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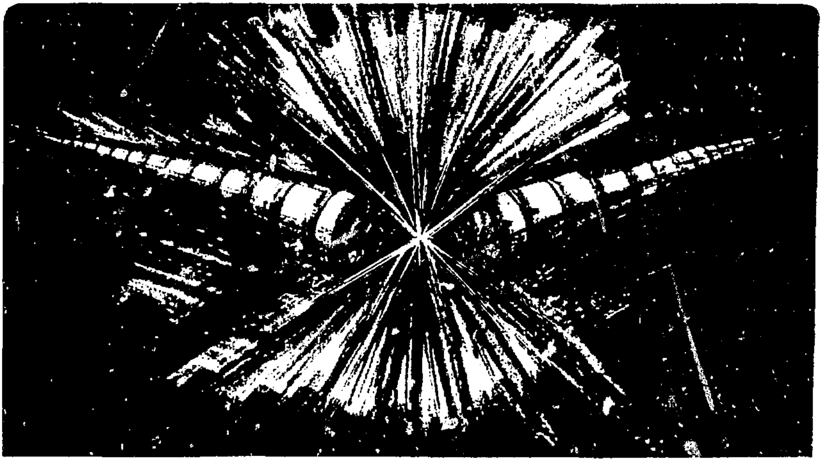

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ABSTRACT

The proposed Superconducting Supercollider presents several new challenges with regard to materials for dipole magnets. One design requires a NbTi superconductor with J_c (5T) greater than 2400 A/mm^2, whereas the Tevatron recently completed at Fermilab required a J_c (5T) $\geq$ 1800 A/mm^2. In addition, the high field design requires a conductor with a filament diameter of about 2.5 μm, if correction coils are to be eliminated. Finally, the high field design utilizes a 30-strand cable which again is a significant increase from the 23-strand cable used in the Tevatron. This paper describes the results of recent R and D programs aimed at meeting the stringent material requirements for the SSC.

INTRODUCTION

A review of the SSC design and program status is presented in another paper in these proceedings.[1] Presently, two dipole magnet designs are under active development. The high-field design option, referred to as Design D, requires a 30-strand cable for the outer layer and a 23 strand cable for the inner layer. The low field design, referred to as Design C, requires a 24-strand main cable and a 12-strand correction coil cable. Since the conductor requirements for the low field design are the same as those for the high field inner cable, the discussion here will focus on the superconductor requirements for the Design D dipoles. The conductor parameters for the Design D cables are listed in Table I.

A Reference Designs Study for the Superconducting Super Collider (SSC) was prepared for DOE during Feb.-May 1984. During this study the choice of a target critical current density for NbTi was discussed at length. A conservative choice would have been the value used for the Doubler/Saver magnets and for CBA, i.e., 1800 A/mm^2 at 5T. However, recent results[2] suggested that considerable improvements should be possible and these improvements would result in a substantial cost savings for the magnet system.[3] Consequently, a target value of 2400 A/mm^2 at 5T was chosen.

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During the 14 months since that decision, a number of NbTi billets have been produced; the results show that the J_c value chosen can be met with confidence by a number of U.S. and foreign manufacturers.

Another materials challenge posed by one of the reference design dipoles was the use of a wide cable with 30 strands which represents a step up in difficulty from the 23 strand Doubler/Saver and CBA cables. Once again, results of the SSC R&D program have shown that this cable can be manufactured with a high degree of confidence.

The present thrust of superconducting materials R&D in support of the SSC program is the development of fine filament NbTi as a replacement for the 20 µm filament material presently being used. This work is still in progress; however, initial results are quite encouraging.

As these examples show, the SSC design requirements are providing new impetus for the development of improved superconducting materials. The technical details of these and other SSC R&D programs will be presented.

IMPROVEMENTS IN NbTi CURRENT DENSITY

The "New Era" for high critical current density NbTi was initiated in 1982 with the report by the Baoji group of a J_c = 3900 A/mm^2 at 5T(2) (using a more sensitive criterion for J_c, Larbalestier confirmed a value of about 3450 A/mm^2). This announcement stimulated a new interest in binary NbTi alloys in the U.S., in particular by Larbelestier and coworkers at U. Wisc. This group made an extensive analysis of conductors being produced in the U.S. and found that the composition of the NbTi alloy was quite inhomogeneous. They concluded that this lack of homogeneity prevented these alloys from responding effectively to the multiple heat treatments used by the Baoji group.[4,5] After a series of discussions with the NbTi alloy manufacturer (Teledyne Wah-Chang, Albany) a collaborative experiment aimed at testing these ideas was begun in August, 1983. In this experiment a 10-inch billet (Billet 5183) was ordered by LBL. A special lot of high homogeneity alloy was purchased from TWCA and provided to IGC for processing. After extrusion, the material was divided into two lots - one for processing by IGC using their standard commercial process and the other to be held until Larbalestier could complete a J_c-optimization study and suggest an alternate treatment. As seen in Table II, Billet 5183 processed by conventional techniques produced an improved J_c (about 2300 A/mm^2 compared with about 2000 A/mm^2 for the best Doubler/CBA material). This result (see Billets 5198-1 and 5198-2 in Table II) was verified on two additional billets procured by LBL and processed by IGC while Larbalestier was completing his optimization studies. Larbalestier[6] recommended a new processing schedule and IGC processed the remainder of Billet 5183 (designated 5183-2) with this schedule. As seen in Table II, the J_c values improved significantly (from 2365 A/mm^2 to 2645 A/mm^2 for the 0.6 mm diam. strand). Based on these results, LBL ordered two additional billets (5210-1 and -2) and FNAL ordered five billets (5209-1 through 5) from IGC in July, 1984. This material was delivered in January, 1985; the J_c values in all cases exceeded our target specification value of 2400 A/mm^2. The only problem encountered was a switch of extruded rod labels by the extruder; as a result IGC processed the billets with Larbalestier's heat treat schedule, but not at the specified wire sizes, for billets 5210-1 and -2.

The final material order for Design D dipoles was placed in November, 1984, after competitive bidding won by IGC. IGC delivered 373 kgm (inner layer material) and 373 kgm (outer layer material) in April, 1985, (see Table II); the J_c (5T) values are 2509 A/mm^2 for inner and 2719 A/mm^2 for outer layer material. With the exception of Billet 5210-2, all outer layer material processed with the new heat treatment (3 x 40 hr at 375°C) has a significantly higher J_c than inner layer material. The FNAL material (Billets 5209-1 through 5209-5) is equivalent to outer layer material and also is consistent with this observation. A possible explanation for this behavior is that the additional cold working after extrusion in the case of the outer layer material is beneficial in improving the J_c; if true, this result suggests that it may be possible to get somewhat higher J_c values in the fine filament conductors which also contain more cold working.

Another favorable result from these procurements has been the piece lengths compared with Doubler/CBA experience. The longer piece length greatly facilitates cabling and simplifies testing and quality control.

FINE-FILAMENT NbTi R&D

In addition to the SSC requirement of high current density it is desirable to use conductors with a fine filament size[3] in order to reduce field distortion at low fields due to magnetization effects. If a conductor can be fabricated with filament diameters of 2.5 μm or less, correction coils presently required for each dipole magnet could be eliminated. Another correction approach currently being evaluated would require a filament size in the 5-6 μm range.[7] During the past few months, significant progress has been made in establishing the technical feasibility of fine-filament NbTi (see Fig. 1). These results show that fine filaments are feasible; however, in each case the quantity produced was small and the process was not production scale (with the exception of the Supercon billet discussed below). We will now discuss several problems which must be solved in the large scale manufacture of fine-filament NbTi and several R and D programs that are in progress.

Conventional production of NbTi superconductor consists of a hot extrusion (500-600°C) of NbTi rods in a copper matrix. During this extrusion and the prior heating of the billet, a layer of titanium-copper intermetallic compound, perhaps 1-2 μm thick, can form around the filaments.[8,9,10] This brittle intermetallic layer does not co-reduce and thus can become nearly equal to the filament diameter at final wire size; this results in extensive filament breakage and sometimes strand breakage. This problem can be eliminated by enclosing the NbTi rods at extrusion size in a barrier material, such as Nb or Ta, which prevents the titanium-copper intermetallic formation.[8,11,12] This barrier need only be 0.1 to 0.2 mm thick, and will be reduced to an insignificant fraction of the filament cross section at final filament size.

Another problem can arise from the introduction of foreign particles during the billet preparation operations. Any "dirt" consisting of micron size particles or any inclusions of this size in the NbTi rods or the copper components can result in filament breakage at the final wire size. This type of problem is insidious since processing may proceed successfully until the final wire size in approached. Also,the size of inclusion which is tolerable depends upon the desired filament size, e.g., a one micron diameter inclusion is acceptable for a 20 micron filament, but not for a 2 micron filament. This problem can be minimized by careful selection of raw materials and by clean room practice in billet assembly.

When a large number of rods are stacked in a billet, as is necessary to achieve fine filaments, (Fig. 2), a large void fraction is present, and this can lead to non-uniform reduction in the extrusion step. The filaments are necked down locally and this also leads to filament breakage. This problem can be eliminated by compacting the billet before extrusion.

When these potential problems are eliminated by proper processing and quality control, there is no metallurgical reason why a J_c value of greater than 2400 A/mm^2 cannot be achieved in filaments approximately 2 μm in diameter. In fact, the increased total reduction in area of the NbTi filaments may mean that it is possible to introduce more heat treat/cold work cycles and hence raise the value of J_c.

These potential problems and the proposed solutions were discussed with several superconducting material manufacturers between December, 1983 and August, 1984. In September, 1984, both IGC and Supercon responded with proposals to investigate the production of high J_c, fine-filament NbTi. The deliverable items include material for J_c optimization studies and also material for construction of model magnets. The final reports will include an economic analysis of the fabrication method. The details of these projects are listed in Table III, and the current status of these efforts are reported in other papers at this conference.[13,14]

A practical problem to be solved in producing fine filament NbTi for the SSC Design D configuration is to devise a method of stacking a large number of elements to produce the end product (see Fig. 2). There are at least three promising approaches, which will be discussed below.

First, one can stack a large number of rods in a single billet, and this is the approach being investigated by Supercon (see Table III). To date, they have stacked a 305 mm billet with 4164 rods and completed the extrusion successfully. Small amounts of this material have been processed to .8 mm diam. wire (8 μm filament size) and .3 mm diam. wire (3.0 μm filament size). The results are excellent. The filaments show no signs of degradation and the J_c (5T) = 2950 A/mm^2 for material with 3.0 μm filaments. A decision on final configuration will be made after results are complete on this optimization study and on two-level cable experiments in progress (see discussion below). The second phase of the Supercon study will consist of another 305 mm diam. billet with a 1.8:1 Cu:SC ratio and a filament number yet to be specified. If Supercon can demonstrate an acceptable stacking scheme, a Phase III billet will contain approximately 40,000 filaments and yield a final filament size of 2 μm.

IGC proposed to investigate a double stack-hot extrusion approach in which a number of rods are extruded in the first billet and then this material is stacked in a second billet. The Phase I extrusions consisted of an initial 152 mm diam. billet with 7 NbTi rods and a second 152 mm billet with 7 x 858 NbTi filaments. Approximately 45 kgm of this material has been drawn to final wire size and will be cabled in order to produce samples for I_c and magnetization measurements. Initial results indicate that this material will produce a J_c = 2450 A/mm^2 in 0.6 mm wire with 5 μm diam. filaments. It appears that some filament sausaging is occurring and this limits the J_c; this is discussed in more detail in Ref. 14. IGC is proceeding with Phase II (see Table III) and have procured the raw material for two 254 mm first stage billets. Material from these billets will then be restacked to produce a 254 mm billet of inner layer and a 254 mm billet of outer layer material. This wire should be ready for cabling in December, 1985. If this phase is successful, there will be enough cable for one 16-m model dipole and several 1-m models.

A promising alternative to the use of conventional hot extrusion with diffusion barriers is cold hydrostatic extrusion. Production size hydrostatic presses providing toll extrusion services are available in Europe (but not in the U.S.), and the costs are competitive with conventional extrusion. The maximum billet diameter is 165 mm, but billets to 1600 mm long can be extruded. Hence, one can process approximately the same weight of material using hydrostatic extrusion as can be produced from a 250 mm diam. conventional extrusion. However, the yield of useful material can be much higher in the hydrostatic extrusion case because of reduced end losses. This factor is especially important in a double extrusion process.

In order to evaluate, both technically and economically, the potential of hydrostatic extrusion for producing fine filament NbTi, three billets have been assembled for hydrostatic extrusion (see Table III). The elements for stacking the first two billets are being prepared using a bundle and draw approach. NbTi rods are clad with Cu, then 19 of these rods are loaded into another Cu tube, drawn and bundled to form the billet stacking elements. The third billet will be assembled with NbTi rods containing a diffusion barrier for comparison with the other two billets without barriers.

At the conclusion of this R&D program in December, 1985, we will have a data base on both cost and technical feasibility of various fine filament options. This will allow the SSC management to evaluate the fine filament option and to begin incorporating fine filament NbTi into the SSC long range plan.

CABLE FABRICATION

The effort to develop the cables required for SSC Design D dipoles has been proceeding along two paths - cabling experiments at LBL and process improvements at New England Electric Wire (NEEW). An experimental cabling machine has been constructed at LBL that can produce long continuous lengths of cable (up to about 1500 m. with the present spool system) at production speeds e.g., 4 m/min. In addition, the machine has several features not found on conventional machines, but essential for developing the optimum cabling parameters. These include variable planetary motion for the supply spools, precise tension control for the individual strands, capacity for 36 spools, and easy adjustment of cable twist pitch or cabling direction.

Several trial runs were made at NEEW between February and November, 1984. These trials were disappointing, especially for the 30-strand outer cable. Many crossovers occurred and only about 140 m. could be produced before crossovers recurred. In order to determine whether we were approaching some practical limit on strand number with the 30-strand cable, we attempted a 36-strand cable at LBL and made a successful cable. Additional trials on the LBL experimental cabling machine showed that two conditions contributed to crossovers - uneven tension from strand to strand and a small mandrel diameter (6.4 mm). When these two conditions were corrected at NEEW, the crossover problem disappeared. After these changes were made, a total of approximately 3600 m of cable have been made at LBL at a speed of 3-4 m/min. and a yield of over 95%. The increased yield is due (1) to improved wire lengths and quality, and (2) to improved cabling parameters. Cross sections of the 23-strand and 30-strand cables are shown in Fig. 3 and Fig. 4. At this time, we feel that the Design D cable can be made for the same cost, or perhaps somewhat less, than the Tevatron cable.

Currently, we are investigating several new cables which could have advantages for SSC dipoles. These include two-level cables, internal wedge cables, and internal flat cables. The two-level cable is of interest from the standpoint of fine filaments and increased flexibility. For example, we can use the 4,164 filament material being produced by Supercon as a .8 mm diam. strand with 8 μm diam. filaments, or we can reduce the wire diam. to .28 mm (filament diam. = 2.8 μm), fabricate a 7 element cable, and then fabricate a 23 strand cable from these elements. At LBL, we recently produced a mechanical model of this cable using surplus Isabelle strand material (Fig. 5). The cabling was completed without problems and at a typical production line speed of 3 m/min. This cable will be wound into 1-m coils in order to evaluate its applicability for flush-end magnets. As soon as the new material is completed by Supercon, we will repeat this experiment with high-J_c strand material and make electrical measurements.

CONCLUSIONS

We now have a substantial data base from these production-size billets (15 billets for a total weight of approximately 2270 kgm, including FNAL billets), and several conclusions can be drawn:

(1) The interim SSC specification value for J_c(5T) of 2400 A/mm^2 can be met in industrial scale production. This performance has been demonstrated by a number of U.S. conductor manufacturers.

(2) The specification of high homogeneity NbTi appears to reduce the spread in J_c values (although a more stringent test of this hypothesis, based on a larger data base, is necessary).

(3) The use of high homogeneity NbTi has resulted in extremely long piece lengths.

As a result of cabling experiments at LBL and at NEEW, we feel that the 30 and 23-strand cables planned for the SSC Design D dipoles can be produced in a reliable and cost-effective manner.

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TABLE I

STRAND PARAMETERS	INNER	OUTER
Alloy	Nb 46.5 ± 1.5 wt % Ti High Homogeneity Grade or Equivalent	
Size	0.81 ± .01 mm	.65 ± .01 mm
Critical Current (5T, 4.2K)	535 A (minimum)	282 A (minimum)
Critical Current (8T, 4.2K)	212 A (minimum)	112 A (minimum)
Copper to Superconductor Ratio	1.3 ± 0.1:1	1.8 ± 0.1:1
Twist Pitch	.8 twists/cm	.8 twists/cm
Filament Size*	< 23 μm	< 23 μm
Minimum Length	760 m	760 m
CABLE PARAMETERS	**INNER**	**OUTER**
Number of Strands	23 strands	30 strands
Width	6.76 ± .03 mm	9.73 ± .03 mm
Mid-Thickness	1.458 ± .015 mm	1.166 ± .015 mm
Keystone Angle	1.67°	1.24°
Twist Pitch	74 mm	69 mm
Critical Current (5T, 4.2K)	10453 A (minimum)	7202 A (minimum)
Critical Current (8T, 4.2K)	4142 A (minimum)	2860 A (minimum)
Minimum Length	1082 m	1347 m

*Most Desirable Size is Approximately 2.5 μm.

TABLE II

Designation	Strand Diameter (mm)	J_c Value** $(10^{-12}\Omega\text{-cm})$ 5T	8T	Intermediate Heat Treatment	Final Heat Treatment
5183 - 1 (Cu/SC = 1.36/1)	.8 .65	2280 2365	930 1015	IGC	IGC
5198 - 1 (Cu/SC + 1.35/1)	.8	2238	885	IGC	IGC
5198 - 2 (Cu/SC = 2.05/1).	.65	2273	880	IGC	IGC
5183 - 2 (Cu/SC = 1.36/1)	.8 .65	2545 2645	1030 1070	U. Wisc. (3 X 40 hr at 375°C)	260°C
5210 - 1 (Cu/SC = 1.25/1)	.8	2505	1034	*	260°C
5210 - 2 (Cu/SC = 1.80/1	.65	2435	1070	*	260°C
5212 - 3 (Cu/SC - 1.77/1	.65	2717	1146	U. Wisc.	260°C
5212 - 1 (Cu/SC = 1.28/1	.8	2509	1083	U. Wisc.	260°C

*U. Wisc. heat treatment with slight variation.
**Data obtained by Larbalestier and co-workers, U. Wisc.

TABLE III - FINE FILAMENT R AND D EFFORTS

ORGANIZATION	BILLET SIZE AND Cu:SC RATIO	FINAL WIRE SIZE AND FILAMENT SIZE	QUANTITY	DELIVERY DATE
IGC				
PHASE I	152 mm Diam. Billet 1.8:1	.65 mm Diam. Wire 4μm Filaments	45 kgm	July 1985
PHASE II	254 mm Diam. Billet 1.3:1	.8 mm Diam. Wire 2μm Filaments	182 kgm	Dec. 1985
	254 mm Diam. Billet 1.8:1	.65 mm Diam. Wire 2μm Filaments	182 kgm	Dec. 1985
SUPERCON				
PHASE I	305 mm Diam. Billet 1.3:1	.8 mm Diam. Wire 8μm Filaments .27 mm Diam. Wire For 2-Level Cable 2μm Filaments	182 kgm	Aug. 1985
PHASE II	305 mm Diam. Billet 1.8:1	.65 mm Diam Wire 6μm Filaments	182 kgm	Oct. 1985
LBL HYDROSTATIC BILLETS	165 mm Diam. Billet 1.3:1	.8 mm Diam. Wire 2.5μm Filaments	91 kgm	Oct. 1985
	165 mm Diam. Billet 1.8:1	.65 mm Diam. Wire 2.5μm Filaments	91 kgm	Oct. 1985
	165 mm Diam. Billet 1.8:1	.65 mm Diam. Wire 2.5μm Filaments	91 kgm	Nov. 1985

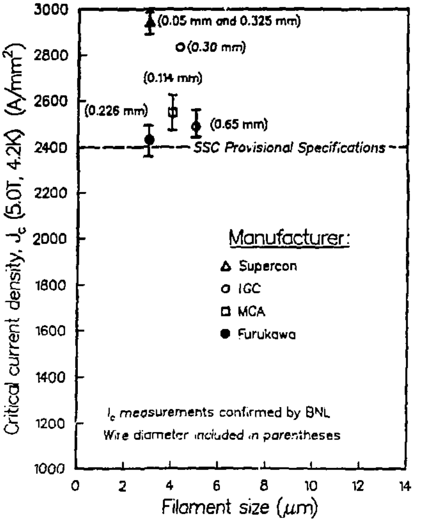


Fig. 1. Recent results show that high J_c values can be achieved in fine filament NbTi. The Supercon result for the .325 mm wire with 3 μm filaments was produced from a 305 mm diam. billet. The other results are from billets smaller than conventional production size billets.

XCG 855-267

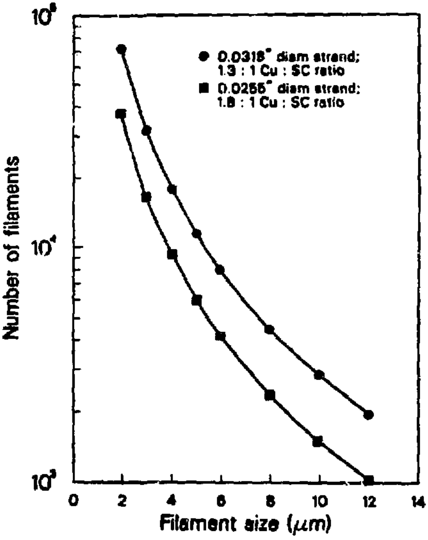


Fig. 2. A Plot showing number of filaments vs. desired filament size for the two Design D dipole conductors. In order to achieve a 2 μm filament size, approximately 40,000 filaments are necessary for the outer layer conductor and over 70,000 filaments are necessary for the inner layer conductor.

XCG 856-300

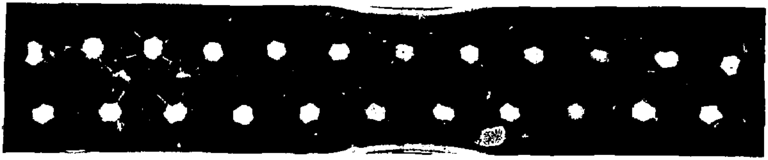
Fig. 3 Cross section of a Design D dipole inner layer cable with 23 strands of 0.8 mm diam. Note that the keystoning results in increased strand deformation at the narrow edge of the cable.

XBB 855-4038

Fig. 4 Cross section of Design D dipole outer layer cable with 30 strands of 0.65 mm diam.

XBB 855-4039

Fig. 5 Cross Section of an experimental two-level cable made from Isabelle type strands. This experiment demonstrates that a two-level cable substitute for the conventional cable shown in Fig. 3 can be made.



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