HTS Cable International Round Robin: 4.4 kA Critical Current Measurements

R. G. Hutson, M. J. Raine, M. Kiuchi, T. Matsushita and D. P. Hampshire

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***Abstract*—The critical current of the core and shield of a 2.1 m long, 40 mm diameter Bi-2223 HTS coaxial cable was measured as part of an International Round Robin organised by Japan involving several international laboratories. In Durham, we found using a 100 μVm^{-1} criterion and an 8 minute trace time that I_c of the core and shield were 4386 A and 4143 A and the n-values were 19.6 and 14.4 respectively. 8 minute trace times were found to be a practical approximation of steady state conditions, with critical current values 0.5 % and 1.2 % larger than values obtained using 2 minute trace times, and n-values not significantly different to 2 minute trace values. Two minute trace time data were compared with equivalent data from other participating labs and excellent agreement was found: I_c was 0.6 % and 1.5 % larger for the core and shield respectively. The E-field range has a significant effect on the n-value measurements, which varied between groups. Good agreement between the participants for the shield was found for electric fields below 100 μVm^{-1}, although larger n-values were found at higher electric fields at Durham and some other laboratories. The polarity of the current and the proximity of the return power cable were demonstrated to have negligible effect ($<$ 0.1 %) on the I_c measurements. Removing conductive and ferromagnetic materials that were part of Durham's experimental set-up increased I_c by $<$ 1 %. An intrinsic trace time dependency was found for I_c for trace times of less than 8 minutes that we attribute to the time required for fluxons to equilibrate with the underlying pinning landscape in a changing net magnetic field.**

***Index Terms*—Superconducting cable, critical current measurements, standards, round robin test.**

I. INTRODUCTION

An international round robin test was set up to measure Bi-2223 superconducting cables manufactured by Sumitomo, as part of the effort to standardise DC critical current measurements of superconducting cables. This Japanese project was started in response to recommendations made by the International Electrotechnical Commission (IEC) [1] and the International Council on Large Scale Electric Systems (CIGRE) [2] to standardise the test method of DC critical current measurements on cables. Such DC superconducting cables are, for example, a potential solution for low-loss, high-power transmission in high population density cities [3] and for offshore renewables [4]. The participating laboratories are from Japan, Korea, the USA, France and the UK. Here we report the test results from Durham, UK, on cable C [5] and compare them with other participating laboratories. Cable C is a 2 m long Bi-2223 High Temperature Superconductor (HTS) cable with a coaxial structure, consisting of an inner core with two superconducting layers that contain a total of 29 tapes and a shield with a single layer of 26 tapes (Figure 1). The critical current of the core and the shield are each $\sim$4 - 5 kA at an E-field of 100 μVm^{-1}.

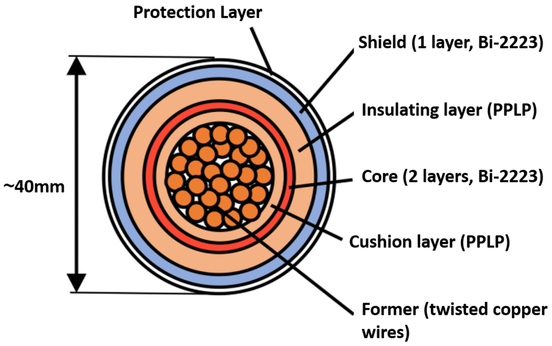

Fig. 1: Cross section of the Bi-2223 cable [5].

II. EXPERIMENTAL SETUP AND ANALYSIS

Our set-up consisted of a 2.4 m long polystyrene liquid nitrogen open-bucket Dewar, stands to support the HTS cable, four 1200 A power supplies, power leads and a connection box, a 6000 A Deltec standard shunt resistor, a commercially calibrated Cernox thermometer, a PC running Labview, a nano-amplifier and several voltmeters. The Dewar and cable stand were designed and built in Durham (Figure 2). The 6000 A shunt was calibrated and corrected by 0.64 % from it's nominal value. In this work, four-terminal I_c measurements were made with a continuously ramped current, as well as bath temperature readings [6], [7]. The measurements were made using a nano-amplifier (× 50k gain) to obtain low noise data ($\pm$ 4 μVm^{-1}) and without the nano-amplifier to obtain data at higher electric fields ($\sim$ 800 μVm^{-1}, see Figure 3 for the core). The cable was cooled for at least 2 hours in liquid nitrogen before measurements began [5]. All the electric field versus current data presented in this paper are baseline corrected by subtracting the inductive voltage so the voltage at low currents is zero. I_c is obtained at a standard criterion

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Fig. 2: One of the two Durham set-ups. It includes an open-bucket Dewar and the use of non-magnetic (and non-metallic) materials - a polythene liner and Tufnol cable supports.

of 100 μVm^{-1}. The index of transition (n-value) was obtained between 100 μVm^{-1} and 800 μVm^{-1}.

III. EXPERIMENTAL RESULTS

A. Trace Time

Critical current measurements were carried out using 1, 2, 4, 8 and 16 minute trace times (the time to ramp from 0 to 4300 A). The data shown were smoothed using four-point adjacent averaging. As seen for the core in Figure 4, faster traces resulted in lower critical currents. There is a $\sim 1\,\%$ discrepancy between the 1 minute and 16 minute traces, and a $\sim 0.1\,\%$ difference between the 8 and 16 minute traces for both the core and shield. Heating in the 6000 A shunt was measured using infra-red thermometry [8] and found to be small. For a 16 minute ramp to 4800 A, the temperature rise was $\sim 20\,^{\circ}$C, corresponding to a change in resistance (and therefore current reading) of $\sim 0.1\,\%$ [9]. We investigated the time-constants in our measuring equipment (i.e. voltmeters and nano-amplifier) by measuring Ohm's law for two normal resistors. A 2000 A standard resistor with a similar differential resistance to the cable was used to test the voltmeters without the nano-amplifier. The rate at which the current was increased produced no significant deviation from Ohm's law, showing that the voltmeter time-constants were negligible (i.e. very fast). We conclude that the apparent decrease in I_c shown in Figure 4 is an intrinsic property of the superconducting material in the cable (discussed below). A lower resistance copper block was also used to test the measuring equipment with the nano-amplifier included and the results are shown in Figure 5. From these measurements we conclude that trace times for I_c measurements of at least 8 minutes are sufficiently long to eliminate the role of the time-constants of the filters in the nano-amplifier. Care must be taken with data taken at fast sweep rates with the nano-amplifier because the data includes a convolution of the intrinsic decrease in I_c associated with the Bi-2223, and the apparent increase in I_c associated with the time-constants of the nano-amplifier's filters (cf. Figure 5). Measurements taken with a trace time of 8 minutes are quasi-static and eliminate both of these effects, so the E versus I traces overlap, both with and without the nano-amplifier (cf. Figure 3).

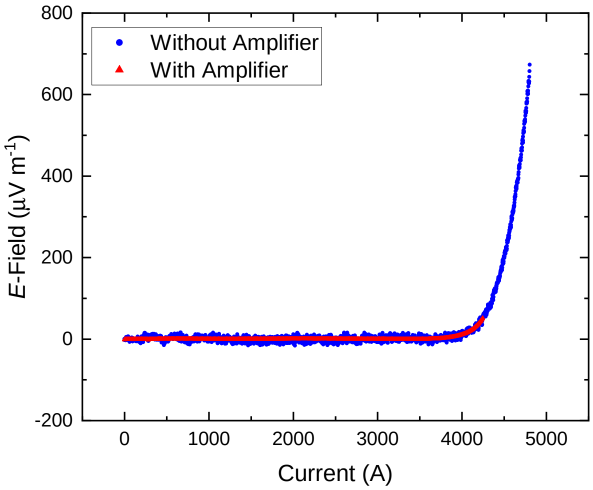

Fig. 3: 8 minute I_c traces for the core, with the nano-amplifier (in red) and without the nano-amplifier (in blue).

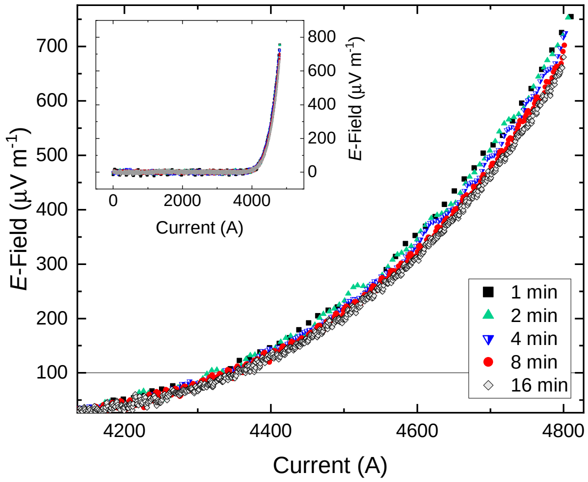

Fig. 4: Core I_c traces using different trace times, without the nano-amplifier, showing trace time dependency.

B. Polarity Switch Check

The results from 8 minute I_c traces with the nano-amplifier for 'normal' and 'reverse' polarity are plotted on a log-log plot in Figure 6. They show that the effect of current polarity was negligible for the core (less than $0.1\,\%$). The shield measurements did contain an anomalous reverse-polarity trace that resulted in a $0.3\,\%$ difference in current at 40 μVm^{-1} compared to the other measurements. However, all subsequent traces agreed to within $0.1\,\%$. We conclude that the effect on I_c of the direction of current flow in the cable, i.e. current polarity, is negligible.

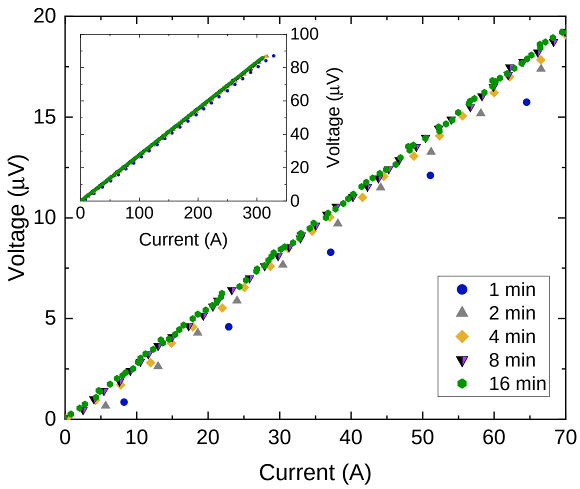

Fig. 5: $I-V$ traces taken for different trace times on a copper bar used to test the effects of the nano-amplifier filter time-constants on the current measurements.

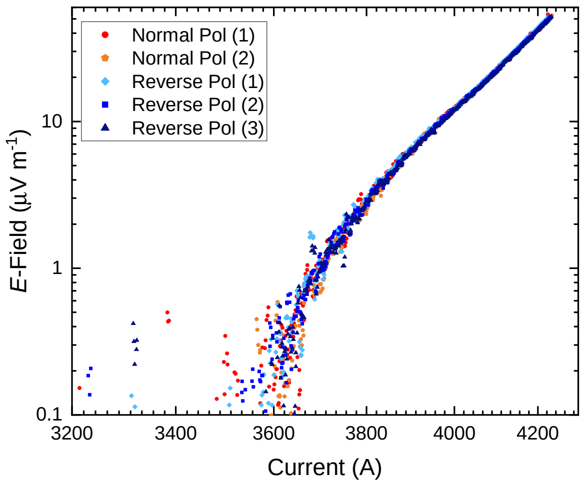

Fig. 6: 8-minute core I_c traces for normal polarity (Normal Pol) and reverse polarity (Reverse Pol), with the nano-amplifier, plotted on log-log axes.

C. Return Cable Effects

The copper return cable that transports the current from the HTS cable back to the power supplies produces its own magnetic field that can interact with the HTS cable. We investigated the effects on I_c of having the return cable near the HTS cable. I_c measurements were made using the nano-amplifier and 8 minute trace times, with the return cable at three different distances from the HTS cable - far ($1.5\,\mathrm{m}$), medium ($0.9\,\mathrm{m}$) and close ($0.3\,\mathrm{m}$, right next to the Dewar). At a criterion of $40\,\mu\mathrm{Vm}^{-1}$, the core I_c was unaffected by the return cable position (to within $0.1\,\%$). The shield I_c varied by up to $0.3\,\%$, however, the variation was not systematic with distance. This suggests that the proximity of the return cable was not significant. The effect of the return cable can also be estimated with reference to Figure 7 as follows: the field from the return cable adds to the self-field of the HTS cable on its near side, and subtracts on the far side. The fields add in quadrature above and below the cable. Data are available for the component BiSCCO tapes from Song et. al. [10]. Ampere's law gives the field from the return cable at a $0.3\,\mathrm{m}$ distance to be only $\sim 3\,\mathrm{mT}$. On the sides of the HTS cable, the field from the return cable is parallel to the HTS cable self field, and also broadly parallel to the Bi-2223 a-b planes, for which Song et. al. have shown I_c is only weakly dependent on an applied field. At the top and bottom of the cable, the self-field of the return cable is perpendicular to the a-b planes. In this case the data from Song et. al. suggests that a $3\,\mathrm{mT}$ field could reduce I_c by as much as $1\,\%$, however, at a $1.5\,\mathrm{m}$ distance this effect reduces to the order of $0.1\,\%$. Therefore, we chose a separation of $1.5\,\mathrm{m}$ between the HTS cable and the return cable for all the measurements presented here.

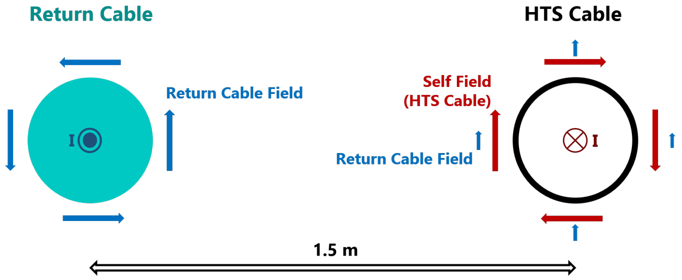

Fig. 7: A schematic showing the magnetic fields around the HTS cable. The net field near the HTS cable is a superposition of the self field from the HTS cable itself and the field from the copper return cable.

D. Non-magnetic Dewar lining and components

In this work, we made measurements using two different configurations for the lining of the polystyrene Dewar and the support for the HTS cable. In the first set-up, the Dewar was lined with both aluminium foil and super-insulation, and the HTS cable support consisted of an insulated mild steel bar running the length of the cable. In the second set-up, we used non-magnetic (and non-metallic) materials - the aluminium foil and super-insulation were replaced with polythene and the steel cable stand was replaced with Tufnol supports, which suspended the cable from above. This eliminated the addition of any extraneous Eddy currents or stray magnetic fields being introduced from our experimental set-up. I-V traces measured with the non-magnetic setup resulted in higher critical currents for both the core and the shield, of $\sim 0.5\,\%$ and $\sim 1\,\%$ respectively. We attribute this small difference to the steel support in the first set-up, but note it is within the measurement uncertainty. We also note that the trace time dependency remained for both set-ups.

E. Temperature Correction

Since the boiling point of the cryogenic liquid depends on both the amount of oxygen dissolved in the nitrogen and the atmospheric pressure in the laboratory [11], we made temperature measurements of the cryogen using a commercially calibrated Cernox thermometer during the I_c measurements.

TABLE I: Core I_c (temperature corrected) and n-values from Durham taken using 2 minute trace times compared to other participating international laboratories.

Lab	Average I_c (A)	$\Delta I_c\%$ from Average	n-values	$\Delta n\%$ from Average	trace time (min)
Lab A	4340	$+0.02$ %	20.3	-3.3 %	-
Lab B	4340	$+0.02$ %	20.7	-1.4 %	-
Lab C	4389	$+1.15$ %	21.9	$+4.3$ %	-
Lab D	4295	-1.01 %	21.0	0.0 %	2
Lab E	4306	-0.76 %	21.8	$+3.8$ %	2
Durham	4364	$+0.58$ %	20.0	-4.8 %	2
Average	4339	-	21.0	-	2

The I_c data taken in Durham were converted to equivalent values at 77.3 K, using equation (1) [5].

$$I_c(77.3\text{ K}) = \frac{I_c(T)}{1 - 0.05082\,(T - 77.3\text{ K})} \tag{1}$$

Note that in this paper, the temperature correction was applied to the I_c data in Tables I and II, but not to the index of transition data i.e. the *n*-values, or the data in the figures.

F. Discussion and Comparison with Other Laboratories

Other participants in this international round robin generally used 2 minute trace times. In Table I, a comparison is provided between the I_c values measured in Durham and those from the other laboratories. Also shown are the *n*-values. It is seen that there is excellent agreement between the different laboratories for measurements on the core of the cable. We note that equivalent data for the shield also showed excellent agreement at low electric fields, but that at high electric fields, the shield showed an increase in *n*-value usually attributed to some heating. This heating may have occurred in a region outside the voltage taps used in the four-terminal measurements, but not sufficiently far from them for the particular set-up in Durham. Some of the other laboratories found similar results at high electric fields, which will be considered in future work. In Table II, data from Durham taken from the average of three measurements made using 8 minute trace times are shown. The numerical data in Tables I and II were both taken using the set-up with non-magnetic materials. We note that the differences between the data in the tables for 2 and 8 minute trace times are not very large, although, for good agreement between different standards laboratories, it may be best to compare quasi-static data that are independent of the filters used in the measuring equipment. However, such a choice has to be weighed against additional measurement time and cost.

A very interesting feature of these data is the intrinsic trace time dependence, which we suggest is a characteristic of the component HTS Bi-2223 tapes themselves. For short trace times, the net magnetic field in the Bi-2223 is changing, which means the fluxons are being continuously swept through the pinning sites as the current approaches I_c. In contrast, when the trace times are long, the fluxons approach the pinning sites more slowly and the flux-line-lattice can adjust to minimise its energy and hence be more effectively pinned [12]. Therefore, the critical current is higher at longer trace times, as found in Figure 4. It would be interesting to investigate this further by measuring I_c for increasing and decreasing applied current and comparing such results to those presented here.

TABLE II: Core and Shield I_c and n-values using 8 minute trace times ($\sim 9\,\mathrm{A\,s^{-1}}$ sweep rate). Raw data measurements and I_c data corrected for 77.3 K are shown. The data are an average of 3 measurements.

	Raw data measurements			Corrected for 77.30 K
	Trace	I_c	n-value	I_c
Core (77.41 K)	1$^{\text{st}}$	4362 A	19.75	4387 A
	2$^{\text{nd}}$	4360 A	19.56	4385 A
	3$^{\text{rd}}$	4362 A	19.55	4387 A
	Average	4361 A	19.6	4386 A
Shield (77.60 K)	1$^{\text{st}}$	4077 A	14.45	4140 A
	2$^{\text{nd}}$	4077 A	14.39	4140 A
	3$^{\text{rd}}$	4085 A	14.48	4148 A
	Average	4080 A	14.4	4143 A

IV. CONCLUSION

The critical currents of the core and shield measured in Durham were 4386 A and 4143 A respectively, using 8 minute trace times. These are 0.5 % and 1.2 % larger than the values obtained using 2 minute traces. A comparison of 2 minute traces with other participant laboratories shows that Durham's I_c measurements were 0.6 % and 1.5 % larger than the average for the core and shield respectively, which is excellent. We found that the effect of the current polarity on the measurements and the effect of the proximity of the return power cable were negligible ($<$ 0.1 %). The replacement of the steel support, aluminium foil and super-insulation with Tufnol and polythene did increase I_c by $\sim 0.5\,\%$ for the core and $\sim 0.9\,\%$ for the shield. An intrinsic trace time dependency for I_c was found and we have provided a simple explanation for it. We conclude that measurements on HTS cables of I_c in the range of 4 - 5 kA can be made at the 1 - 2 % level reproducibly and reliably.

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