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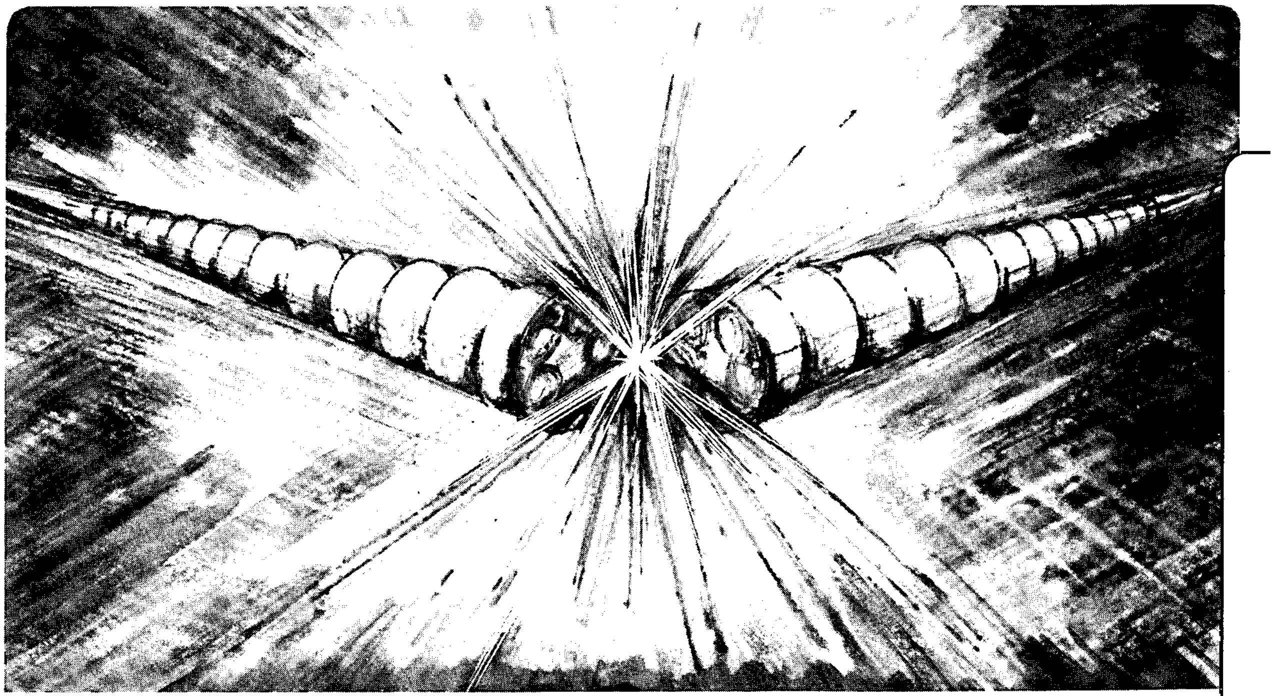

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Recent Improvements in Superconducting Cable for Accelerator Dipole Magnets*

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Abstract

The superconducting magnets required for the SSC have provided a focus and a substantial challenge for the development of superconducting wire and cable. The number of strands in the cables have been increased from 23 for the Tevatron to 30 for the SSC inner layer cable and 36 for the SSC outer cable. Critical current degradation associated with cabling has been reduced from 15% for the Tevatron to less than 5%. R&D which has led to these improvements will be described and the opportunities for further advances will be discussed.

I. INTRODUCTION

For the past decade, a symbiotic relationship has existed between the need for high performance in accelerator magnets and the development of high current density conductors. The requirements for high performance and cost effectiveness in large accelerator projects such as the Tevatron and the SSC have provided the incentive to develop wide cables with improved current density. The existence of these conductors in turn has enabled magnet designers to design dipoles with higher operating fields and quadrupoles with higher gradients. The advances in J_c and cable width associated with recent accelerator projects are shown in Table I. A number of these cables were developed at LBL using a 36-strand cabling machine developed in 1984. These include the 23-strand Inner and 30-strand Outer Layer cables for the SSC 40-mm bore dipole [1], the 30-strand Inner and 36-strand Outer Layer cables for the SSC 50-mm bore dipole [2], and the 36-strand cable for the FNAL Low Beta Quadrupole [3]. Development work included the establishment of cabling parameters, the reduction in critical current degradation associated with cabling, and the transfer of this technology to industry [4].

In order to continue this development and to identify the practical limits for Rutherford-type cables, we have designed, built, and tested a new cabling machine with the capacity for 48-strands of 1.3 mm diameter and lengths greater than 1500 m. Initial results for wide cables made on this machine will be presented, and some of the factors limiting cable size will be discussed.

II. 48-STRAND CABLING FACILITY DESCRIPTION

The new cabling machine incorporates many features which were found to be essential for producing cables with low critical current (I_c) degradation and good dimensional control with the 36-strand cabler [5]. These features include the following: (1) magnetic hysteresis brakes capable of maintaining strand tension to ± 200 gm; (2) variable planetary motion to remove residual twist from the cable; (3) mandrel designed to support the strands all the way to the Turkshead rolls; (4) temperature control for the Turkshead; (5) on-line measurements of the cable dimensions.

For the upgrade the basic support structure and drive mechanism was maintained and the 36-spool wheel was replaced with one having 48-spools (Fig. 1). Careful layout using a CAD system allowed the placement of these 48 spools and associated components on a wheel with the same outer diameter as the 36-spool wheel. Consequently, the new machine has the same wire capacity and same maximum speed as the earlier 36-strand cabler.

Since the LBL cabler is currently being used to fabricate the 36-strand Outer Layer cable for 50 mm bore SSC dipoles, the changeover to the new wheel had to be done with a minimum of disruption. This changeover was

Table I. Evolution of Dipole Cable Designs

Project or Magnet I.D.	Cable Dimensions (mm) (Minor/Major edge x width)	Number of Strands	Minimum Strand J_c (A/mm^2 at 4.2K, 5.0T)
Tevatron	1.12/1.40 x 7.8	23	1800
HERA	1.28/1.67 x 10.0	24	2600
SSC Dipole (40mm Bore)	Inner 1.33/1.59 x 9.30	23	2750
	Outer 1.06/1.26 x 9.73	30	2750
SSC Dipole (50mm Bore)	Inner 1.33/1.59 x 12.3	30	2900
	Outer 1.05/1.26 x 11.7	36	2900
LHC	Inner 2.06/2.50 x 17.0	26	-
	Outer 1.3/1.67 x 17.0	40	-
LBL Model D-20 (Proposed)	Inner 1.26/1.6 x 14.4	36	-
	Outer 1.08/1.4 x 16.5	48	-

completed in one week, and production of the 36-strand SSC cable was resumed without any change in cable quality.

Initial R&D with the new machine has focussed on cables with increased numbers of strands made from strands ranging in diameter from 0.65 mm to 1.3 mm. The primary emphasis has been to identify limiting factors and to devise ways to overcome these limits. Using 0.65 mm diameter strand, moderate lengths of a 45-strand, 14.6 mm wide, cable have been produced. The cable degradation was measured as zero % (see following section for more discussion on cable degradation). From this study two limiting factors emerged. First, the mandrel shape and position was found to be more critical than was the case for narrow cables. Second, the tendency for cable collapse increases substantially as the width to thickness ratio increases. These results have led to the installation of two additional improvements to the cabling machine. The first is a cable tension monitoring system which utilizes strain gages mounted on the Turkshead support frame. Second, a powered Turkshead is being introduced in order to reduce the tensile load on the cable in the place where cable collapse occurs, i.e. between the Turkshead and the caterpillar. These new features will be utilized to extend the capabilities to finer strands and to more strands.

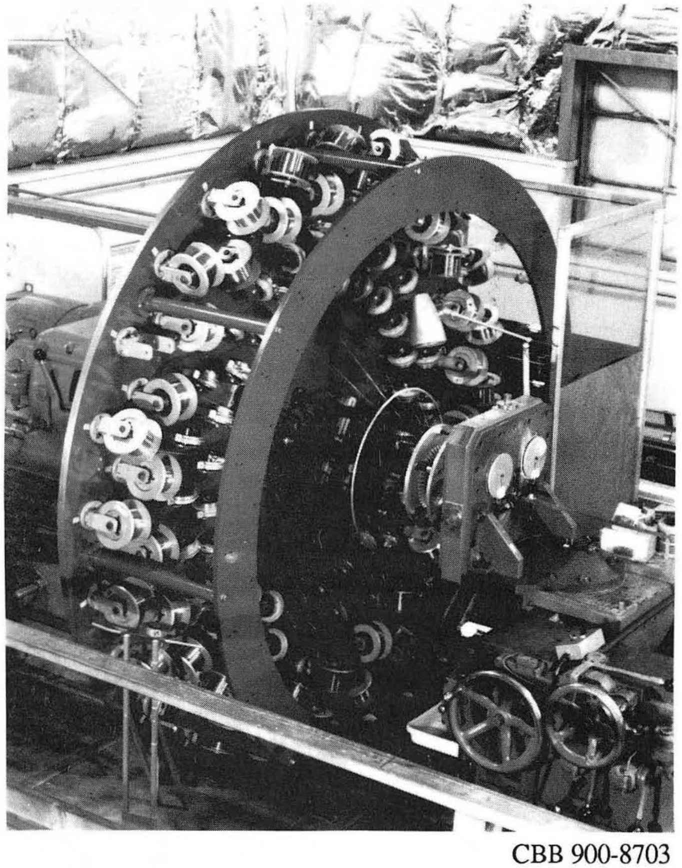

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Figure 1. Overview of 48-strand cabling facility.

Another series of tests were performed with the large diameter strands which have been chosen for the LHC cable [6]. Initial results indicate that the 28-strand Inner Layer cable can be made as a conventional Rutherford cable, but the cable is extremely stiff and may present substantial difficulties in bending around the ends of a small bore dipole. One option which would greatly improve the flexibility of this cable is the use of a two-level cable design [7]. The 1.3 mm diameter monolith can be replaced with a compacted, solder filled 7-strand subcable. This approach also has the advantages of (1) fewer filaments in the strands provide for easier billet assembly, and (2) larger cold work range afforded by the smaller strand diameter will enhance the critical current density. In our future work on wide, thick cables we will further explore this option.

The main problem encountered with the LHC-type Outer Layer cable was the excessive narrow edge compaction necessary to achieve the specified cable dimensions. Further experiments are underway to explore this problem and to identify the cause.

III. CABLE DEGRADATION STUDIES

Equally important as the ability to make cables with precise dimensions is the ability to control I_c degradation and a discussion of some reasons for these improvements have been presented [5]. We now will present some additional results which are based on the development of the 30-strand Inner Layer and 36-strand Outer Layer SSC dipole cables. The initial parameters for these cables were obtained by scaling from the parameters for the 23-strand Inner Layer and 30-strand Outer Layer cables which had been developed earlier [5]. In particular, the narrow edge compaction factor $PF_1 = \eta d/2w_1$, where d= strand diameter and w_1 = narrow edge width, was maintained constant at a value of 0.95. PF_1 (packing factor), has been a useful guide in selecting cable dimensions. However, the situation at the cable edge is too complicated to be described by only one parameter. Additional factors inlcude the cable pitch, which affects the cable compaction, and also the relative amount of compaction performed by the side rolls compared with the wide face rolls. Detailed studies of cable degradation have shown that the damage is localized at the edges of the cable and actually occurs at both the narrow and the wide edge of the cable [8]. Since the PF_1 value for the wide edge is significantly larger than that for the narrow edge of a typical keystoned cable, we concluded that deformation at the cable edges due to the side rollers must be more deleterious than that of the wide rollers. Consequently, the width to thickness ratios for the new SSC dipole cables were adjusted slightly before the dimensions were frozen. As can be seen in Table II, the average degradation for the SSC Outer cables has decreased from 5% to less than 3%, and from 3% to zero for the Inner cables.

Table II. Critical Current Degradation Values for 50mm Dipole Cables Compared with 40mm Dipole Cables.

Cable	Degradation (%)
23-strand inner	3.0
30-strand inner**	-3.6
30-strand outer	5.3
36-strand outer	1.1

**Negative degradation is partly due to the use of strand I_c data which is not corrected for self-field effects, whereas the cable data are adjusted for self-field.

All degradation values reported here are those measured by BNL in a self-consistent manner, i.e., adjustments are made for cable self-field effects but not for wire self-field effects. This procedure will underestimate slightly the true cable degradation [9]; however, as stated, the results are self-consistent and can be used for the intercomparisons made here. The degradation values reported in Table II were obtained over several years, and the strands were made by several manufacturers as well as being produced from different billets. In order to eliminate the wire source as a variable, two Outer Layer cables were produced from an identical lot of wire. The degradation measured for the 30-strand Outer Layer cable was 4.3%, compared with a value of only 0.1% for the 36-strand Outer Layer cable.

The reasons for this increased sensitivity to side roll deformation are not yet clear. One possibility is an increased filament area reduction or increased filament sausaging in this region of the cable. We have used quantitative image analysis to examine the filament size and filament size distributions in strands at the edges of cables in comparison with relatively undeformed strands near the middle of the cable (Fig. 2). However, the results at present do not show a large effect or a clear trend, either for filament areas or for spread in filament areas.

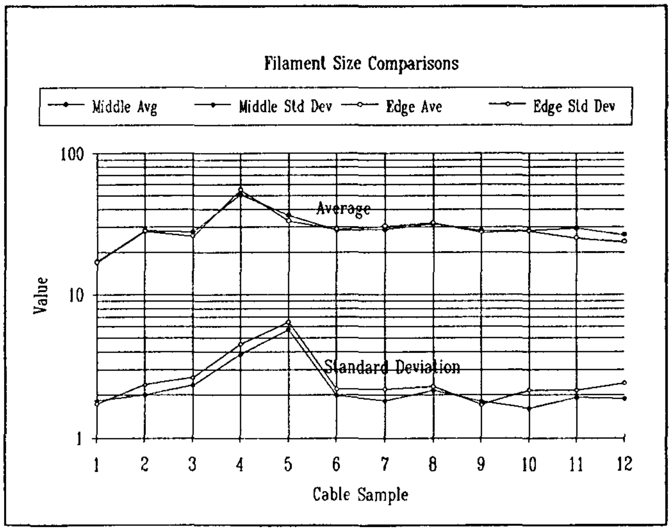

Figure 2. Image analysis results on filament sizes (top) and distribution of filament sizes (bottom) for strands from the middle and from the narrow edge of cable samples.

Another possible cause for this apparent degradation may be the development of J_C anistropy. The effects of rolling on the development of J_C anistropy were shown earlier [10], and were found to be quite large for present generation material [11]. Unfortunately, this effect is quite difficult to insolate in a cable I_C measurement.

IV. SUMMARY AND CONCLUSIONS

1. A 48-strand cabling machine has been developed in order to provide flexibility in cable designs for future accelerator magnets.
2. The successful fabrication of wider cables with large numbers of strands is possible, but more precise measurement and control of cable parameters, in particular cable tension, is required.
3. Decreased I_C degradation has been demonstrated for the SSC 50 mm bore cable designs relative to the I_C degradation in the 40 mm bore cables.

V. ACKNOWLEDGMENTS

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