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A Public Database of High-Temperature Superconductor Critical Current Data

Stuart C. Wimbush and Nicholas M. Strickland

Abstract—**One of the major impediments to the industrial take-up of high-temperature superconductors is the paucity of comprehensive, reliable and relevant performance data on commercially available wires. To address this, the Robinson Research Institute is making available its internal database of wire performance data, acquired on our in-house 1 kA critical current measurement system. The database is freely accessible via the world wide web at http://www.victoria.ac.nz/robinson/hts-wire-database and allows download of both graphical images of the data as well as the underlying data files. The database will continue to be expanded into the future, and submissions of commercially available wires for independent characterization and inclusion are invited.**

We demonstrate the utility of this data in terms of a case study on the design of our 1.5 T 2G HTS MRI system and by outlining a comparison of correlations between low-temperature and 77 K performance across 2G HTS wires sourced from different manufacturers that demonstrates that this is useful only for wires of a particular type produced under similar conditions (for example, several batches produced using the same process). These examples highlight the need for complete characterization of different wires under the operating conditions of interest.

Index Terms—**critical currents, flux pinning, high-temperature superconductors, superconducting device engineering.**

I. INTRODUCTION

A PREREQUISITE for the efficient technological use of any material is a detailed knowledge of its physical properties of relevance to the particular application. In the case of superconducting wires, the primary characteristic of relevance to application is the critical current, I_c. For the high-temperature superconductors, generally we are faced with the unfortunate fact that — due to the high degree of material anisotropy and the complex microstructural pinning landscape responsible for the generation of the desirably high critical currents — the critical current is not a simple material parameter, but rather a multidimensional property, strongly dependent in its final form upon the detailed (and variable) operating conditions of temperature, magnetic field strength and direction, amongst other more fixed conditions. Combined with this is the dual impediment that manufacturing processes for the newer materials tend to be in a state of "continuous improvement" such that the materials' properties are always evolving, and manufacturers tend to specify only the barest minimum of data to characterize their product, for example the 77 K self-field I_c, which is widely recognized to be a poor indicator of performance across the entire operating range.

The low-temperature superconductor (LTS) community has been well served by a relatively stable, well-characterized product, whose performance can be relied upon to vary systematically and predictably with the operating conditions. The existence of a well-respected and authoritative database [1] of comparative wire performance likewise serves both research scientists and production engineers faced with the thorny problem of materials selection. The high-temperature superconductor (HTS) community in contrast remains in the position of having to work with material whose properties vary strongly from supplier to supplier, and even batch to batch, and whose variation under moderate changes in operating conditions is unpredictable.

By providing a freely-accessible database [2] of detailed high-temperature superconductor I_c performance data spanning all widely-available wire products, it is our intention to contribute to plugging this knowledge gap, spurring consideration and comparisons of datasets relating to differently-manufactured wires with the aim of increasing understanding, as well as providing a reference point for designers seeking to specify wire for the more efficient construction of high-temperature superconducting machines and devices.

II. DATABASE SCOPE

A. *Criteria for Inclusion*

It is the intention of the database to feature materials of general and widespread public interest. Typically, this will be commercially available product. However, it is recognized that many nascent 2G wire manufacturers are at a pre-production stage of development, and it is beneficial to include as many examples of different manufacturing processes as can be sourced. For this reason, a non-commercial example of a wire associated with a given manufacturer and manufacturing process is also an acceptable inclusion. Datasets presently available include sample 2G wires from AMSC (Amperium®), Fujikura, STI (Conductus®), SuNAM, SuperOx, SuperPower (AP) and THEVA.

In rare cases, research samples of particular general interest (for example, fabricated by a novel process or revealing significant peculiarities of behavior) that thereby warrant full characterization can also be included.

The scope of the database is not limited to 2G wires, but is open to all HTS materials. It already features a Sumitomo DI-BSCCO® 1G wire, as well as an early Nexans Bi-2212 wire.

The authors are with the Robinson Research Institute of Victoria University of Wellington, Wellington, New Zealand (e-mail: stuart.wimbush@vuw.ac.nz and nick.strickland@vuw.ac.nz).

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Materials for independent characterization and inclusion in the database can be supplied by arrangement direct to the authors.

B. Updates

The database is not intended to be static, but will be updated as and when new materials are released, more comprehensive datasets become available, or improved data quality or extent is achieved. At the same time, it is an overriding objective to keep the data timely and relevant, so superseded datasets will also be removed.

III. Experimental Details

A. Measurement System and Limitations

The data featured in the database has been acquired on our in-house high-current critical current characterization system, described fully in [3]. The same system is available for commercial sale to third parties [4]. The present capabilities of the system are temperatures down to 20 K, magnetic field strengths up to 8 T, and transport currents approaching 1 kA. I_c values are determined using a standard electric field criterion of 1 μV/cm. In practice, this enables typical contemporary ~4 mm wires to be measured over the full range of conditions; wider wires can be measured over a restricted range of conditions or can be cut/patterned to a narrower width and the results scaled to the full width. Wire samples up to 12 mm wide can be accommodated in 40 mm lengths.

B. Standard Measurements

A standard dataset includes a self-field temperature dependence of the critical current, a set of field dependences of the critical current under particular field orientations (included to meet conventional expectation, although we note our own reservation as to their general utility [5], and caution against blindly relying upon them without giving due attention to the full angle dependence), and a set of field angle dependences of the critical current at particular temperatures and magnetic field strengths. The field angle is set in relation to the wire normal (0° is perpendicular to the wire surface, 90° is in the plane of the wire), maintaining the maximum Lorentz force geometry of field and current perpendicular. The angular range of the measurement is typically set to extend from 0° to 240° in order to clearly reveal any pinning contributions to I_c in the perpendicular orientation. Example results from these three standard measurement types are shown in graphical form in Fig. 1, for a Conductus® wire sample from STI.

IV. Data Format

To enhance its utility and potential for re-use, the data in the database is presented in a number of complementary forms, described below. An attempt has been made to standardize the data format across samples, although inevitably it has evolved somewhat over time.

A. Graphical Images

For the most immediate and straightforward utility, graphical images of the dataset are provided in the form

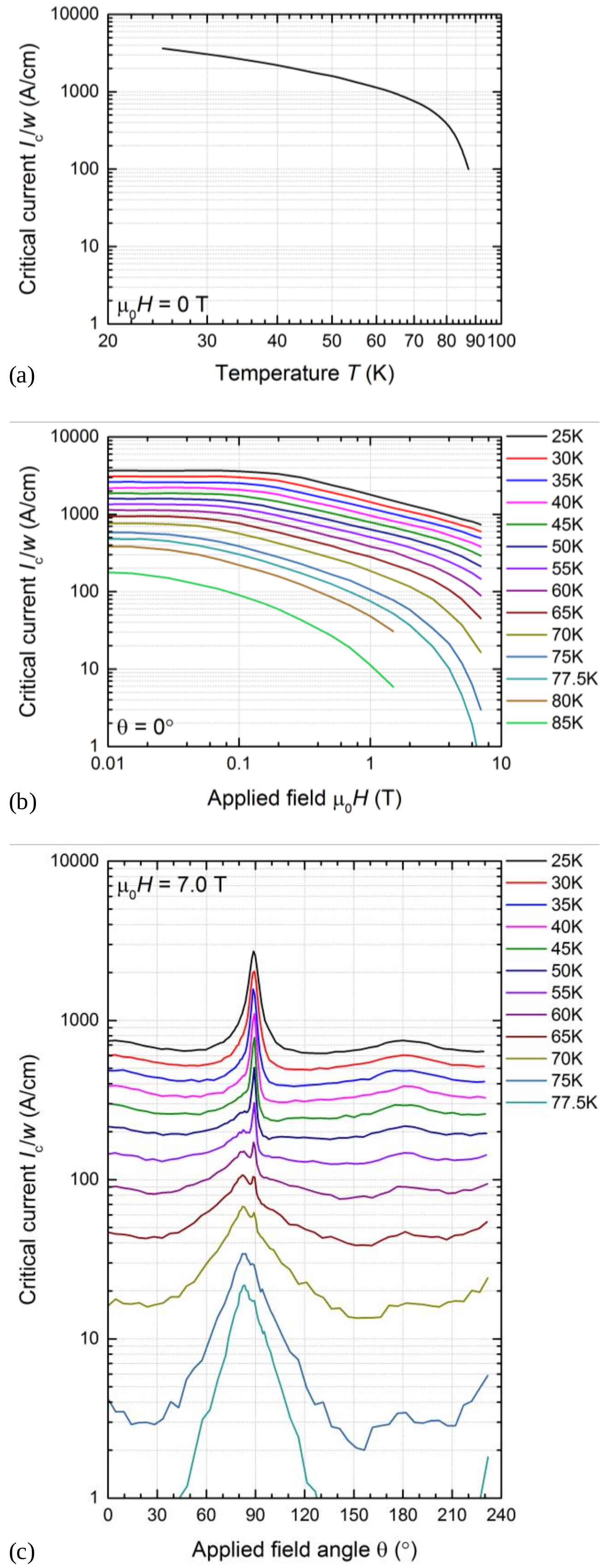

Fig. 1. Graphs showing the (a) temperature, (b) field, and (c) angle dependence of the critical current of an STI Conductus® wire sample under the specific conditions noted on the graphs, as an example of the standard measurement types included in a dataset.

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exemplified in Fig. 1. These can be browsed directly online and provide an immediate overview of the performance of the particular sample, similar to a manufacturer data sheet, but in far more comprehensive detail.

B. *Excel Files of Critical Current Data*

The critical current data used to generate the graphical images is supplied in a number of Excel (Open XML .xlsx format) files. The data is duplicated multiple times across these files in an attempt to provide it in the most immediately accessible form for any given usage. This format was chosen in preference to a raw ASCII format due to its capacity to store multiple "worksheets" of related data (for example, the angle dependences at a given field for all temperatures) in a single file. An example of the individual file format is shown in Fig. 2. The different types of file are as follows:

1) *All data.xlsx*

This file contains every measured data point for the sample in a single continuous list on a single worksheet. This file can be most usefully used to filter the data on a particular set of conditions in order to extract just the data of interest, or to export to an alternative format for further processing.

2) *0T temperature dependence.xlsx*

This file again comprises just a single worksheet containing the self-field critical current values of the sample as a function of temperature, as exemplified in Fig. 1(a).

3) *nnn° field dependences.xlsx*

These files comprise multiple worksheets each containing a field dependence of the critical current acquired at a particular field orientation across a range of temperatures. Such a file contains the entire dataset plotted in Fig. 1(b), with each curve appearing on a separate worksheet.

4) *nn.nT angle dependences.xlsx*

These files comprise multiple worksheets each containing an angle dependence of the critical current acquired at a particular field, across a range of temperatures. Such a file contains the entire dataset plotted in Fig. 1(c), with each curve appearing on a separate worksheet.

5) *nn.nK angle dependences.xlsx*

These files contain the same angle dependences detailed in point 4 above, but this time collated under a particular temperature (for all fields). This file would be of interest if it was desired to observe the evolution of the angle dependence of the critical current with respect to field rather than temperature.

C. *Raw Data Files of Underlying IV Curve Measurements*

The data files discussed until now contain critical current data values extracted from a power law fit to the underlying *IV* curve measurement of the sample. In addition to the critical current (I_c) value itself, a value normalized to the width of the sample (I_c/w) is provided for comparison across samples of different widths or in cases where cut-down sample widths have been used to extend the measurable data range. The exponent of the power law fit (commonly termed the n-value) is also enumerated, as well as an arbitrary voltage offset value, and a linear voltage component that may arise in some samples due to incomplete current transfer.

	A	B	C	D	E	F	G	H	I	J
1	Temperature (K)	Field (T)	Angle (°)	Ic/w (A/cm)	Ic (A)	n	V0 (µV)	V1 (µV/A)	Hall field (T)	Hall angle (°)
2	25	7	0	735.87	36.79	19.7	0.08783	-0.00211	6.963	-3.57
3	25	7.001	5	742.93	37.15	19.2	0.0118	-0.00244	6.966	-0.12
4	25	7.001	10	748.19	37.41	22.03	-0.07854	-0.00116	6.975	4.49
5	24.98	7.002	15	737.93	36.9	20.78	-0.04113	-0.00326	6.993	9.43
6	24.98	7.002	20	727.82	36.39	22.4	-0.03091	-0.0003	7.009	13.9
7	24.97	7.002	25	708.63	35.43	21	-0.00791	0.00541	7.022	18.24
8	24.96	7	30	688.26	34.41	19.64	-0.14673	0.00202	7.032	23
9	24.98	7.001	35	677.82	33.89	20.19	0.10244	-0.00127	7.044	27.47
10	24.99	7.001	40	660.66	33.03	18.4	0.02151	-0.00005	7.056	32.15
11	24.98	7.001	45	662.43	33.12	20.98	0.01581	0.00476	7.063	36.77
12	24.99	7.001	50	652.45	32.62	20.95	-0.03892	-0.00257	7.07	41.37
13	24.99	7.002	55	643.63	32.18	17.65	-0.00529	-0.00187	7.075	45.97
14	24.99	7.002	60	646.41	32.32	17.66	0.01172	0.00505	7.078	50.43
15	24.99	7.002	65	654	32.7	17.89	-0.01465	-0.00064	7.079	54.97
16	24.98	7.002	70	654.58	32.73	15.66	-0.05902	-0.00032	7.077	59.56
17	25.01	7.002	75	687.82	34.39	16.96	-0.43543	0.00389	7.075	64.09
18	25.02	7.002	80	722	36.1	16.18	0.01103	0.00563	7.071	68.57
19	25	7.002	82	730.88	36.54	13.76	-0.05282	-0.00202	7.068	70.45
20	24.99	7.002	84	763.57	38.18	13.94	-0.18272	0.00103	7.066	72.36
21	25	7.002	86	791.64	39.58	13.41	-0.35141	0.0009	7.064	74.22
22	25	7.002	88	845.01	42.25	13.95	-0.35514	0.00169	7.061	76.14
23	25	7.002	89	868.9	43.44	13.27	0.1538	-0.00118	7.058	77.11
24	24.98	7.002	90	906.02	45.3	13.29	-0.19909	0.00378	7.056	78.05
25	25	7.002	91	933.79	46.69	11.99	-0.01831	0.00015	7.055	79.01
26	24.99	7.002	92	980.67	49.03	12.12	-0.00063	-0.00275	7.054	79.98
27	24.98	7.002	93	1050.49	52.52	12.4	-0.27224	0.00665	7.052	80.93
28	24.99	7.002	94	1100.32	55.02	11.24	-0.10809	-0.00044	7.048	81.89
29	24.99	7.002	95	1200.26	60.01	12.32	0.02212	-0.00171	7.047	82.85
30	25.01	7.002	96	1303.34	65.17	10.87	0.02547	0.00125	7.045	83.82
31	24.99	7.002	97	1474.43	73.72	10.99	-0.22902	0.00244	7.043	84.77
32	25	7.002	98	1718.16	85.91	12.03	-0.12591	0.0009	7.039	85.75

25K | 30K | 35K | 40K | 45K | 50K | 55K | 60K | 65K ...

Fig. 2. An example of the format of the Excel data files, in this case relating to the graph shown in Fig. 1(c). Note the existence of different worksheets within the single data file for the data relating to each different temperature.

For situations where it is desirable to analyze the measurement is greater detail, the raw data files for each individual *IV* curve measurement are also provided. Each of these exists in a separate ASCII file containing columns of current and voltage data, together with a timestamp and an instantaneous readout of the sample temperature. All of these raw data files are bundled together into a single .zip file for ease of download. A directory structure contained within the .zip file preserves the form of the measurement (either temperature, field or angle dependence), while the individual filename specifies the actual measurement conditions. Within each directory, a summary file collates the processed results of each measurement; it is from this summary file that the Excel files have been generated.

V. Utility of the Data

We anticipate that the collation of data of such unprecedented detail on diverse examples of high-temperature superconducting wires and its broad publication will find multiple uses ranging from the basic science of understanding the complexities of flux pinning in real-world HTS materials, through the development of strategies for enhancement or optimization of the properties of HTS wires manufactured via different processing routes, to ultimately improving the design of efficient and thereby more cost-effective HTS devices. We offer two examples of this process here.

A. *Optimization of the Design of an HTS MRI System*

As an example of how detailed wire characterization can increase device efficiency, and thereby contribute to lower system cost, we outline one aspect of the design of our 1.5 T YBCO-based HTS MRI system detailed in [6]. As described there, this system was initially designed using rather sparse (but nonetheless in-house acquired) wire performance data, aiming for an operating temperature of 20 K. This already represented an improvement in the design methodology that typically adopts a simple minimum I_c value as a safe, but inefficiently over-engineered, design parameter.

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Subsequent to construction, it was found that it would be beneficial to the operation of the instrument if the system could be allowed to exceed 20 K during image acquisition. While this lay outwith the original design specification, a more detailed characterization *of the same wire*, with a finer temperature and angle resolution, followed by remodeling of the coil assembly as indicated in Fig. 3, gave confidence that the magnet could be safely operated at a higher temperature while maintaining the same safety margin between operating current and wire I_c as originally designed.

If applied during the initial design stage, this demonstrates that the use of more refined wire characterization data *even for the same wire* can lead to significant and tangible gains in operating conditions or equivalently wire quantity required, which translate directly to lower overall system cost.

B. Necessity for Complete Wire Characterization

In an attempt to reduce the quantity of data required to adequately characterize anisotropic superconducting materials such as HTS, we often seek either scaling laws (which have been particularly successful in the case of 1G material, as also demonstrated by our data [7]) or, where these fail, simple correlations between performance under different operating conditions. In the case of the latter, recent work [8] has suggested a heightened degree of correlation between the I_c value obtained at 77 K, 3 T and that obtained across the full range of temperatures and fields (applied perpendicular to the sample) for a large number of similar samples. It is important to treat such correlations with caution, however, since even where they are found to exist, our data clearly demonstrates that they can be valid only for a very small set of similarly-prepared samples. There exists no such general correlation across 2G HTS samples prepared by different methods or even featuring different treatments, and a cursory examination of the data shows that there never could be. It is unsurprising that a degree of correlation exists between the I_c value under one condition and that under another – this is to be expected, and indeed is the basis of interpolation between data points. It is only the deviations from this typical degree of correlation that have any significance, and we can state that it is as easy to find negative correlations in specific samples as it is to find positive ones. Furthermore, even where such a correlation may be found to exist, it could clearly never account for the complexity and variety of the anisotropy observed in the angle dependence of I_c of contemporary pinning-optimized 2G wires, as exemplified in Fig. 1(c), while to consider only perpendicular and parallel fields as being of importance is to make exactly the oversight we have highlighted in [5]. As we have demonstrated above, it is precisely in the detail of this complexity in the data that true device optimization and ultimate cost-efficiency of device construction is to be found.

VI. Conclusion

Essential to the efficient design of superconducting machines and devices is a detailed knowledge of the performance characteristics of the underlying superconducting wire across the varied operating conditions of interest.

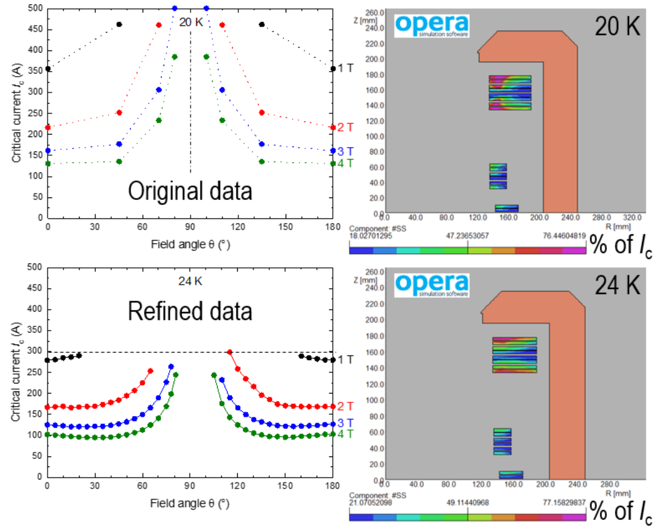

Fig. 3. Results of modelling the I_c utilization of a 1.5 T HTS MRI coil using an original and refined wire characterization dataset. A similar maximum I_c utilization of 77% is obtained at an operating temperature of 24 K after refinement as was obtained at 20 K using the original data.

Through our detailed characterization of emerging commercial superconducting wire materials and public release of the resulting datasets, it is hoped that more cost-effective device designs can routinely be developed, spurring the broader uptake of high-temperature superconducting technologies.

Acknowledgment

We are grateful to Ben Parkinson for providing the images of his modelling of the HTS MRI coil shown in Fig. 3.

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