measurement system installed at CFS. The magnet at the bottom right is a 12 T split-pair conduction-cooled HTS magnet. The chamber on top of the magnet is a separate vacuum space containing the sample cooling elements. The rack at left includes magnet power supplies, measurement power supplies, temperature monitors and control electronics.

II. SYSTEM DESCRIPTION

A. HTS Magnet

The magnets for both the VUW and CFS systems are split-pair transverse-field HTS magnets designed and manufactured by HTS-110 Ltd. The conductor in both magnets is BSCCO HTS tape. The 8 T VUW magnet has been described in [12]; the 12 T CFS magnet is similar in concept, conduction cooled to below 15 K by a Cryomech PT815 cryocooler. The full field of...
Fig. 2. Gas-flow circuit for cooling the sample and the current leads.

12 T is achieved by a current of 210 A with a ramp time of 18 minutes. A Lake Shore 2Dex hall probe is mounted adjacent to the bore and the reading corrected for its off-center positioning. Active feedback from this reading is used to set and stabilize the field with 0.1 mT resolution. A magnet monitor can activate a dump-circuit system to rapidly ramp the current to zero in the event that the magnet temperature rises beyond set limits or large voltage imbalances are observed.

B. Gas-Flow Sample Cooling

The sample cooling system is nominally identical on the two systems and is slightly improved relative to the previously reported version. The gas circuit is shown in Fig. 2. In the main circuit, in bold lines, the gas is pumped by the circulating pump (hermetic diaphragm pump) through the cooling side of a cryogenic recuperator, successive heat exchangers on the two stages of the SHI RDK-408D2 (VUW) or RDK-415D (CFS) cryocooler, to the variable-temperature insert (sample space). The gas exits the insert part-way along the current leads, passes through the heating side of the recuperator, through a three-way gas-flow balancing valve and back to the pump. The secondary circuit has part of the gas stream flowing up the full length of the insert to recombine with the main stream at the balancing valve. Helium gas inlet and vacuum outlets are positioned appropriately so that during and after a sample exchange, fresh helium gas will tend to flow into the coldest parts of the circuit first and then flush air-contaminated gas directly out of the insert to the vacuum system. The major improvements on the original system described in [12] are the addition of the automated gas-flow balancing valve and the outlet regulator. The balancing valve is controlled by the software to optimize the division of gas flow either to cool the recuperator, and thereby the precooling of the gas returning from the circulating pump, or to cool the current leads to reduce the heat load to the sample. The outlet regulator prevents the high-pressure side of the system (after the circulation pump) from developing too much pressure when the sample temperature is increased, by releasing pressure directly to the vacuum system.

C. Sample Rod and Current Leads

The design of the sample rod, shown in Fig. 3, including current leads, must balance thermal and electrical conductance as well as provide torsional stiffness against large forces acting on the superconducting sample. The structural body of the rod is a G10 insulating rod. The current leads are built on 12 mm × 3 mm stainless steel bars, which are bolted into recesses in the G10 rod to provide further rigidity. A 0.15 mm-thick copper shim is soldered to the full length of the stainless-steel bars. Additional current carrying elements vary in three sections along the length. The bottom (cold) section has two 4 mm wide BSCCO HTS tapes soldered onto the copper. These are intended to carry most, if not all, of the current at low temperatures, resulting in negligible heating of the current leads in the vicinity of the sample. In the central section, the HTS tapes continue, and there is a further 0.3 mm-thick copper or silver shim applied on top. The top section has no HTS components and a thicker 1.2 mm copper plate added to the full-length shim. In addition to strength, the underlying stainless-steel bars provide a thermal buffer to absorb Joule heating during a high-current ramp.

By comparison with a conventional current lead [13] these leads are significantly under-rated but are appropriate as cooling is through gas flow in addition to conduction and high current flows only with a very low duty cycle.

Temperature measurement is provided by a Cernox sensor bonded to a sapphire plate immediately under, and in contact with, the sample which is soldered to the copper sample mount. Two orthogonal Hall sensors provide a direct measurement of the sample angle relative to the field.

III. MEASUREMENT STRATEGY

A. Current Ramp

The stepwise current ramp \( I_n = I^* (1 + r)^n \) with \( I^* = 1 \) A and \( r = 0.02 \) was described in [12]. It is a rapid modified exponential ramp in which each current step is typically a 2% increase over the previous current. This ramp function is shown in Fig. 4(a).
For each current step 20 ms is taken to ramp and stabilize the current and 20 ms (1 power-line cycle) of readings are collected and averaged. Power supplies used to provide the current include the Agilent 6680A, providing 1000 A under analogue control, and Sorensen SGX series providing 1200 A in a single unit or 1600 A through two parallel units.

The exponential ramp provides two advantages. Firstly, the ramp to 1000 A takes 14 s, but very little of this time is at high current. For example, only 1.5 s is spent above 500 A, and in this way Joule heating is kept to a minimum. Secondly, it is not necessary to estimate the critical current before commencing the measurement. For any value of critical current a similar number of data points are available in the fraction of the data representing the onset of dissipation. The voltage is recorded and evaluated in real time and the ramp stops when this exceeds a chosen threshold (typically 5–10 μV).

The current is measured by directly measuring the voltage across a current shunt, while the sample voltage is amplified by an EM Electronics A23 nanovolt amplifier. Fig. 4(b) shows a V(I) curve, with 18 separately measured curves overlaid, demonstrating excellent reproducibility of this ramp method. With an average $I_c$ of 985.6 A, there is a standard deviation of only 0.6 A, corresponding to only 0.02 K if sample temperature variation is the major source of this deviation.

### B. Thermal Performance

The 18 V(I) curves described above were taken in measured succession, initially with 60 s intervals then with 30 s intervals, to determine the level of heating in the sample and in the current leads. The temperature traces are shown in Fig. 5.

Fig. 5(a) shows the sample temperature variation, with very consistent temperature rises at the end of each measurement of 0.07 K. In fact, most of this temperature rise comes after the measurement is completed as it arises from Joule heating due to current passing through the sample mount (which is not superconducting to avoid shielding effects) or in the transition into the sample, rather than within the sample itself.

Fig. 5(b) shows the heating of the current leads at three locations along their length. At the bottom (cold) end, the current is carried almost entirely by superconducting tape so there is negligible heating. At the top (hot) end, there is a modest temperature rise of 10 K for each measurement. In the central region of the current lead where the current is shared by the thin copper shim and superconducting tapes above their transition temperature, the temperature rise is around 40–50 K. However, this temperature rise recovers very quickly, firstly as heat is taken up by the stainless-steel bars and secondly through active cooling by the helium gas flow. The temperature recovers in about 1 minute. When measurements proceed faster than this recovery time, as in the second half of this series, there is a gradual build-up of temperature in the current leads. Eventually the measurements must pause to allow the leads to cool. In practice, it is seldom the case that very high current measurements are taken repetitively at this rate: time is required between measurements to stabilize temperature or field changes and $I_c$ tends to vary greatly over a series of measurements.

### IV. SOFTWARE AND AUTOMATION

The instrument is monitored and controlled through a LabVIEW software program, providing data collection, automation, protection and diagnostic features.

#### A. Batch File Automation

Data collection is greatly facilitated through batch-file programming in which a series of measurements can be specified in a text file listing temperature, magnetic field and angle conditions to be set for each measurement. Nested lists and sub-file calls are provided for, simplifying the process of composing large measurement sequences. Temperature, magnetic field and angle are monitored continuously, and measurements proceed only if all are stable within specified tolerances.

#### B. Speed of Measurement

The fastest mode is measuring angle dependences, since in this case the temperature and field remain steady while the angle can be changed rapidly. A typical angle dependence comprising 50–60 V(I) curves takes 15–30 minute125s to collect if not limited by thermal stabilization. Thermal stabilization can cause this to be slower when measurement currents are high over a significant portion of the dataset. Resetting the temperature and field between angle dependences takes 2–15 minutes depending on the level of change.

#### C. Thermal Protection

With an effective batch capability, the instrument can be left to run unattended. It then becomes important to protect the system against unforeseen situations such as power surges, cooling water failure and computer failure. The HTS-110 magnet has a set of fail-safe protection electronics and a dump circuit to protect it by way of a rapid current dump in the event of overheating. There are also some risks associated with high current continuing to flow to the sample. The current leads are deliberately underrated for continuous current flow and will gradually heat under rapid repeated measurement as illustrated in Fig. 5. Under normal operation the upper sensor is warmest, and the software is designed not to proceed unless this is below a safe level. In addition, all three sensors on the current lead are monitored by a Lake Shore 218 temperature monitor and are linked to relay outputs that interlock the power supply with latching action if any of the temperatures exceeds a safe level (e.g., 325 K). There is also a latching thermostat on the current
measurement shunt that will also interlock the power supply if it exceeds 45 °C (about 10–20 s at continuous maximum current). Importantly, both interlock mechanisms are independent of the computer or software operation.

V. EXAMPLE DATA

A. Temperature and Field Dependences

Examples of temperature and field dependence data acquired on the CFS system are shown in Fig. 6 for a 4 mm wide SuperOx tape. Fig. 6(a) shows temperature dependences at different perpendicular applied fields illustrating measurements up to 12 T, up to 1500 A and down to 15 K. Fig. 6(b) shows magnetic field dependences at different temperatures and sample orientations for a 4 mm wide SuperOx tape, illustrating measurements up to 12 T, up to 1500 A and down to 15 K.

B. Angle Dependences

Angle dependences taken on the VUW system at 7 T are shown over a wide range of temperatures for a 4 mm Shanghai Superconductor tape in Fig. 7, where angles are relative to the tape normal. This dataset illustrates an evolution of $I_c(\theta)$ curves with a large and broad 90° (parallel field) peak at high and low temperatures, a near-isotropic behavior around 60 K and sharp and strong 90° peak around 35 K.

C. $n$-Values

As well as the critical current, power-law fits to the $V(I)$ data give the power-law index, $n$. Often neglected, this index also varies significantly with temperature, field and angle, and should be included in a complete electromagnetic model of an HTS magnet. An example of $n$-value variations is shown in Fig. 8 for the same Shanghai Superconductor sample as Fig. 7. In Fig. 8 the angle dependences of $n$-values and $I_c$ are overlaid for a range of temperatures, all at 5 T. It is notable that (1) there is significant variation of $n$ across field angles as well as versus field magnitude, with peaks and dips appearing at different temperatures, and that (2) variations in $n$ do not necessarily correlate with variations in $I_c$. At 50 K, for example, we see that at 90° there is a peak in $I_c$ but a dip in $n$. This can arise as $I_c$ and $n$ are differently influenced by the defect pinning potential and defect density of the pinning landscape.

A database of $I_c$ and $n$-values for several commercial HTS wires, including the Shanghai Superconductor data shown here, has been compiled using the VUW system [14], [15].

VI. CONCLUSION

The operational parameters and usability of the SuperCurrent $I_c$ measurement system have been significantly extended since we reported the prototype instrument [1]. Thermal stability and data fidelity have been improved and we have completed a 10 K, 12 T, 1600 A system that is installed at Commonwealth Fusion Systems for quality control and parameter-space mapping and has seen over 1000 samples characterised in 12 months.
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