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CORRELATION OF SUPERCONDUCTOR STRAND, CABLE, AND DIPOLE CRITICAL CURRENTS IN CBA MAGNETS*

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MASTER

Abstract

A calibration between vendor critical current data for 0.0268" diameter superconductor strand supplied to Fermilab, and the BNL 10^{-12} ohm critical current specification is presented. Vendor critical current data for over 400 Fermilab type billets are shown, both as supplied by the vendor and converted to BNL units. Predictions of cable critical current are made using the sum of the critical currents of the 23 strands, where all strands from the same half billet are assigned the same critical current. The measured critical current shows excellent correlation to the predicted value and is approximately 14 ± 2 percent below it. Colliding Beam Accelerator (CBA) full length dipoles reach the conductor critical current limit, essentially without training. Magnet performance is predictable from the measured critical current of a short sample of cable to within 2%.

Fermilab Experience Compared to BNL Expectations

Fermilab superconductor strand and cable have been adopted for CBA magnets.¹ The strand is identical to Fermilab strand (strand diameter 0.0268", Cu:Sc ratio 1.7, resistance ratio 90, 2070 μ filaments of Nb 46.5 wt% Ti with 4 twists/inch). The cable has the same width and average thickness as the Fermi cable but has a slightly smaller keystone angle and all 23 strands are coated with stabrite (0.0465" $\times$ 0.0525" $\times$ 0.307", transposition length 2.5", compaction 0.85).

Fermilab has provided us with the manufacturer's current certifications at 5.0 Tesla 4.2 K for a representative strand from each half billet for 120 half billets labelled 163-1 through 222-2 from MCA and 282 billets numbered 02 through 348 from IGC. Also, as part of their proposal to us, IGC submitted data on 82 strands from 41 billets numbered in the range 301 to 350.

All this data has been entered into a data base. For MCA, separate entries are retained for each half billet, but for IGC the two samples per billet are averaged. A histogram of all the data is shown in Figure 1. The means and standard deviations of the distributions are nearly identical but the MCA distribution is more skew, having a longer tail at low currents. Based on this information, a requirement of a 240 ampere minimum for the material seemed reasonable since only 4.2% of the MCA conductor and 1.4% of the IGC was below this value.

According to the Fermilab strand Spec. 1610-ES-54654 and engineering note EN-740904-1 the short sample critical current is defined at an effective resistivity of 10^{-12} ohm. If the sample quenches at a lower effective resistivity, then the quench current is used. Through the cooperation of Bob Remsbottom and Al McInturff of FNAL, and Bruce Zeitlin and Kanithi Hemachalam of IGC, a cross comparison was made between BNL's measurement of 10^{-12} ohm critical current, as specified in ISA Spec. No. 89, and the data given by the strand manufacturers to Fermilab. Seven wire samples were provided to us by IGC. MCA wire samples were provided by Fermilab as part of our cable

procurement. Table I shows a comparison between the same sample measured at IGC, BNL and FNAL. Agreement between BNL and IGC is excellent. Four of the FNAL measurements agree but two are high by ~ 10%.

Figure 1

TABLE I
Critical Current Data From Long and Short Sample Tests
Conducted at MCA, IGC, and FNAL

Resistivity	1×10^{-12} ohm			1×10^{-12} ohm			BNL Spec FNAL GATE
	MCA	IGC	FNAL	MCA	IGC	IGC	
Sample Length	Long	Long	Short	Long	Long	Short	
Sample No.							
327-01	244	244	250	237	235	175	0.862
327-11	273	273	275	266	268	302	0.881
329-15	270	269	275	263	262	290	0.907
335-05	283	280	280	276	272	302	0.914
337-29	243	244	275	235	234	270	0.870
339-13	308	298	305	302	292	325	0.920
Ave:							0.892
RMS:							0.024

At the time when these measurements were performed, a comparison between our own measurements and those sent by IGC to Fermilab revealed that the numbers in IGC's strand certification to FNAL were about 12% higher than the 10^{-12} ohm measurements. IGC then informed us that their certification to Fermilab was at an effective resistivity of 1.3×10^{-11} ohm, which explains the difference. They subsequently suggested that we change the minimum current specification accordingly if we wanted to use our 10^{-12} ohm critical current definition. The reason for their request becomes clear if we normalize their billet data to our 1×10^{-12} ohm definition by multiplying by a factor of

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0.892 as determined from Table I. The conversion factor for MCA is 0.875 as determined from the data in Table II. The average conversion factors are used for all billets. For both manufacturers the actual conversion factor on a billet varies from the average with a $\sim 3\%$ RMS spread.

TABLE II
Test Results with MCA Strand

Place of Test	BNL Spec BNL	FNAL Cert. MCA	BNL Spec
Sample No.	$1 \times 10^{-12} \Omega \text{cm}$	Amps	FNAL Cert
S179-1-M	248	301	0.824
S180-2-1-M	235	269	0.874
S187-1-10-M	255	287	0.904
S192-2-M	252	282	0.894
S189-2-5-M	240	278	0.863
S175-2-17-M	245	274	0.894
S177-1-9-M	241	272	0.886
S176-2-4A-M	242	276	0.877
S190-1-5A-M	244	267	0.914
S174-1-4B-M	226	265	0.853
S190-2-12-M	243	283	0.859
S188-1-11-M	240	276	0.870
S173-1-1-M	225	261	0.862
		Avg RMS	0.875 0.024

The manufacturer's billet data converted to the BNL current definition are shown in Figure 2. The data for both manufacturers are now nearly indistinguishable. They can be characterized by a mean current of 244 amperes, with a standard deviation of 16 amperes (or 6.5%) about the mean. While it is pleasing to see such consistency among the manufacturers, the distressing part is that 40% of the conductor would fail the 240 ampere minimum current according to our definition. Our desire was to specify Fermilab's actual material, so ISA Spec. 89 was revised (Rev. A, March 3, 1982) to require 220 amperes minimum current and a length weighted average current over four billets of at least 240 amperes. This was meant to reflect the data of Figure 2. For both manufacturers, about 5% of the billets in Figure 2 fall below 220 amperes and would be rejected.

Figure 2

A more common method of displaying manufacturer's yield curves is to use probability paper. The critical currents corresponding to the percentiles of the integrated distribution are plotted. The trick of probability paper is that the probability scale is linear in standard deviations (for a Gaussian) so that a pure Gaussian distribution will be a straight line. As shown in Figure 3, the IGC distribution is Gaussian from the 5 to 98 percentile while the MCA has a tail at low currents and is truncated at higher currents.

Figure 3

Another question to ask with this data is whether there was improvement or consistency over the production. The manufacturer's billet data in BNL units are plotted in Figures 4 and 5 against billet number. The IGC data (Fig. 4) shows all the unacceptable billets at the beginning of production and then reasonable consistency over 300 billet numbers. Unfortunately, the MCA data (Fig. 5) show poorer billets in the latter part of their production. We shall soon be in a position to evaluate this information with our own strand. However, it has been enlightening to be able to analyze, as a warm-up, data from Fermilab on superconductor corresponding to 425 full length CBA dipoles.

Figure 4

As a closing remark to this section, we can hazard a very educated guess on the discrepancy in short sample currents between Fermilab and BNL. Brookhaven National Laboratory defines the critical current at an effective resistivity of $1.0 \times 10^{-12} \Omega \text{cm}$ over the full strand diameter with the full gauge length of 50 cm subjected to a perpendicular component of magnetic field within 1/2% of the 5.0 Tesla specified value. In the Fermilab sample holder used for both strand and cable, the sample is held in a 3"

Figure 5

diameter semi-circle in the plane of the magnetic field of the solenoid. Thus only 6 to 9% of the sample is subjected to a perpendicular component of magnetic field within 1/2% to 1% of the specified value. If the effective resistivity is calculated using the full semi-circular length of conductor between the voltage taps, an error of a factor of 11 to 16 in effective resistivity results. This is consistent with IGC's statement that the effective resistivity in the FNAL sample holder is 1.3×10^{-11} Ω cm rather than 10^{-12} .

Comparison of BNL Cable Short Sample Measurements With Billet Data and Cable Maps Supplied by Outside Vendors

For each cable supplied by NEEWC,* a map of the strands is provided. Koldwelds are made when spools of strand are changed. These maps have been entered into the data base. In addition, the billet critical currents provided by the strand manufacturers have also been entered. A program has been written to sum the manufacturer's billet currents (corrected to BNL units) for the 23 individual superconductor strands for each segment of cable between Koldwelds. In this way a map of the critical current variation over the entire cable can be obtained. This is shown in Figure 6 for a typical cable, C0021IN, in which the computed critical current varies from 6017 amps at the start of

the cable to 6154 amps at the end. From the production point of view, the worst cable we have received is C0020IN (Fig. 7) whose computed critical current varies from 5467 amps at the start to 6017 amps at the end. Of course from the R&D point, this is the most interesting cable.

Figure 7

The 10' short sample of cable whose critical current is measured is always taken from the start of the reel. The start of a finished insulated reel of cable is the same as the start indicated on Figures 6 & 7 because the cable is wound on a reel after cabling and then rewound in the course of insulating. The measured short sample current, I_c , has been compared to the computed value, I_{ss1} , from the front end of the cable maps. This is tabulated in Table III. Note that the critical current at an effective resistivity of 2×10^{-12} Ω cm, I_{c2} , is used in this cable since well insulated cables are stable up to this value.²

TABLE III
Measured Critical Currents (2×10^{-12} Ω cm) in Cables Compared to Computation From Summing The Critical Currents of the 23 Strands

Cable	Measured I_{c2} Amps	Computed I_{ss1} Start	I_{c2}/I_{ss1}	I_{ss2} End	Min/Max
4M	4935	5362	0.920		
5M	4930	5532	0.891		
6M	4770	5532	0.862		
9I	5270	6107	0.863	5940	0.972
10I	5235	6023	0.869	6107	0.973
11I	5190	5957	0.871	6022	0.984
12I	5255	6022	0.873	5939	0.983
13I	5250	5928	0.886	5875	0.991
14I	5260	5880	0.895	5843	0.991
15I					
16I	5155	5806	0.888	5775	0.995
17I	4825	5775	0.835	5543	0.960
18I	4740	5543	0.855	5364	0.967
19I	4705	5364	0.877	5467	0.981
20I	4705	5467	0.861	6017	0.908
21I	5060	6017	0.840	6154	0.977
22I	5051	6154	0.821	5785	0.940
23I	4945	5785	0.855	5473	0.945
24I	4945	5473	0.903	5710	0.958

Avg. 5039 0.866 0.968
RMS 214 0.023 0.023
RMS in % 4.3% 2.6%

Figure 6

* New England Electric Wire Corp., Lisbon, N.H.

Concentrating on cables C0009IN through C0024IN (9I thru 24I in the table), the mean I_{c2} short sample current is 5039 amps and the variation about the mean is 4.3% RMS. The ratio of the measured short sample (I_{c2}) to the computed short sample current averages 0.866 with a variation of 2.6% RMS. The reduction in variance indicates a correlation between the computed and measured short sample critical currents, although only at a 94% confidence level. The problem is made more difficult by the high quality of the cables. The ratio of the minimum to maximum critical currents of each cable is also tabulated (Table III). The average variation over a cable is only 3%. The largest predicted short sample variation is from the start of cable 20 to the end of cable 20 (which is identical to the start of cable 21). The measured data nicely track this. Also, a plot of I_{c2}/I_{csl} on probability paper (Fig. 8) shows an impressively good Gaussian distribution in agreement with the fitted parameters.

Figure 8

With the data illustrated above, it would appear that we now have the possibility to predict the short sample critical current of each foot of each cable to a precision of 2.6% RMS. Two questions arise: Is it worth it? and can we do it any better? For the R&D phase it is probably worth it because the magnets are stable in quench current to a reproducibility more like 0.1% RMS. For the production phase, we would expect that the cables could be made considerably more reproducible than at present. The manufacturer's billet data in Figure 2 indicate a mean current of 244 amperes and a 6.5% RMS spread. If we had enough billets to make cable with 23 random samples from this distribution, we would expect an average cable I_{c2} of 4860 amperes, with a spread about the average of 1.4% RMS. Of course if we carefully matched strands, we could reduce the spread still further. The present cables have a larger spread because they are made with strand from only 2 to 5 billets, and in some cases contain strand from only a single billet.

There is also plenty of room for improvement of the calculated short sample current. The present example used manufacturer's data on critical current for two representative strand short samples for each billet. As shown in Tables I and II, the correlation of our own measurements of $1 \times 10^{-12} \Omega \text{cm}$ critical current to the manufacturer's FNAL definition strand current was only good to 2.7% RMS, the same precision as our correlation to the cables! In this light, the correlation to the predicted cable short sample is really impressive and we would expect to do much bet-

ter when we use our own directly measured values for the strand critical current.

The other aspect is how well the two selected strands represent the critical current of the 210,000 feet of strand in a billet. This problem will be addressed in a future study.

Relationship Between Cable Short Sample Current and Magnet Performance — Is There Any?

In order to relate the cable short sample measurement at 5.0 Tesla and 4.2? K to the magnet performance, one needs to know the variation of critical current with magnetic field and temperature, and the magnet transfer function. The CBA dipole transfer function decreases at high fields due to iron saturation. The parameterization

$$\tau = \frac{B(I)}{I} = 1.3732 (1 - 0.065 [I - 4.000])$$

is adequate for $2.5 < I < 4.0$ kA. (The units are Tesla and kiloamperes.)

The critical current variation with temperature and magnetic field is not adequately mapped for the 6 Tesla 3.0 Kelvin regime we are working in. The best data comes from the old, braided, conductor (Fig. 9). Note that any constant transfer function gives a load line short sample current behavior versus temperature which is remarkably linear and extrapolates to zero between 9.5 to 9.6 K. This is shown on Figure 9 for $\tau = 1.50, 1.40$, and 1.25 . Note that this does not depend on the assumption $BI = K(T)$, or any other assumption since it is obtained directly from the measured data. Thus if a magnet is at short sample at one temperature, its behavior at another is predicted by a straight line passing through 9.6 K for a constant τ . However, since our τ varies, the extrapolation is done using the local τ . Also the conductor behavior for fields above 5 Tesla and temperatures below 4.2 K is not available. Hence the data of Fig. 9 must be re-measured for a typical 4900-5000 amp cable at fields from 0 to 6 T and temperatures from 10 K to as low as possible.

Figure 9

For all the cables measured there is typically a 1 to 2% loss in $B \times I$ at 5.5 T compared to $B \times I$ at 5.0 T. Thus the magnet short sample is computed as follows using I_c at $2 \times 10^{-12} \Omega \text{cm}$ 5.0 T and a peak enhancement of 1.02.

$$I_{LL} = \sqrt{\frac{0.98 \times 5.0 \times I_{c2}}{\tau(I_{LL}) \times 1.02}}$$

The weaker cable of the inner coil is used for the computations. For LM6 this is 141, 5.260 kA and for LM5, 181, 4.740 kA. The equation is solved by iteration starting with $\tau(4 \text{ kA})$.

Figure 10

The results are plotted in Figure 10, compared to the magnet performance. Some slight training occurs, so the initial and plateau quench currents of the magnet are both plotted, connected by a vertical line. The points near 4.5 K are all at the same temperature; but are drawn separated for the sake of clarity. At 4.5 K, the prediction for LM5 is 1.8% too low but for LM6 it is right on. It is rewarding that the magnet with higher current cable performs better. However the 1.8% discrepancy for LM5 is larger than we would have liked. More data would help sort this out. It is also interesting to note that at 3.8 K, LM5 performance agrees with the extrapolation from 4.5 K but LM6 falls below it, even after considerable training.

Conclusion

The cable conductor electrical properties are now understood to a precision of roughly 2% RMS. If we obtain vendor performance equal to the FNAL history once our own strand pipeline is filled, then it would be possible to obtain cable with an average I_c (at $2 \times 10^{-12} \Omega \text{cm}$ resistivity, 5.0 Tesla and 4.22 K) of 4860 amperes, and a 1.4% RMS spread about the average. Furthermore, magnet current limitation due to superconductor critical current should be predictable at the 1/2% level.

References

1. R.B. Palmer et al, "The Two Layer ISABELLE Cable Magnet", ISA Technical Note 320, September 1981.
2. M. Garber, W.B. Sampson, M.J. Tannenbaum, "Critical Current Measurements on Superconductor Cables", these Proceedings.