LBNL-49902
SC-MAG 765

DEVELOPMENT OF COST-EFFECTIVE NB_3SN CONDUCTORS FOR THE NEXT GENERATION HADRON COLLIDERS

R. M. Scanlan[1], D. R. Dietderich[1] , and B. A. Zeitlin[2]

[1]Lawrence Berkeley National Laboratory
Berkeley, CA, 94720, USA
[2]Supergenics LLC, Sarasota, FL 34242, USA

ABSTRACT

Significant progress has been made in demonstrating that reliable, efficient high field dipole magnets can be made with Nb_3Sn superconductors. A key factor in determining whether these magnets will be a cost-effective solution for the next generation hadron collider is the conductor cost. Consequently, DOE initiated a conductor development program to demonstrate that Nb_3Sn can be improved to reach a cost/performance value of $1.50/kA-m at 12T, 4.2K. The first phase of this program was initiated in Jan 2000, with the goal of improving the key properties of interest for accelerator dipole magnets--high critical current density and low magnetization. New world record critical current densities have been reported recently, and it appears that significant potential exists for further improvement. Although new techniques for compensating for magnetization effects have reduced the requirements somewhat, techniques for lowering the effective filament size while maintaining these high Jc values are a program priority. The next phase of this program is focused on reducing the conductor cost through substitution of lower cost raw materials and through process improvements. The cost drivers for materials and fabrication have been identified, and projects are being initiated to demonstrate cost reductions.

INTRODUCTION

Improvements in conductor and magnet design made during the past few years have been effective in demonstrating that efficient accelerator dipole magnets can be made to operate at higher fields (Fig.1). In order to operate at fields higher than about 8.3 T (the

LHC operating field at 1.8 K), it is necessary to use a superconductor with a higher upper critical field than NbTi, e.g., Nb_3Sn, Nb_3Al, or one of the HTS conductors. At present,

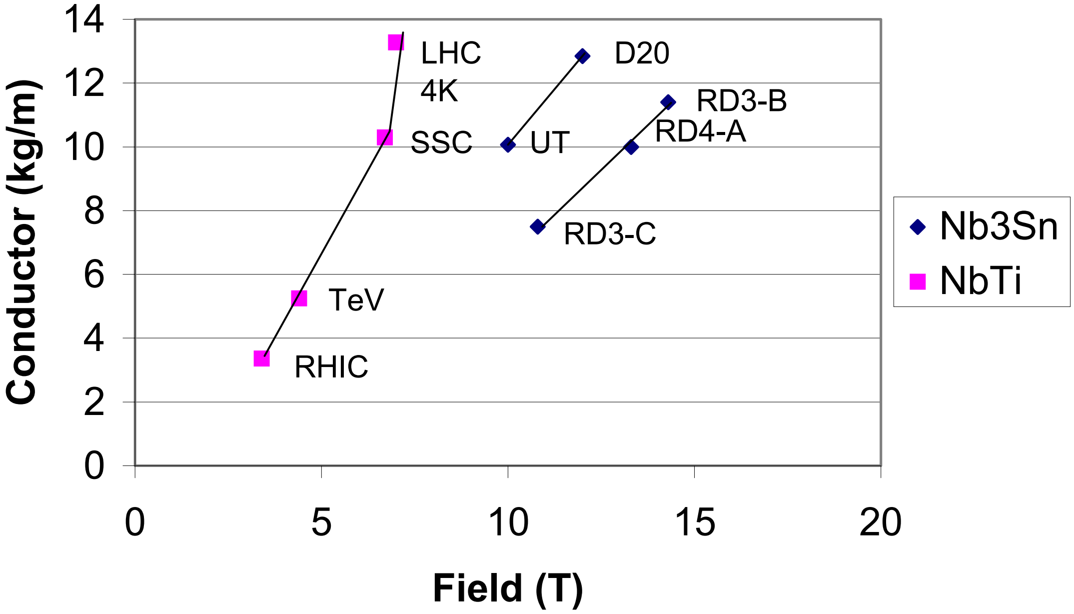


Figure 1. The amount of superconductor required to produce a dipole field in an accelerator quality magnet. All designs have been normalized to a 50 mm bore and an operating temperature of 4.2 K for comparison purposes.

Nb_3Sn is the high field conductor of choice, due to the established manufacturing processes and the high critical currents that are being achieved. Although Nb_3Sn has the intrinsic properties needed to produce a cost-effective high field dipole magnet, the conductor cost at present is too high to consider for a large accelerator such as the VLHC. At present, Nb_3Sn is being produced on a small scale, and the properties of most interest for accelerator dipole magnets have not been optimized. Recognizing this, DOE HEP initiated a conductor development program in January 2000 with the goal of producing a cost-effective Nb_3Sn conductor for use in accelerator magnets. This program is envisaged to last 5-6 years and will explore several conductor manufacturing approaches. The first 2-3 years will be focused on technical performance goals. This will be followed by scale-up and cost improvement efforts that will assess the capability of the manufacturing approaches to reach the cost goals. The technical and cost goals of the program are listed in Table 1.

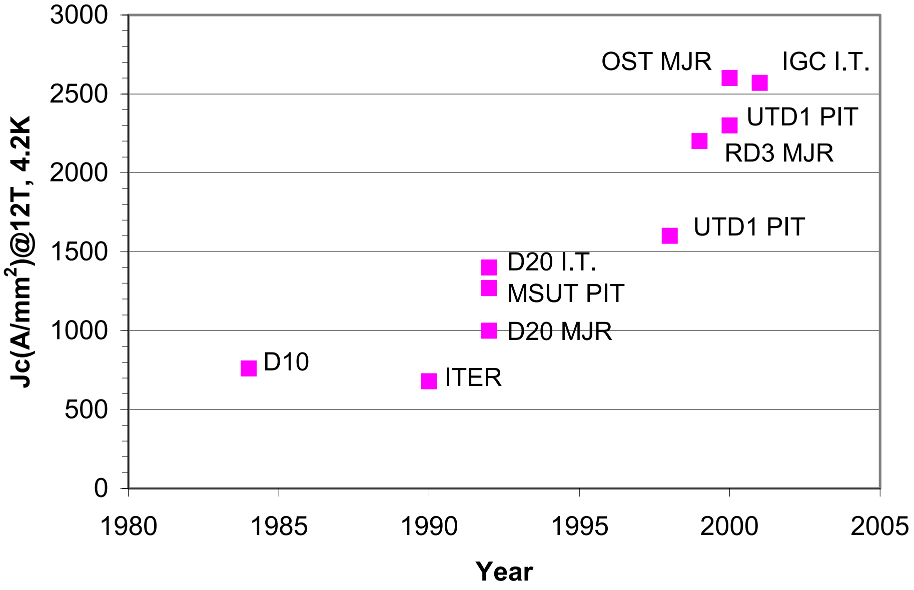
Table 1. Technical and cost performance goals of the High Energy Physics conductor development program.

Specification	Target value
Jc (noncopper, 12T, 4.2K)	3000 A/mm^2

Effective filament size	Less than 40 microns
Minimum piece length	Greater than 10,000m in diameters of 0.3 to 1.0 mm
Wire cost	Less than \$1.50/kA-m (12T, 4.2K)
Heat treatment times	Less than 200 hrs

PRESENT STATUS

Prior to 1990, the primary impetus for Nb_3Sn R&D came from ITER program for magnetic fusion energy. The ITER conductor requirements represented a trade-off between Jc and losses, since the ITER coils must operate under pulsed conditions. Thus, the ITER specification called for Jc(12T,4.2K) > 700 A/mm^2, with losses less than 680 mJ/cm^3[1]. Most accelerator magnet applications will require a relatively slow ramp to a constant field, so the loss criterion can be relaxed. However, accelerator magnets still require a small effective filament size so that the wires are intrinsically stable and have low magnetization effects. During the past 10 years, the HEP magnet R&D programs have been stimulating the development of higher Jc Nb_3Sn by setting higher specifications and procuring conductor for the model magnet programs. Also, the demand for higher field NMR magnets has served as a stimulus for Nb_3Sn conductor development. In response to these two applications that require higher Jc, the critical current density for commercially available wires has steadily increased, and these conductors have been used to fabricate a series of magnets that operate at higher fields (Fig 2). Most recently, LBNL [2] tested a dipole magnet fabricated from a modified jelly roll (MJR) Nb_3Sn conductor that reached a record high field of 14.7 T (Fig 3). After training, which began at a field of 8 T, the magnet reached the short sample current limit, which is about 2000 A/mm^2 (12T, 4.2K). This test demonstrates that high field dipoles can be built from a brittle material such as Nb_3Sn, and that the cabling and subsequent coil fabrication did not lead to degradation of the wire Jc.



.

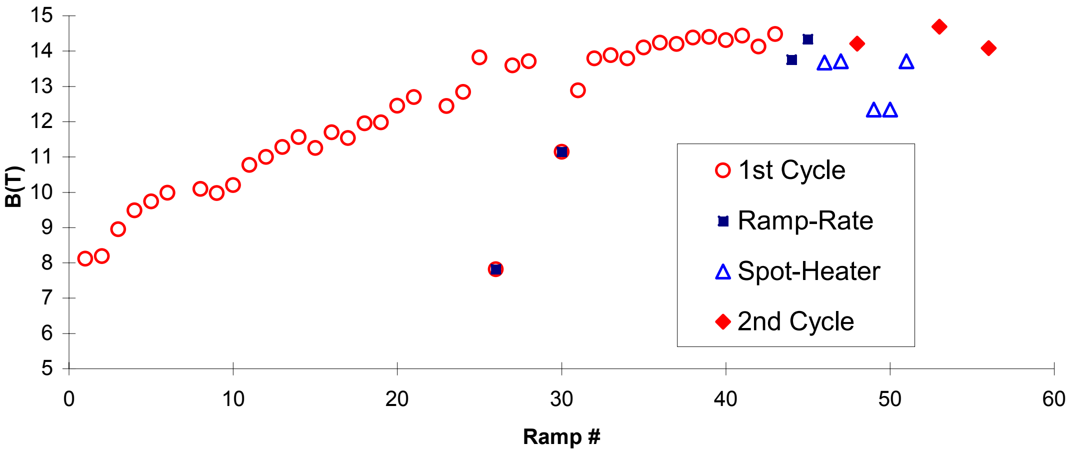


Figure 2. Improvements in critical current density with time for Nb_3Sn superconductor wire. Present generation magnets (RD3, UTD1) use conductor with Jc(12 T, 4.2K) = 2000-2200 A/mm^2. Magnets currently under construction will use conductor with Jc(12T, 4.2K) = 2400 A/mm^2.

Figure 3. Training curve for dipole magnet RD-3b, which achieved a record bore field of 14.7 T at 4.5 K. The training quenches for the first cooldown are indicated as open circles, and the training quenches for the second cooldown are indicated as solid diamonds. Solid circle points indicate ramp rate studies and are not training quenches. Triangle points are quenches induced by firing the spot heaters. The magnet retained its training after the thermal cycle.

In addition to the dipole magnets shown in Fig.2, model magnets are being made using Nb_3Sn conductor at BNL [3], FNAL [4], TAMU [5], and Twente U.[6]; however, the test results are not yet available. These magnet tests are providing important feedback to the HEP conductor development program, which is discussed in the next section.

CONDUCTOR PERFORMANCE IMPROVEMENTS

During the first year of the HEP conductor development program, efforts were focused on understanding the factors that control Jc and on improving the overall conductor Jc. Two R&D contracts were placed in April 2000--one with Intermagnetics General Corp.(IGC), and the other with Oxford Superconducting Technology(OST). The IGC program [7] is focused on their internal tin fabrication approach, and a series of billets with varying Nb, Sn, and Cu contents were produced. A complimentary effort, investigating different compositions and larger filament sizes, was carried out in parallel on an SBIR contract [8]. Together, these two programs allowed the investigation of Nb/Cu local area fractions (LAF) in the first stage billets from 0.53 to 0.8. Also, overall Nb compositions from 34 at % to 45 at %, Sn compositions from 12 at % to 16 at %, and Cu from 39 at % to 53 at % were investigated. All compositions are averages for the areas inside the diffusion barriers, and effectively cover the ranges that are practical from the fabrication standpoint. The Jc results for a portion of the Nb composition study are shown in Fig. 4. The compositions calculated for these three billets were checked by measurements made by three different methods (weighing and etching components, image analysis, and EDX analysis). The measured values of Nb are somewhat larger than those calculated; this may be due to selective removal of the Cu cladding from the Nb rods during the assembly process. However, both sets of data show a strong dependence of Jc on the Nb composition. Data for the full range of compositions are shown in [9]. As a result of this study, IGC can now accurately predict the Jc of their internal tin conductors, and can produce a conductor with a Jc of at least 2550 A/mm^2 at 12 T. Higher values may be achieved in the future, since the heat treatment has not been optimized. In addition, there is evidence from thin film studies [10], that the intrinsic Jc can be increased significantly by reducing the Nb_3Sn grain size. Efforts to demonstrate this in a practical multifilamentary conductor are underway in the FY 2001 HEP conductor R&D program at IGC.

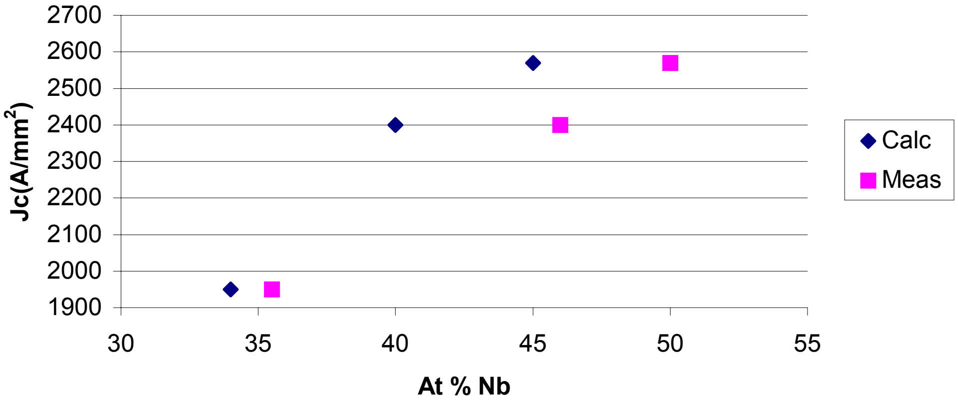


Figure 4. Critical current density (noncopper, 12 T, 4.2 K) as a function of Nb content for three different billets.

In their internally funded R&D, OST [11] has demonstrated that a Jc (12T) of 2600 A/mm^2 can be achieved in their modified jelly roll (MJR) process for fabricating Nb_3Sn. However, it is not easy to scale-up this process to achieve the cost goals of the HEP program, so OST is pursuing an alternate approach, the hot extruded rod (HER), in order to produce a cost-effective conductor. This approach uses the technology that has been established for producing the multifilamentary NbTi conductors with a cost/performance value of around $1.00/kA-m (5T, 4.2K). The hot extrusion process has not been used in the past to fabricate high Jc Nb_3Sn, since the pure Sn component will melt in a hot extrusion process. However, a modification in which powdered salt is used as a surrogate for the Sn during extrusion has proved successful [12]. The main goals of the OST R&D effort for FY2000 were (1) demonstrate proof of principle that the HER process can be used to produce multifilamentary Nb_3Sn, and (2) to explore a range of Nb filament sizes in order to find an optimum tradeoff between Jc and small effective filament size. OST has been able to demonstrate the HER process by successfully extruding two multifilamentary billets. With regard to the effective filament size issue, OST was able to show that relatively large filaments, with spacing adequate to prevent coalescence during reaction, could be reacted in a reasonable time from a high Sn matrix. However, the Jc values were rather low, and the FY2001 work will focus on finer filament size composites. In summary, initial tests of a HER approach are encouraging, and the costs appear in line with those for NbTi billets [13].

Other methods for reducing the effective filament size have been demonstrated [14,15]; however, most result in a loss of overall Jc, or at present are not cost-effective. For example [14], it has been shown that rows of filaments can be left out of the initial billet stack in order to prevent the Nb_3Sn filaments from coalescing across the entire subelement. Large filaments or shaped filaments can provide for a thicker Cu matrix; however, it has not yet been demonstrated that high Jc can be obtained in these filaments. Finally, accelerator designers have shown that some designs are less sensitive to filament magnetization effects [15], and also that ferromagnetic material can be added at strategic locations to compensate for large magnetization effects [15]. One goal of the conductor development program is to investigate the possible solutions for reducing magnetization effects, and to establish their costs. Ultimately, the choice of effective filament size will be made on the basis of overall system costs, i.e. incremental conductor costs for finer filaments will be compared with the costs of ferromagnetic correction shims and/or correction coils.

COST REDUCTION STUDIES

As part of the HEP conductor development program, cost studies have been initiated for several promising Nb_3Sn fabrication approaches, including internal tin, MJR, PIT, and HER. In some cases, a bottom-up estimate has been performed using raw materials costs and processing costs for each of the processing steps [8]. Although the details vary with the specific processing approach, some general conclusions can be drawn. These conclusions provide the basis for choosing the specific cost drivers where the conductor development program can be focused in order to reduce costs. Broadly speaking, the costs can be broken into two categories--raw materials and labor. Raw materials and outside services typically account for 50-75 % of the finished conductor cost, so these factors must be considered as well as the direct manufacturing labor in any cost reduction plan.

For purposes of illustration, the cost breakdown for an internal tin process is presented in a spreadsheet form (Table 2). This is not a process in use at present, since the scale exceeds the present demand for Nb_3Sn wire. However, it contains all the processing steps and the costs associated with producing Nb_3Sn from billets 300 mm in diameter, yielding 430 kg of wire per billet. This particular case illustrates the results on the wire cost of an alternative, less expensive source of Nb rod (see discussion below).

TABLE 2. Production cost analysis for Nb_3Sn, based on an internal tin process with 300mm diameter multifilamentary billets.

Materials	Quantity	Unit	Unit $ MfgA	Unit $ MfgB	Total$MfgA	Total $MfgB
Cu can kit	1	ea	2164	2164	2164	2164
Cu clad Nb hex	315	kg	123	81	38745	25515
Cu filler hex	180	kg	8.8	8.8	1584	1584
Cu filler rnd	10		8.8	8.8	88	88
Sn alloy	93	kg	55	55	5115	5115
Nb sheet	14	kg	176	176	2464	2464
Ta sheet	14	kg	1320	1320	18480	18480
Cu tube	200	kg	8.8	8.8	1760	1760
Assembly						
Weld	1	ea	150	150	150	150
HIP	1	ea	450	450	450	450
Labor	25	hr	14	14	350	350
Extrude/grind	1	ea	780	780	780	780
Gun drill	1	ea	1600	1600	1600	1600
Shipping/handling	1	ea	1120	1120	1120	1120
Bundle subelements						
Draw/hex	8	hr	14	14	112	112
Load tube	16	hr	14	14	224	224
Wire processing						
Rod draw	8	hr	14	14	112	112
Wire draw to 0.8 mm	50	hr	14	14	700	700
Overhead	3	100%			3486	3486
Total cost	$				79484	66254
Price/w 40% margin	1.4				111278	92756
Wire yield = 80 %	430	kg				
Length/weight conv.			228 m/kg	228 m/kg		
Price/kg	$				259	216
Price/m	$		228 m/kg	228 m/kg	1.14	0.95
Wire Ic			0.9 kA	0.9 kA		
Price ($/kA-m)					**1.26**	**1.05**

Raw materials cost factors

The two largest materials costs are for Nb and Ta. At present, for small (100 kg) quantities, Nb rod at the restack size (approximately 10 mm diameter) costs $230/kg, while Nb sheet costs $175/kg for thick sheet and $300/kg for thin sheet. While the cost for Nb is relatively stable, the cost of Ta undergoes wide swings in response to changing needs of the high quality capacitor market, which is the largest application. The cost shown in Table 2, $1320/kg, is near the high end of the current cycle. The cost of the Sn-Ti alloy, $55/kg, is significant as well, and is addressed below.

Several opportunities exist for reducing the raw materials costs. The cost for electron beam melted Nb in the form of large ingot is only $60/kg [16]. Thus, it is attractive to purchase large ingots, insert these ingots into a Cu can, extrude and draw to restack size. This approach is more cost-effective than fabricating Nb rod and Cu hex tubes separately and then stacking [8]. The cost impact of this change is shown in Table 2, by comparing the "MfgA" and "MfgB" columns. The main technical challenge here is to produce a relatively fine, equiaxed grain structure in a large Nb ingot. This is one of the tasks that can be addressed in the process scale-up phase of the conductor development program. With regard to Ta, since the superconductor industry is a relatively small customer, the most attractive solution may be to look for an alternate material that will serve as a Sn diffusion barrier. In addition to being effective as a Sn diffusion barrier, the optimum material must be highly ductile. Among the options that may turn out to be technically acceptable and also cost-effective are V alloys, Nb-Ta alloys, or multilayer barriers using only a relatively thin Ta sheet adjacent to the Sn alloy matrix. Fabrication procedures that allow the application of the diffusion barrier near the final processing stages are desirable, since this helps alleviate the ductility requirement.

The next most costly raw material is the Sn-Ti alloy. This alloy requires special preparation to insure that the Ti-Sn intermetallic particles are fine and well dispersed in the Sn matrix; otherwise, these particles can cause filament and diffusion barrier damage at the final wire size. Alternative methods of introducing the Ti are being investigated. These include use of Cu-Ti alloy and the introduction of NbTi rods into the Nb billets at large sizes, as first proposed by Pantsyrnyi et al [17].

Labor cost factors

Significant labor cost savings can be realized simply from the economics of scale. In order to demonstrate this, two projects are underway, and several more are in the planning stages. OST is developing the Hot Extruded Rod process described above. A cost estimate [13] done as part of this work indicates that the cost breakdown for this process is 27 % labor, 27 % outside services and Cu components, 25 % Ta, 11 % Nb, and 10 % Sn alloy. The wire cost estimate is less than \$3/kA-m for a Jc = 2000 A/mm^2 and less than \$2/kA-m for a Jc = 3000 A/mm^2, using current raw materials costs. Thus, if these labor cost savings can be achieved, together with the materials cost savings described above, the HEP conductor development program cost targets are within reach.

Another cost savings approach is to reduce the amount of Cu that is co-processed with the superconductor, and then add the Cu required for magnet protection at the end of the conductor manufacturing process[18]. This can be accomplished for accelerator magnets by cabling pure Cu strands together with the superconductor strands when the Rutherford Cable is fabricated. The feasibility of fabricating such cables has been established recently at LBNL (Fig 5). In addition to the method shown in Fig. 5, cables have been made with the Cu strands added at a small (subelement) size, and then cabled into a Rutherford-type cable (see the MEIT process discussion below). Short sample measurements are in progress in order to verify that current transfer is effective in these cable designs. This will be followed by small coil tests to insure that current sharing and transfer are satisfactory in mixed strand cables in the epoxy impregnated coil configuration as well. If these tests are positive, this type of cable will be incorporated into full-size magnet designs [5]. The cost

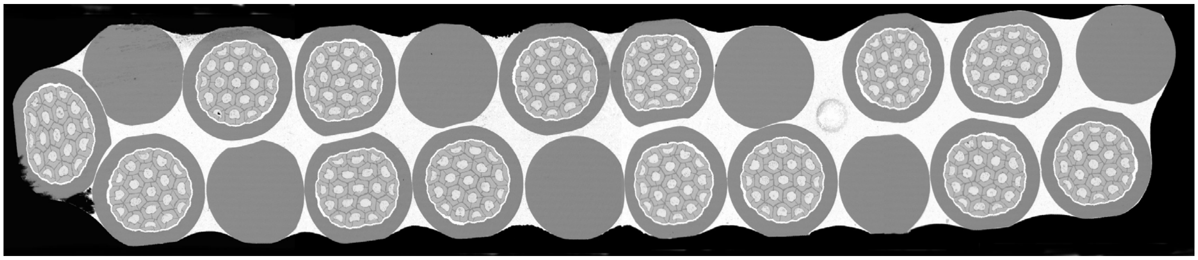


Figure 5. Mixed strand cable utilizing pure Cu strands to increase the copper content for purpose of magnet protection. A standard design superconductor strand can be used for a wide range of magnet applications.

savings from a mixed strand cable approach will depend on the specific application and, in particular, how much Cu is necessary for protection. As an example, the RD-3 outer cable used strands with 60 % Cu. If the Cu can be reduced to only 25 % on the superconductor strand with the remainder added as a pure Cu strand in the cable, the labor savings will be approximately 15%. This results in a 7.5 % savings in the overall conductor cost. In addition, the manufacturer saves the engineering, inventory, and quality control costs associated with multiple product lines, since a standard composition strand can be supplied for the different magnet designs.

A cost-effective modification to the internal tin approach, named the monoelement internal tin (MEIT), has been proposed by Zeitlin [8]. This approach utilizes the large extrusion billet approach, but gains additional cost savings by producing a composite with a single Sn core and diffusion barrier. This composite is drawn down to a fine wire size without the restacking step currently used in internal tin manufacture. The fine wire (for example, 0.2-0.3 mm diameter) contains a single diffusion barrier and a small amount of stabilizing Cu. The additional Cu required for protection is added in a cabling step at the end of the process. Cost estimates for this process have been presented [8], and they are substantially less than the target value used for the HEP conductor development program. This approach is being reduced to practice under a SBIR program grant, and progress is reported in [19].

CONCLUSIONS

1. Significant progress has been made in demonstrating that reliable and efficient high field dipole magnets can be made using Nb_3Sn superconductors.
2. A critical factor in determining whether these dipoles will be a cost-effective choice for a VLHC is conductor cost.
3. DOE HEP has established a conductor development program aimed at improving the performance and reducing the cost of Nb_3Sn superconductors.
4. Record Jc values have been achieved, and the target goal of 3000 A/mm^2 appears realistic.
5. Areas where raw materials and manufacturing costs can be reduced have been identified, and a program to demonstrate cost savings is in progress.

ACKNOWLEDGEMENTS

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098, and SBIR Grant DE-FG02-99ER82899.

The HEP program goals and target specifications presented here were developed in collaboration with the Conductor Advisory Committee: Giorgio Ambrosio (FNAL), Ted Collings (OSU), Dan Dietderich (LBNL), Arup Ghosh (BNL), David Larbalestier (UW Madison), Peter Lee (UWMadison), Peter Limon (FNAL), Peter McIntyre (TAMU), Ron Scanlan (LBNL), Bruce Strauss (DOE), Peter Wanderer (BNL).

The authors acknowledge the contributions of the conductor development teams at IGC (E. Gregory, T. Pyon, M. Vincenzi, M.Dormandy) and OST (S.Hong, J.Parrell, M.Field, Y. Zhang). Critical current measurements and microstructural measurements were provided by E.Barzi (FNAL), P. Lee (U.W.Madison), K. Molnar and K. Saito (LBNL).

REFERENCES

1. Mitchell, N. et al, "Conductor Designs for the ITER Toroidal and Poloidal Magnet Systems," in *IEEE Trans on Magnetics* **30**, pp1602-1607 (1994).
2. Benjegerdes, R. et al, "Fabrication and Test Results of a High Field, Nb_3Sn Superconducting Racetrack Dipole Magnet," in *Proceedings of the 2001 Particle Accelerator Conf*, Chicago, June 2001.
3. Gupta, R., et al, "Common Coil Magnet Program at BNL," in *Trans on Applied Superconductivity* **11**, pp 2168-2171 (2001).
4. Kashikhin, V. and Zlobin, A., "Magnetic Designs of 2 in 1 Nb_3Sn Dipole Magnets for VLHC," ibid, pp 2176-2179.
5. Battle, C., et al, "Optimized Block-Coil Dipoles for Future Hadron Colliders," in *Trans on Applied Superconductivity* **10**, pp 334-337 (2000).
6. Den Ouden, A., et al, "Conductor Development for a Wide Bore 10 T Nb_3Sn Model Dipole Magnet," in *Trans on Applied Superconductivity* **10**, pp 302-305 (2000).
7. Pyon, T. and Gregory, E., "Nb_3Sn Conductors for High Energy Physics and Fusion Applications," in *Trans on Applied Supercondictivity* **11**, pp 3688-3691 (2001).
8. Zeitlin, B., Gregory, E., and Pyon, T., "High Current Density Low Cost Niobium3Tin Conductor Scalable to Modern Niobium Titanium Production Economics," *Trans on Applied Superconductivity* **11**, pp 3683-3687 (2001).
9. Gregory, E., and Pyon, T., "Internal Tin Nb_3Sn Conductor Development for High Energy Physics Applications," Paper I-15A-02, CEC/ICMC, Madison, Wisconsin, 2001.
10. Dietderich, D., Kelman, M., Litty, J., and Scanlan, R., "High Critical Current Densities in Nb_3Sn with Engineered Microstructures," in *Adv in Cryo Eng* **44B**, Plenum Press, N.Y., 1998, pp 951-958.
11. Parrell, J., Zhang, Y., Hentges, R., Field, M., and Hong, S., "Nb_3Sn Strand Development at Oxford Superconducting Technology," Paper I-15A-03, CEC/ICMC, Madison, Wisconsin, 2001.
12. Field, M., Hentges, R., Parrell, J., Zhang, Y., and Hong, S., "Progress with Nb_3Sn Conductors at Oxford Instruments, Superconducting Technology," in *Trans on Applied Superconductivity* **11**, pp 3692-3695 (2001).
13. Parrell, J., Oxford Superconducting Technology, private communication.
14. Pyon, T., and Gregory, E., "Niobium-Tin for Fusion, High Energy Physics and Other Applications," in *Trans on Applied Superconductivity* **9**, pp 2509-2512 (1999).
15. Kashikhin, V. and Zlobin, A., "Correction of the Persistent Current Effect in Nb_3Sn Dipole Magnets," in *Trans on Applied Superconductivity* **11**, pp 2058-2061 (2001).
16. Caniero, T., RMC, private communication.
17. Pantsyrnyi, V., Shikov, A., Vorobieva, S., Soudiev, A., Kozlenkova, N, and Beliakov, N., "Superconducting Properties of Internal-Tin Nb_3Sn Wire with Enhanced Current Capacity," in *Trans on Applied Superconductivity* **11**, pp3591-3594 (2001).
18. Scanlan, R. and Fietz, W., "Multifilamentary Nb3Sn for Superconducting Generator Applications," in *IEEE Trans on Magnetics* **MAG-11**, pp 287-290 (1975).
19. Zeitlin, B., Gregory, E., and Pyon, T., Paper I-15A-05, CEC/ICMC, Madison, Wisconsin, 2001.