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The Evolution of Tooling, Techniques, and Quality Control for Accelerator Dipole Magnet Cables

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Abstract -- The present generation of particle accelerators are utilizing the flattened, compacted, single layer cable design introduced nearly 20 years ago at Rutherford Laboratory. However, the requirements for current density, filament size, dimensional control, long lengths, and low current degradation are much more stringent for the present accelerators compared with the earlier Tevatron and HERA accelerators. Also, in order to achieve higher field strengths with efficient use of superconductor, the new designs require wider cables with more strands. These requirements have stimulated an active research effort which has led to significant improvements in critical current density and conductor manufacturing. In addition they have stimulated the development of new cabling techniques, improved tooling, and better measurement techniques. The need to produce over 20 million meters of cable has led to the development of high speed cabling machines and on-line quality assurance measurements. These new developments will be discussed, and areas still requiring improvement will be identified.

I. INTRODUCTION

In order to provide for long beam lifetime in storage rings, the magnetic field must be highly uniform and predictable. In addition, the bore of the superconducting magnets must be kept small and the field must be high, in order to keep costs to a minimum. Finally, in order to build magnets which do not train below about 90% of their short sample limit, a controlled, uniform prestress must be applied to the coils; this requires that the coil sizes be precise and reproducible. These requirements have led to a significant increase in the performance required, and a reduction in the allowable tolerances for the current generation of accelerator magnets, i.e. SSC and LHC, compared with those for earlier accelerator magnets, i.e. those for HERA and the Tevatron. For example, the dipole cable mid-thickness tolerance for HERA is ±.02 mm, while the tolerance for SSC is ±.006 mm. Recent experience has shown that these decreases in the tolerances can be achieved through improvements in tooling, cabling techniques, and measuring equipment. The technological advances which have led to these improved properties and tighter tolerances will now be discussed.

II. SELECTION AND OPTIMIZATION OF STRAND PARAMETERS

A. *Critical current density and filament diameter*

The initial parameters for the SSC collider magnets were selected in the Reference Designs Study (RDS) in 1984 (1), Table 1, which identified three optional designs for further evaluation. In order to compare these options on an equal basis, a critical current density of 2400 A/mm^2 at 5 T was chosen as a mimimum specification value. This represented a significant increase over the value of 1800 A/mm^2 which was specified for the NbTi superconductor used in the Tevatron (2). Since this value had not yet been achieved in large scale production, an R&D program was begun to demonstrate that these parameter choices were justified (1). The filament sizes specified in the RDS were 22 microns for the inner layer conductor and 17 microns for the outer layer conductor. These values were chosen after discussions with the conductor manufacturers, who felt that the goal of increased current density could more easily be reached with the larger filament sizes. This choice required the use of bore tube correction coils, and an additional priority of the conductor R&D program was to explore the feasibility of reducing the filament diameters while maintaining the high current density. The other relevant conductor design parameters are listed in Table 1, for one of the reference designs.

Table 1
Parameters of the Conductors for the SSC Reference Design A Coils

	Inner Layer	Outer Layer
Operating current[A]	5400	5400
Maximum field[T]	6.82	5.43
Reference critical current density[b] [A/mm^2]	2400	2400
Copper-to-superconductor ratio	1.3	1.8
Filament diameter [μm]	22	17
Strand diameter [mm]	.81	.65
Dimensional tolerance [mm]	±0.0025	±0.0025
No. of filaments	525	400
Copper residual resistivity ratio (before extrusion)	>220	>220
Strand twist pitch [per cm]	0.8	0.8
Strand coating	Stabrite	Stabrite

[a] High-homogeneity material
[b] At 5T, 4.2 K, and a resistivity of 10^{-14} Ωm

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Between the RDS report in 1984 and the Conceptual Design Report in 1986 (3), an active R&D program was pursued for both magnets and conductors to refine and narrow the parameter choices. The success of the conductor R&D program led to two significant changes in the conductor specifications. The minimum critical current specification was increased from 2400 A/mm^2 at 5 T to 2750 A/mm^2 at 5 T and 1100 A/mm^2 at 8 T, and the filament diameter was reduced to 5 microns (Table 2). The key factors that make these changes possible are: use of high homogeneity NbTi alloy and improvements in the flux pinning as a result of changes in the cold work and heat treating sequences (4), and the use of a diffusion barrier between the filaments and matrix (5),(6). The main forum for discussion and implementation of these improvements was a series of NbTi Workshops which were hosted at approximately 6 month intervals by the Univ. of Wisconsin and by LBL.

Table 2
Parameters of the Conductors for the SSC
Conceptual Design Study

Parameter	Inner Layer	Outer Layer
Cable width	9.30 mm	9.73 mm
Cable thick, narrow edge	1.22 mm	1.06 mm
Cble thick, wide edge	1.59 mm	1.27 mm
Keystone angle	1.6	1.2 deg
Strand diameter	.808 mm	.648 mm
No. of strands	23	30
Filament diamenter	5	5 microns
Filaments/strand	11,000	6,000
Cu/SC area ratio	1.3/1	1.8/1
Short-sample limit	613	243 Amp/ strand
Critical current density	1100 A/mm^2 (8.0 T,4.2 K)	2750 A/mm^2 (5 T, 4.2 K)
Cable length	1,076	1,341 m

These new specifications were achieved by several manufacturers in full production size billets in 1986 (6), Figure 1, but the realisation of reliable, economical production of this conductor did not follow easily. Among the more serious problems encountered were wire breakage leading to short piece lengths, billet assembly problems, and filament sausaging. In fact, these problems appeared so serious that, at one point in 1987-1988, an effort was begun to produce a 9 micron filament size conductor as a back-up (7). These problems are associated with the fine filament and high current density requirements. The 5 micron filament size leads to a requirement of 11000 filaments for the inner conductor and 6000 filaments for the outer conductor. Several different billet fabrication methods were developed to meet this requirement, and the results are described in detail in (6). A three extrusion step process (monofilament, 7-55 element second, followed by a 200-1500 element third extrusion) made billet assembly easier, but led to a loss in critical current density due to sausaging of the elements at the edge of the intermediate stack. An intermediate sub-bundle approach was also explored, but cleanliness problems compromised the results (8). This method has recently been revived, with more promising results (9). The large single stack approach required working with small diameter elements and a large area of exposed surfaces, which made billet assembly and cleaning difficult. Several approaches, including the stacking of round elements (6), were attempted. However, the large single stack of hexagonal elements was eventually adopted after improved rod straightening methods and clean room procedures for billet stacking were developed. The long piece lengths now being reported (9,10) are proof that the large single stack is appropriate for the SSC conductors.

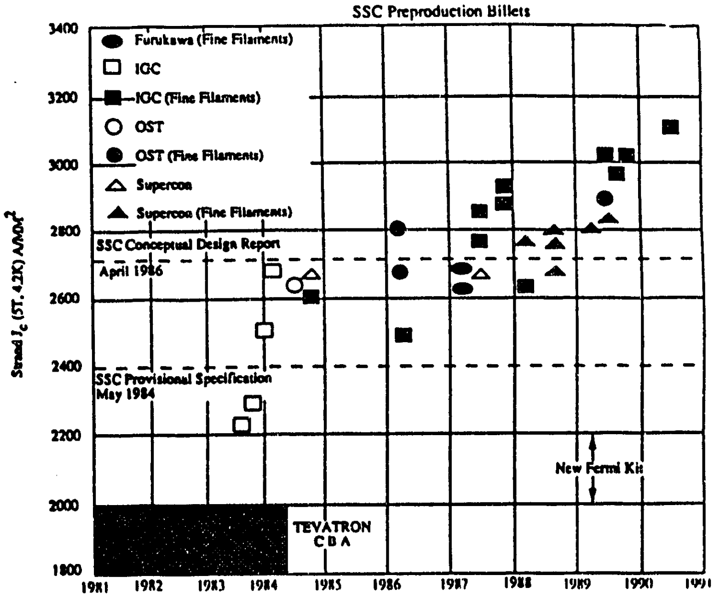

Figure 1. Improvements in J_c during the SSC R&D phase.

An important factor in solving the difficulties in achieving high critical current densities and at the same time producing long, uniform lengths of wire was the understanding that performance may be limited by both intrinsic and extrinsic factors. In order to make progress in optimizing the intrinsic factors, the extrinsic factors must first be understood and controlled. For example, it was impossible to optimize the cold work/heat treatment sequence for improving Jc as long as intermetallic compound formation was occuring at the same time and leading to a deterioration in filament quality. A number of the extrinsic factors which have been identified and are now being controlled are listed in Table 3, together with the intrinsic factors which ultimately limit Jc in SSC conductors.

Buoyed by the successful reduction of the filament size from 20 microns to 5 microns, some effort was made to achieve a further reduction, to 2.5 microns. This effort actually helped identify and correct several problems in the fabrication of 5 micron filament conductors, since the problems were exacerbated at the 2.5 micron size and hence easier to identify. It also uncovered an additional problem--the coupling of closely spaced filaments due to the proximity effect (11). As the spacing was reduced below about 1 micron, significant filament coupling was observed in magnetization measurements made at low magnetic field levels. It appeared that the magnetization would be unacceptable at the proposed SSC injection field level of 0.3 T. The technique developed earlier to reduce filament coupling in a.c. conductors, i.e. the use of a Cu-Ni alloy

Table 3
Factors Limiting J_c in SSC Wire

Extrinsic Factors	Intrinsic Factors
NbTi Homogeneity Intermetallic Formation Filament Spacing Extrusion Temperature	Available Cold-Work Range Precipitate Volume/Distribution Proximity Effect Current Distribution in Multifilamentary Conductors
Composite Bonding Quality of Billet Assembly	NbTi Ductility??
Progress in eliminating these extrinsic factors has led to an increase in J_c from 2000 A/mm^2 to 3000 A/mm^2 at 5 T.	These factors lead to an intrinsic J_c limit for precipitate pinning in NbTI of 3800-4000 A/mm^2 at 5 T.

matrix, was considered but rejected due to the reduction of strand stability and the extra cost. Collings (12) suggested the use of Mn as an alloying element for the Cu matrix, since the Mn would reduce the coupling via the spin-orbit scattering and would be about 15 times as effective as Ni, which reduces coupling by increasing the matrix resistivity (13). Cu 0.5 wt% Mn was substituted for the Cu matrix and a model dipole was made in order to demonstrate conductor manufacturability, reduced coupling, and to see if there was any detrimental effect on stablility. This test was successful (14, 15), thus proving that Cu-Mn alloy matrix can be used for this purpose. However, the SSC machine parameters were changed in 1990, thus allowing a Cu matrix, 6 micron filament combination to meet the requirements, with a combination of lower cost, higher Jc, and better manufacturability. The fine filament, Cu-Mn option was considered for the High Energy Booster (HEB) conductor, since the HEB is pulsed at a higher rate than the main ring. However, it appears that a more cost effective solution is to provide for additional refrigeration capacity to handle the increased heat load, and to use the 6 micron filament size material. Thus, the development of finer filaments for the SSC has been stopped, and efforts are focused on optimizing the manufacture of the 6 micron filament conductors.

B. Copper to Supercondutor Ratio

Another issue which has recieved considerable attention in the SSC R&D program is the copper to superconductor ratio (Cu/SC). The initial choice of 1.3/1 for the inner and 1.8/1 for the outer layer conductor was made in order to balance the operating current and the protection of the inner and outer layer conductors, and hence achieve cost effective magnet design (1). After considerable training in the inner layers was observed in the early SSC model dipoles, it was suggested that better performance might result from increasing the copper content of the inner layer conductor (16). This suggestion was supported by the observation of training of cable samples in a short sample test fixture (17). However, it was not supported by calculations of cable stability (18). After the evaluation of a number of magnets having either 1.3/1 or 1.5/1 copper to supperconductor ratios in the inner layer conductor, no clear trend has emerged (19). Since the lower Cu/SC ratio clearly leads to a higher operating to short sample margin, the lower ratio is presently specified for the SSC inner layer conductor.

C. Strand Diameter

The choice of this parameter represents a trade-off between Jc, wire manufacturing cost, cable design and magnet manufacturing. As a general rule, it is easier to get a high Jc value for finer wire due to the increased strain space available. Also, a finer wire is preferred in order to improve the flexibility of the cable. The main penalty for fine wire is in wire drawing, where the cost is increased, and the sensitivity to breaks due to inclusions is greater. The wire sizes for various cables used or proposed for recent accelerator magnets are listed in Table 4. These range from the 0.53 mm wire used for the FNAL quadrupoles (20), to the 1.29 mm wire originally proposed for the LHC dipole inner layers. The SSC wire diameters lie in the middle of these two extremes.

Table 4
Strand Parameters for Accelerator Dipole Magnets

Project	Wire Diam.	Filament Diameter	Cu/SC Ratio	Minimum Jc (A/mm^2, 5 T, 4.2K)
Tevatron	.68	9	1.8/1	1800
HERA	.84	15	1.8/1	2600
RHIC	.65	6	2.25/1	2600
SSC Inner	.81	6	1.3/1	2750
SSC Outer	.65	6	1.8/1	2750
LHC Inner	1.29	5	1.6/1	—
LHC Outer	.84	5	1.8/1	—

D. Process Reliability and Cost

Much attention is being given to these issues in the Vendor Qualification Program now in progress (21), and this work will not be discussed here. During the earlier SSC conductor R&D phase, some initial consideration was given to these issues. In particular, the billet size and extrusion methods were studied. A major process change compared to the Tevatron conductor was the use of a clad monofilament which is produced by extruding a 145 mm diameter NbTi billet rather than using a small diameter NbTi rod which is loaded into a copper tube prior to assembly into the second stage extrusion billet. This change has resulted in a more cost effective process for producing the fine filament SSC conductors. However, it does require the use of a diffusion barrier between the copper can and the NbTi, and also requires that the NbTi be produced with a fine grain size and homogeneous composition at the monofilament billet size.

Conventional extrusion billets of 200, 250, 300, and 350 mm diameter were produced and evaluated. The larger billet sizes are preferred from the standpoint of ease of stacking, cold reduction strain space, and reduction in the total number of extrusions required. However, other considerations, including press availability and length/diameter ratio are also important, and these have led to the 300 mm diameter becoming the typical size for the SSC final extrusions. Hydrostatic extrusion was also evaluated, and received particular attention when the reaction between matrix and filament was a problem. However, that interest faded with the realization (22) that the reaction also occurred during the intermediate heat treatments as well as during extrusion, and with the development of reliable, cost effective niobium diffusion barriers (5). Several changes in the final strand processing were also made in order to reduce costs. The stabrite solder coating was eliminated from the wires. Also, the wire final anneal was eliminated when it was determined that this improved the quality of the cable and that the copper matrix was annealed in the subsequent coil epoxy curing step. Wire twisting is a time consuming step, and the option of twisting the wires on the cabling machine was studied. We concluded that this change was possible, but not practical until the wire quality could be improved to the point that wire breakage during twisting is eliminated. If a wire fails during twisting on the cabling machine, the entire cable is lost, in contrast to the smaller consequences if the wire breaks on the wire twisting machine.

E. Remaining Issues For Strands

Many of the remaining issues which are relevant to the SSC conductor production are being addressed in the Vendor Qualification Program (21) However, there are a number of issues which are not being addressed in this program, and which will be mentioned.

1. Can 2.5 micron filament size conductors be manufactured with long piece lengths and high J_c?
2. Will significant improvements in Jc and cost be achieved with the Artificial Pinning Center approach?
3. Can the useful field range of ductile alloys be extended by the development of ternary alloys such as NbTiTa?
4. Can higher Jc values be achieved in NbTi, without experiencing serious ductility and piece length problems?

II. SELECTION AND OPTIMIZATION OF CABLE PARAMETERS

A. Number of Strands

The number of strands in a cable represents another trade-off between magnet designer and cable manufacturer. It is desirable to use the number of strands as a variable in order to balance the inner and outer layers of a two layer dipole and in order to choose a strand diameter which allows optimization of strand critical current densitiy (see strand diameter discussion). However, at the time of the SSC RDS, the experience base with Rutherford type cables only extended to 23 strands and it was not certain that acceptable cables could be made with large numbers of strands. The Reference Design A used the standard 23-strand cable for the inner layer and extrapolated to a 30-strand cable in order to have a matching outer layer cable. Preliminary efforts to make such a cable on conventional cabling equipment were not successful, and an R&D effort was initiated in order to determine whether there was a fundamental limit to the number of strands which could be made into a Rutherford type cable. An experimental cabling machine with 36 strand capability was designed and built at LBL for this purpose. This machine was used to develop the tooling and set the parameters necessary to make the SSC 30 strand outer layer cable (23). Later, it was also used to select the parameters for the 30 strand inner and 36 strand outer cables for the SSC 50 mm bore dipole magnet (24). The cable and tooling parameters were also incorporated into a specification for a production cabling machine, which was purchased and installed in an industrial facility in order to make the cable required for the SSC R&D magnets.

In 1990, the R&D cabling machine was rebuilt with a 48 strand capability in order to push to new limits in number and size of strands (25). Cables with up to 48 strands have been made successfully on this machine, so magnet designers are now using this increased flexibility to design new dipole magnets (26).

B. Cable Size

The cable should be sized so that the inductance of the resulting dipole is not so large that magnet protection is a problem. On the other hand, the cable must be flexible enough that it can be bent around the ends of a dipole magnet without damage or displacement of the strands which could lead to excessive magnet quenching. Again, the SSC cables are in the mid-range for this parameter--larger than the Tevatron and HERA cables, but smaller than those planned for the LHC (Table 5).

C. Keystone Angle

The RDS Design A dipole, the subsequent 40 mm bore, and 50 mm bore SSC dipoles all have what is known as partially keystoned cables. That is, part of the wedge required to provide the Roman arch structure is provided by the keystone angle of the cable while the remainder is provided by the insertion of copper wedges. The wedges serve two purposes: first, they help produce a highly uniform dipole field, and second, they allow a cable with a smaller keystone angle to be used. At the start of the SSC R&D program, it was shown that most of the damage which leads to critical current degradation occurs at the narrow edge of the cable (27), and that this damage is a function of the keystone angle and cable compaction (24). In addition, as the keystone angle is increased, the difference in mechanical properties between the narrow and the wide edge of the cable is increased. This makes magnet construction more difficult, and is believed to

Table 5
Cable Parameters for Accelerator Dipole Magnets

Project	Number of Strands	Cable Dimensions(mm) (minor/major edge X widrth)	Keystone Angle (degree)	Cable Lay Pitch (mm)	Packing Factor (P) (%)	Minor Edge Packing Factor (P.F.1)
Tevatron	23	1.12/1.40 X 7.8	2.06	66	88.0	.95
HERA	24	1.28/1.67 X 10.0	2.22	95	92.3	1.03
RHIC	30	1.06/1.26 X 9.7	1.21	73	91.0	.96
SSC Inner	30	1.33/1.59 X 12.3	1.20	86	88.9	.96
SSC Outer	36	1.05/1.26 X 11.7	1.01	94	90.4	.97
LHC Inner	26	2.06/2.50 X 17.0	1.56	1.20	92.5	.98
LHC Outer	40	1.3/1.67 X 17.0	1.18	12.0	92.0	1.01

be one of the causes of excessive training, since it is difficult to provide uniform compression across the face of the cable. Consequently, a partially keystoned cable is the final choice for the SSC and LHC dipoles, although fully keystoned versions have been investigated for the SSC dipoles (28) and quadrupoles (29).

D. Cable Compaction

Cable compaction is not uniform for a keystoned cable, so two different compactions are defined. First is overall compaction P, defined as the ratio of the sum of the areas of undeformed wire cross sections to the area of the enclosing trapeziod. Second is the narrow edge packing factor, P.F.1, which is the ratio of the area of two undeformed strands to that of a rectangle with dimensions of the narrow edge thickness times the wire diameter. In both cases, the area of the strands is the area taken through a plane at the turkshead; since the strands approach the turkshead at an angle defined as the cable pitch angle, the expressions for P and P.F.1 are :

$$P = \frac{n \pi d^2}{2 w (t_1 + t_2) \cos \phi} \quad ;P.F.\,1 = \frac{\pi d}{2t_1}$$

where d = strand diameter
n = number of strands
w = cable width
t_1 = narrow edge thickness
t_2 = wide edge thickness
ϕ = keystone angle

Both P and P.F.1 are determined empirically by making cables with varying compaction and keystone angles and then measuring the amount of critical current degradation. It is then a matter of judgment to set the values which provide the highest compaction, consistent with acceptable critical current degradation. One note of caution: the rate of degradation as a function of narrow edge compaction is not linear (24). Thus, when one is choosing values for a large production run such as the SSC, the compaction value is somewhat conservative in order to allow for other manufacturing tolerances which affect compaction, such as strand diameter. The overall packing factors in present day cables are in the range of 88 to 92.5% (Table 5). Typical values of narrow edge compaction are in the range of .95 to 1.03 (Table 5). The other important dimension in the cable is the width. The strands must be compacted somewhat on the cable edges in order to provide locking so that the cable is held together. However, current degradation again increases dramatically with overcompaction in this direction. When the SSC dipole design was changed, the cable width relative to strand diameter was actually increased somewhat in an attempt to decrease critical current degradation. This change appears to be successful, when the 40 mm dipole and 50 mm dipole cables are compared (25).

III. QUALITY ASSURANCE PROCEDURES

A. Requirements on Wire

The first step in meeting the dimensional, mechanical, and electrical requirements of these cables is to control these parameters for the wire used to make the cable. For example, if the cable thickness is to be controlled to ± .006 mm, while at the same time the maximum strand compaction must be controlled in order to control current degradation, the wire diameter tolerance must be less than half the cable thickness tolerance, or ± .003 mm. This requirement can be met, but it requires continuous monitoring of the wire with a laser micrometer, and a good die maintenance program to replace worn or faulty dies. In addition, the surface of the wire is important. If the oxide layer on the wire is variable, the wire/mandrel friction will vary and wire crossovers or uneven strand position may result. Also, if the wire surface is contaminated with foreign material, this material will tend to accumulate on the turkshead rolls and change the cable dimensions.

The most important mechanical requirement of the wire is to withstand the severe deformation which occurs at the edge of the cable as the wire passes through the turkshead. This deformation is a complex combination of tensile, torsion and compression which is very difficult to simulate with the standard type of mechanical test. Consequently, we have developed a special test and a test fixture which we use to evaluate the suitability of a wire for subsequent cabling. The test fixture is used to constrain the wire while the wire is formed into a sharp bend with a blade which is the same width as the wire. This test is a good measure of the ability of the wire to withstand the severe bending which occurs at the edges of the cable, and has been incorporated into the SSC (30) and the RHIC (31) wire specifications.

Another property of the wire which is important for good cable quality is the springback. We found that cables made with wires from different heat treatment lots or from different manufacturers will result in cables in which the adjacent wires will protrude from the cable. In extreme cases, these protruding strands make the cable prone to decabling, and even in less severe cases will result in strands being locked out of position when the spiral wrap insulation is applied. We have developed a test fixture and a test procedure for evaluating the springback of composite wires, and this requirement also has been incorporated into the SSC and RHIC wire specifications. Recent experiments on cables with wires having a wide range of springback characteristics show that it is the uniformity of springback, rather than the absolute value, which is important in obtaining flat cable. Future specifications which make use of a springback requirement should be modified to account for these results.

B. Dimensional Requirements for the Cable

The tight dimensional tolerances discussed in the introduction have required significant improvements to both the tooling used to make the cables and also to the capability to make on-line measurements. Early R&D cables made for SSC dipoles suffered from three types of dimensional tolerance problems which were associated primarily with the turksheading operation. The nature and origins of these problems were only understood after the on-line cable measurement system was put into operation, so this system will be discussed first.

During the production of the cable for the Tevatron, CBA and HERA programs, the dimensions were measured in two fixtures. The first is referred to a 10-stack measurement and consisted of stacking 10 pieces of cable with the keystone angle opposed for every other cable. The mid-thickness value is obtained by loading the stack, making a measurement, and dividing by 10 to obtain the individual cable thickness. The keystone angle was determined by mounting a cable in a fixture with a pivoting arm and once again making a measurement with the cable under load. These methods both suffered from two serious drawbacks: first, the measurements were destructive and had to be performed after the cable was made, and second, they were local measurements and could not provide indications of the variability along the length of cable.

These limitations were recognized at both BNL and FNAL; both groups began work on the design for an on-line measuring system. FNAL completed the first prototype unit in 1986 (32), and then built two additional units for the SSC Central Design Group. One of these units was sent to LBL and installed on our cabling line in 1987. This machine has been in operation at our facility since this time, and has been invaluable in determining the causes of dimensional variability. A number of improvements have been made to this machine by the LBL staff, including a new software package which allows the operator to display graphs of the cable dimensions and perform statistical analysis in real time. These machines are now being produced commercially, and are being installed on all the cabling lines which will produce cable for the SSC magnets.

The following causes of dimensional variability have been identified and corrected: (1) changing keystone angle; (2) short period variation in thickness; (3) long period variation in thickness. The changing keystone angle resulted from the inherent variability in the side roll pressure which occurs in the conventional turkshead roll assembly , and was corrected by changing the turkshead roll configuration. The short period variation is due to eccentricity in the turkshead rolls and is corrected by requiring that the rolls be ground with the shaft in place and that the eccentricity be checked after grinding. The long period variation is due to differential heating of the turkshead rolls relative to the turkshead frame. For example, in the present turkshead with 130 mm diameter rolls, a temperature differential of 6 C will cause the mid-thickness value to change from the midpoint to the limit of the specification range. This is corrected by heating the turkshead frame so that the temperature difference between frame and rolls is mimimized.

A recent improvement in the control of the mid-thickness dimension has been demonstrated by the use of statistical process control (SPC). A reoccurance of the short period variation was identified and traced to a bearing/roll interface problem. Also, on-line adjustments have been made to the turkshead in order to demonstrate that it is possible to further reduce the mid-thickness variations (33).

C. Mechanical Requirements for the Cable

A mechanical property of the cable which is important from the coil winding standpoint is the residual twist in the cable. If the residual twist is such that the cable strands are unlocked when the cable is forced to lie flat, it will tend to decable during coil winding. This cable twist arises from the memory release of the wire twist during the flattening operation which occurs at the turkshead, and the degree to which this release occurs is dependent on the wire process history. This release can be compensated for by twisting or untwisting the wire on the cabling machine by use of a variable planetary system (23), which was first introduced on the experimental cabler at LBL. This feature is now standard on the cabling machines which will produce the SSC cables.

Another mechanical requirement for this type of cable is freedom from sharp edges which may damage the insulation and lead to coil shorts. Sharp edges rarely occur on cable made with good tooling and good dimensional control; however, when large quantities of cable must be produced at high line speeds, it is necessary to replace the visual surveillance of the cable by the take-up operator with an automated system. Several techniques have been considered, including eddy current, optical, and insulation breakdown testing. One difficulty with all of these is the need to provide smoothe, reproducible movement of the cable through some type of on-line sensor. At present, the eddy current technique shows promise in detecting this type of defect, as well as other defects of interest such as crossovers, broken strands, and cold welds. Efforts to develop a reliable, on-line system are underway (34).

D. Electrical Requirements for Cable

The procedures for making measurements of the electrical properties of superconducting cables have been developed extensively by the group at BNL (35,36). These tests include critical current measurements for the cable, the copper RRR, strand magnetization, and interstrand resistance. These measurements are very important, but the results have been presented in the references listed above, and they will not be repeated here. However, we will refer to these measurements in the following discussion of critical current degradation as a result of the cabling operation. This degradation has been reduced dramatically during the period of SSC R & D activity from 1984 to 1991. The allowable degradation for the Tevatron, CBA, and the HERA cables was 15%, and this level of degradation was often seen in the Tevatron/CBA cable as well as the early SSC R & D cables (37). By 1991, the critical current degradation for SSC R&D cables had been reduced to nearly zero for the Inner Layer cables and to below 5% for the Outer Layer cables. This reduction is primarily due to three factors: (1) improvement in wire quality, (2) improvements in cabling techniques, and (3), a change in the definition of degradation.

F. Remaining cable issues

1. What is the ultimate limit on cable size and strand number?
2. Are there other methods for cable fabrication?
3. On-line Q.A. for broken strand, sharp edge, and cold weld detection must be developed.
4. Does interstrand resistance need to be controlled, and what is the best method?

IV. SUMMARY

1. The SSC R&D program has led to a significant improvement in critical current, piece lengths, and overall manufacturing capability for multifilamentary NbTi superconductors. These improvements are the result of setting ambitious goals for the project, and then providing the necessary resources to meet these goals.
2. The technical requirements of the SSC strand and cable are being met. The most significant remaining task, scale-up to produce the large quantities required for the SSC, is underway (see Paper LQ-3).

V. ACKNOWLEDGMENTS

This paper summarizes the results of the SSC R&D program from 1984-1990. We have attempted to reference the key contributions to the program, but we wish to call special attention to the support and inspiration provided by M. Tigner during his tenure as head of the Central Design Group. We also recognize the importance of NbTi Workshops, initiated by D. Sutter, in providing a forum for the exchange of ideas and results in a timely manner.

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