SSC-N-473
9/84

I_c (H, T) MEASUREMENTS FOR MULTI-KILOAMPERE SUPERCONDUCTING MAGNET CONDUCTOR

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Abstract

Measurements of the transition current as a function of both applied magnetic field and temperature are presented as an equivalent resistivity for various production and prototype magnet conductors. The current range is from a few amperes to 14.0 kiloamperes from '0' T to 10.0 T applied field. The range in temperature was 1.7K to 4.6K. The statistical average of the over 900 Tevatron magnet cable samples was 5,107 amperes for an effective resistivity of 2 x 10^{-12} Ω-cm at 5T and 4.2K. Data are presented for the new 10kA, 10T "Rutherford Style Cable" and for the temperature range of 1.7 to 4.3K for NbTi and NbTiTa, and the 5.0T, 7kA, 4.4K conductor for the "SSC" models[1], "Superconducting Super Collider"[2].

Introduction

These data represent probably the largest number of high current (5kA) at 5.0T critical current measurements made. The majority of the critical current tests were done on hairpin samples, but those results were carefully calibrated against long sample tests, both at Fermilab and other Labs. Therefore, the sensitivity of the hairpin test was quite good for the bulk of the 'Tevatron' samples, but had to be recalibrated for each new cable geometry or multikiloampere conductor used in newer magnet prototypes. The facility at Fermilab that measures these cables has a maximum current capability of 21 kiloamperes with a maximum magnetic field of 10.5 Tesla and operates down to a temperature as low as 1.6K. The basis for this system was the short sample test facility for the 'Tevatron' cable conductor. During the last few years, however, the emphasis gradually changed over to magnet conductors which would be suitable for the new proposed 'Superconducting Super Collider' prototype magnets. Fermilab has also been involved with "KEK" in a development program for a 10T dipole, based on a ternary 10kA cable wound into a magnet winding operating in a superfluid environment. Due to the variety of uses and needs of the magnet protype program (see paper this Conference), the facility's range of operating parameters has gradually increased to the present values.

Experimental Test Procedures

There are two solenoids with the 7.6cm aperture which are available to produce the magnetic fields used in the measurements, one producing a maximum of 7.0T, and the other 10.5T. There are also 1 meter dipoles available for tests up to 14kA and 5.0T at temperatures between 3.2 to 4.6K. The long sample measurements in this paper, as well as the resistivity correlation "long to hairpin" samples were done on small coils where the sample was soldered onto a stainless bobbin with copper input rings.[3] Brookhaven National Laboratory also furnished cable measurements obtained in their 5T dipole, using bifilar sample coil measurements[4]. These were used as another independent source of calibration for the system. The accuracy of the hairpin samples for the half Cu-O and silver tin coated strand cables was ±1.5 x 10^{-13} Ω-cm and ±2.5 x 10^{-13} Ω-cm for the all Stabrite (Sn-Ag) strand cables at 5kA, 5.T, and 4.2K.

There are 3.2 to 4.2K sample test set-ups for both the 7 and 10.5 Tesla solenoids. In addition, there is an ambient pressure superfluid sample holder and heat exchanger for the 10.5T solenoid which is presently capable of currents up to 14kA. There is also a high field calorimeter which has a range from 1K to room temperature for the T_c determinations at field up to 10.5T.

The long sample measurements have attained sensitivities of 2 or 3 x 10^{-13} Ω-cm repeatedly. The samples are measured with a four terminal network with the voltage taps far enough away from the current joint so as not to be included in the current transfer length.

Results

The statistical average of the 900 plus 'Tevatron' cables measured was 5107.1 ±24 amps for an effective resistivity of 2 x 10^{-12} Ω-cm at 4.25K and 5.0T perpendicular magnetic field to the wide surface of the sample. The data is broken down into yearly intervals and the older cables (those produced in an earlier year and being retested) are taken out of the sample. The results are shown in Table 1.

Table 1

'Tevatron Cable Chronological Performance'
5.0T, 4.2K, ρeff = 2 x 10^{-12} Ω-cm

1981	466 samples	5122 ± 44 amperes
1982	275 samples	5002 ± 49 amperes
1983	104 samples	5134 ± 18 amperes
1984	45 samples	5822 ± 36 amperes
	Different Cut	
80 - 82	735 samples	5077 ± 29 amperes
83 - 84	157 samples	5248 ± 19 amperes

'Low β Quad Cable Chronological Performance'

83 - 84	20 samples	6780 Amps

Standard Tevatron Cable

strand	1.8 copper volume/1 NbTi vol. (strand diameter 0.0268") NbTi 2050 filament each 9 microns in diameter
cable	11 Stabrite coated strands 12 Cu-O coated strands

Low "β" Quad Cable

strand	1.3 copper volume/1 NbTi vol. (strand diameter 0.0268") NbTi 500 filament each 20 microns in diameter
	Cable - 23 strands of Stabrite

*Operated by Universities Research Assn. Inc., under contract with the U.S. Department of Energy.
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Manuscript received September 10, 1984.

In Table 3, in the right hand column, there are typical 'N' values given for about a quarter of the samples measured and evaluated at the ρeff = 2 x 10^{-14} Ω-cm point and the second column of N's include only those with less than 2 standard deviations from the average.

Table 2
'Tevatron Cable Chronological Performance'
N = log ρeff/log I

	N	N
Late 1980	15.3	
Early 1981	20.5	20.5
Late 1981	18.1	17.1
Early 1982	16.2	15.3
Late 1982	14.2	11.7
Avg. 1983	16.6	15.1
Avg. 1984	25.1	20.3

An experiment was performed to determine the degrading factor of the strand critical current after it had been fabricated into a multi-kiloampere cable.

The cable was first made rectangular and then keystoned to the normal value used in the 7.6cm aperture dipole magnets.[3] Length of the keystoned cable was used to make a magnet (model), a test length was cut to short sample, and a test length of the rectangular cable was cut with enough excess length of each strand before the compacting and cabling steps that they could be tested individually. Then the rectangular cable, the keystoned cable, and the individual strands were tested.

The relationship between the strand short sample and that of a finished cable is shown in Figure 1. "A" stands for the summation of the strand currents and the arrows show the correction applied for the self field of the cable. "W" stands for the worst strand x23 in the cable. There was no measurable difference between the keystoned cable and the rectangular one. There is about a 13% loss in current carrying capacity in a 5.0T field at 4.2K for a 6000 ampere cable over the strand summation current. Figure 2 shows this same data in the form of J_c (H) 4.2K versus magnetic field.

In Figure 3, the critical current density is plotted as a function of applied magnetic field for the last 100 Tevatron cables in 1983 with a point showing that of the new 1984 high current density cables. The 1982 Tevatron cable is shown in the same plot. The fourth magnet conductor shown in Figure 3 is the 4.2K cable data for the 10kA, 10T superfluid (1.8K) magnet conductor.

The current to compare the 10T conductor to the standard Tevatron cable, is the 10kA, 10T cable conductor carried 13,100 amperes at 5.0T, 4.25K at a ρeff = 2 x 10^{-14} Ω-cm.

The high field cable prototype differed from the final version in that it was made with filaments which were about twice the diameter of those in the proposed conductor. Table 3 gives a brief description of the cables strand. Table 4 gives the critical currents for various cables measured for the prototype program.

In Figure 4, the data for the ternary cable is plotted as critical current density as a function of applied field for the ternary alloy. The remainder of the NbTiTa billet (≈ 1/2) will be made into a cable similar to cable 5 in Table 3.

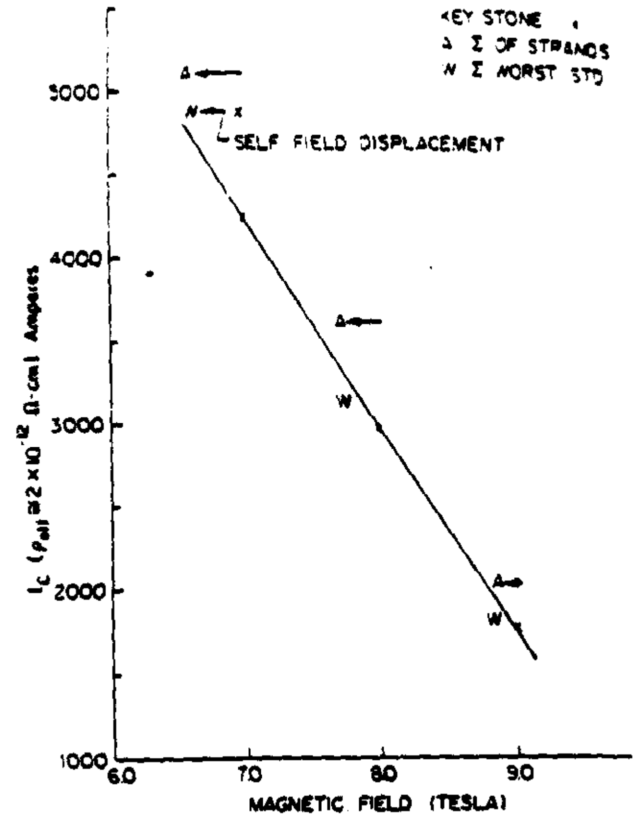

Figure 1

The critical current is plotted as a function of the applied field for the 23 strand cable. Points are plotted for the summation of the currents in each of the strands corrected for self-field (Arrow length). The worst strand current times 23 is also plotted similarly.

TABLE 3

Cable and Strand Description

Strand Types:

Type Symbol	Strand Cu/Sc Vol	Filament Size Dia microns	# Strand	Strand Dia mm	Twists cm	Alloy	Use
A	1.8/1	9.0	7000	.681	1.2	NbTi	Std. 'Tevatron' cable
B	1.3/1	20.0	500	.681	1.2	NbTi	'Low β Quad' cable
C	1.3/1	13.0	1700	.681	1.5	NbTiTa	'Model Magnet' series
D	1.6/1	20.0	500	.830	0.8	NbTi	'10T, 1.8K' model magnet
E	1/1	10.3	2300	[illegible]	1.1	NbTi	'10T SSC' model magnet

'Rutherford Style' Cables

Cable Symbol	Strand Type	Number of Strand	Physical Dimension in 'mm'	Nomenclature
1.	A	23	1.069 x 7.871 x 1.372	Std. 'Tevatron'
2.	B	23	1.087 x 7.871 x 1.372	'Low β Quad'
3.	C	23	1.087 x 7.871 x 1.372	'Ternary'
4.	A	19	1.27 x 6.223	'Super ferric'
5.	D	27	1.372 x 11.[illegible] x 1.676	'10kA, 10T'
6.	E	30	1.778 x 12.[illegible]	'[illegible] 10T'

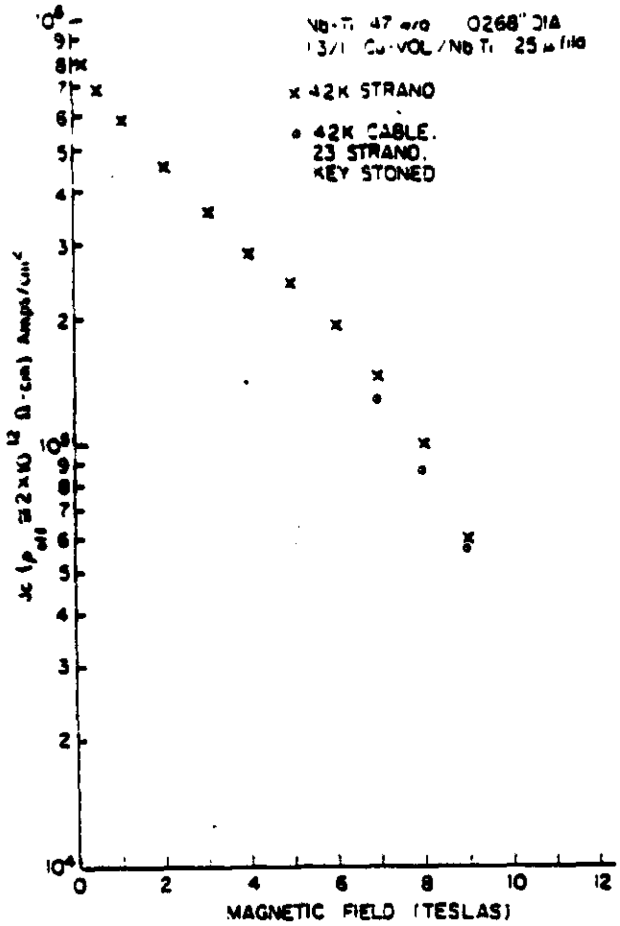

Figure 2

The current density of the average NbTi filament of the average strand in a cable is plotted as a function of field. The finished keystoned cable is plotted as well (same type cable as that in Figure 1).

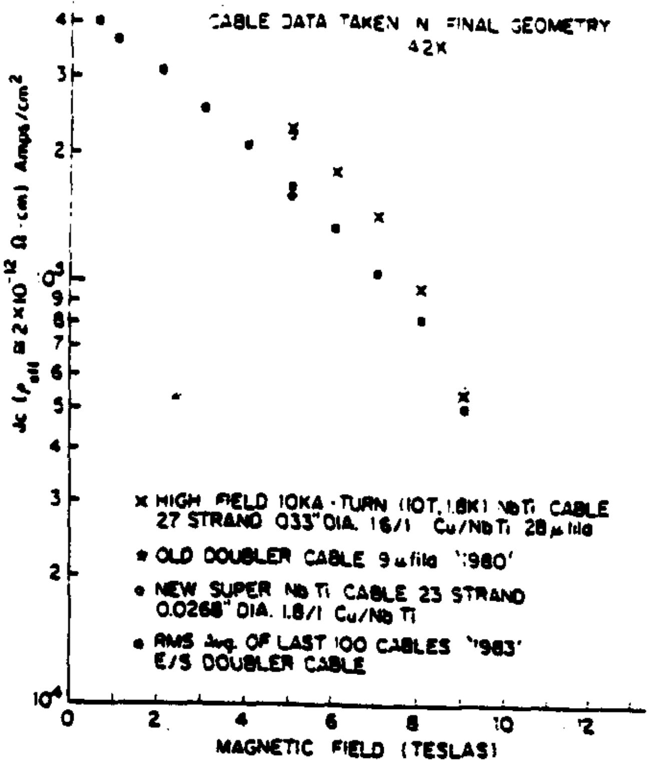

Figure 3

The average NbTi filament current density for various cables are plotted as a function of applied field.

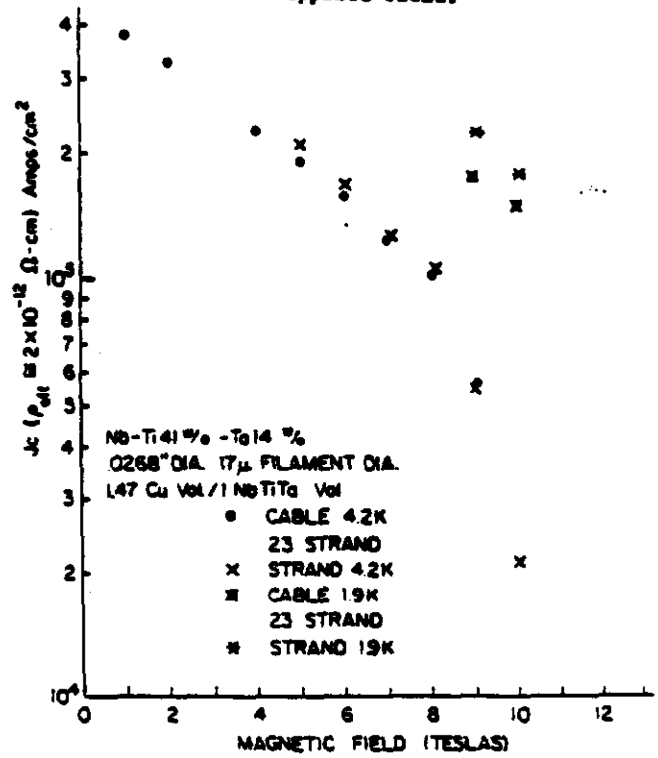

Figure 4

The average current density of a NbTiTa filament is plotted as a function of perpendicular magnetic field for a strand and a Tevatron size NbTiTa 23 strand cable for two different temperatures of 4.2K and 1.9K.

TABLE 4

Critical Current (ρ_{eff} = 2 x 10^{-14} Ω-cm)

Temp = 4.2K — I_c (ρ_{eff} = 2 x 10^{-13} Ω-cm)

Applied B (T)	Cable # 1	Cable # 2	Cable # 3	Cable # 4	Cable # 5	Cable # 6	Strand A	Strand B
0.22							630	1226
0.55	11,000			9875			735	1377
1.0	10,000		12,700	9000			650	917
2.0	9,381		10,000	7700			405	714
3.0	7,620			5900			382	556
4.0	6,270		7,500	5000			306	446
5.0	5,061		6,375	4075	13,200		257	386
6.0	4,020		5,220	3325	10,475		212	310
7.0	3,130	4,320	4,200	2600	8,290	8,700	155	230
8.0	2,460	2,960	2,125	2025	5,300	6,050		162
9.0	1,500	1,710	1,750	1240	3,046	4,000		97
10.0	720				1,050	1,340		

Temp = 1.9K

Applied B (T)	Cable # 1	Cable # 2	Cable # 3	Cable # 4	Cable # 5	Cable # 6	Strand C
7.0							
8.0		3,150		6,900			
9.0		4,600		5,000	14440		301
10.0		3,200		3,040.	10,200		245

TABLE 4

Critical Current [illegible]

Temp = 4.2K	I_c [illegible]							
Applied H (T)	Cable # 1	Cable # 2	Cable # 3	Cable # 4	Cable # 5	Cable # 6	Strand A	Strand B
1.22							830	1230
1.35	11,880			3075			730	1073
1.5	10,000		12,700	3000			650	917
2.5	9,885		10,000	2700			486	710
3.0	7,838			1990			382	560
4.0	6,270		7,500	1000			300	440
5.0	5,341		6,375	4075	13,300		287	380
6.0	4,325		5,220	3325	12,475		215	310
7.0	3,130	4,220	4,200	2660	8,290	8,700	155	230
8.0	2,450	2,850	3,325	2025	5,500	5,600		162
9.0	1,400	1,710	1,750	1240	3,005	4,000		97
10.0	725				1,050	1,340		

Temp = 1.8K							Strand C
7.0							
8.0		5,550		6,900			
9.0		4,600		5,800	10400		301
10.0		3,250		5,340	10,200		246

Discussion

A lot of progress has been made in the last few years in the understanding of how to obtain high current densities (i.e., ~ 2000A/mm² 5T, 4.2K in NbTi alloys) and this is reflected in the present high performance cables[6]. For example, 1984 Tevatron cables with 6250 Amp critical currents versus 5200 Amps at the start of construction, in 1980, for 5T, 4.2K. The critical current densities of the ternaries at reduced temperature up to fields of 10T make it possible to design an efficient 10T dipole at the present time.

References

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