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Conductor Development for High Energy Physics--Plans and Status of the U.S. Program

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Abstract— In order to provide a cost effective high field magnet option for the next generation HEP accelerator, higher performance Nb₃Sn superconductor is required. These requirements have been recognized by the DOE, and a conductor development program has been initiated. The goal is to produce a cost-effective conductor with a J_c(noncopper,12T,4.2K) exceeding 3000 A/mm² and an effective filament size of less than 40 micrometers. Although the Nb₃Sn conductors manufactured at present have produced J_c values in excess of 2200 A/mm², no conductor being manufactured at present can achieve both the aggressive J_c and effective filament size goals. The first phase of the present program is underway, and is focused on improving the understanding of the factors that control J_c. Samples are being manufactured by industry and are being characterized with respect to J_c and magnetization as a function of composition and heat treatment condition. Using this new knowledge as a base, the program will move into a fabrication scale-up phase where the performance and cost-effectiveness can be demonstrated on production size quantities. The status and accomplishments of this program will be reviewed, and the plans for the scale-up program will be presented.

Index Terms—Nb₃Sn, accelerator magnets

I. INTRODUCTION

Historically, the improvements in performance of accelerator dipole magnets have been tied closely to improved superconductors. For example, the Tevatron used a NbTi conductor with a J_c(5T, 4.2K) = 1800 A/mm² to reach an operating field of 4.5 T, whereas the SSC dipole magnets achieved a field of 6.6 T using an improved NbTi conductor with a J_c(5T,4.2K)=2750 A/mm². The LHC, presently under construction, will operate at a field of 8.6 T using NbTi superconductor at a reduced temperature of 1.8K. However, the LHC is pushing near the practical limit for NbTi, and to continue the advance to higher fields, a superconductor with higher upper critical field, B_{c2}, must be used. In contrast to NbTi, all prospective higher field superconductors are brittle materials, so new conductor fabrication and magnet fabrication techniques must be developed.

At present, Nb₃Sn is the only practical choice in terms of properties, availability, and price. The Nb₃Sn conductor currently being used in the HEP magnet R&D programs has a J_c(12T,4.2K) greater than 2000 A/mm², and the price is not prohibitive for the relatively small quantities needed for these

R&D magnets. However, in order to achieve a cost-effective high field dipole for a future high field hadron collider, the J_c must be improved and at the same time, the conductor cost must be reduced. The Advanced Technology Development Program in DOE recognizes this, and is taking an active role in promoting cost-effective high field conductor development in industry. In this paper, we discuss the conductor development goals, the long-term program strategy, and the results of the program to date.

II. CONDUCTOR DEVELOPMENT PROGRAM GOALS

The basic outline for this program was developed from discussions at HEP conductor workshops that were held in 1998 and 1999. These goals are derived from the needs presented by the magnet R&D community, the potential performance improvements presented by the wire development groups, and the cost improvements projected by the wire manufacturers. The overall goal of the program is to provide a cost-effective, high-performance superconductor for the high-field magnets required for the next generation high-energy physics colliders. The target specifications for this conductor are listed in Table I. Improvement in the critical current density, in the non-copper component, is the highest priority, followed by reducing the effective filament diameter (D_{eff}). Reducing the cost of the conductor through process improvements and large scale manufacturing techniques will be important in the later phases of this program.

TABLE I.
Target specifications for HEP conductor

J _c (noncopper, 12T, 4.2 K):	3000 A/mm ²
Effective filament size:	40 micrometers or less
Piece length:	Average piece lengths greater than 10,000 m in wire diameters of 0.3-1.0 mm
Wire cost:	Less than \$1.50/kA-m (12 T, 4.2 K)

A conductor for a practical accelerator magnet will have other requirements in addition to those listed in Table I, such as sufficient copper to non-copper ratio to protect the magnet during quench. However, these parameters can be defined only in the larger context of magnet design, and thus are not specified at this time. The superconductor magnetization requirement, in particular, is under intensive study by the accelerator physics groups, and several innovative methods for accommodating a relatively large effective filament size are being proposed[1], [2]. This is important, since it appears

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that there is a tradeoff between J_c and D_{eff} for many conductors under consideration in this program.

In addition to the technical considerations, another important factor shaping this program is the funding situation. The present program has been designed to take advantage of the very significant work being done in industry under the DOE SBIR program. Also, the University and National Laboratory groups who are members of the Conductor Development Group (see acknowledgement section) are doing much of the sample characterization and testing.

In section III, the experimental results and status of wire development will be reviewed. In the following section IV, the results of cabling studies on these wires will be presented. Finally, in section V, the cost reduction plan will be described.

III. EXPERIMENTAL RESULTS--WIRE DEVELOPMENT

A. Nb_3Sn

At present, development work is proceeding on three types of conductor that show promise for meeting the requirements for the next generation collider--these are Nb_3Sn , Nb_3Al , and Bi-2212. This paper will focus on Nb_3Sn ; however, in order to present a complete picture, the status of Nb_3Al and Bi-2212 conductor development will be summarized and references listed that provide a more complete discussion.

The bronze process for fabricating Nb_3Sn has been shown to be limited in overall J_c to levels below the interest for use in high field accelerator magnets, so the work described here is focussed on three Nb_3Sn fabrication processes that have demonstrated J_c (12T, 4.2K) performance above 1500 A/mm². These are the modified jelly-roll (MJR), internal tin (IT), and the powder in tube (PIT).

Oxford Superconducting Technology (OST) is utilizing the MJR process, and they have supplied wire, or have orders for wire, from several accelerator magnet groups (BNL, FNAL, LBNL, and TAMU). Fig. 1 shows a cross section of the MJR wire supplied to LBNL for the common coil magnet.

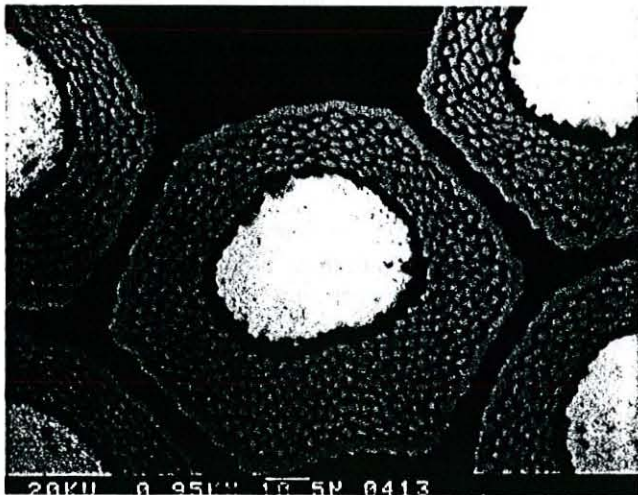


Fig. 1. MJR sub-element showing Sn core, Nb filaments, and Nb diffusion barrier. Sub-element width is 70 microns.

Two coils (designated RT-1) were fabricated from this conductor and tested in Feb., 2000. These coils reached a field of 12.2 T, the short sample limit of the conductor, with minimal training [3]. Although a J_c (non-copper) exceeding 2200A/mm² is being achieved, a shortcoming of this wire is residual resistivity ratio (RRR) of about 15. Analysis of this wire showed that the Nb diffusion barrier was almost completely converted to Nb_3Sn and that Sn had diffused into the copper matrix. OST has modified the conductor design to prevent this from occurring on new wire orders. This modification, and perhaps a modified heat treatment, is expected to restore the RRR to the levels in the conductor specification (RRR greater than 70). This problem notwithstanding, the coils performed very well in the RT-1 coil test. This result has prompted the magnet design team to reconsider the amount of high conductivity Cu matrix material that is required for good coil performance [4]. A set of inner coils, also using OST wire, have been completed and the magnet (RD-3) is under test.

Although the MJR process has been shown to produce a very high J_c conductor, there are some concerns with respect to process scaling and hence the potential for significant cost reductions. Also, it is not clear that the MJR process wire can reach the desired 40 micron effective filament diameter-- D_{eff} is around 70 microns in the present wire. Consequently, OST is developing an alternative, called the hot extruded rod (HER) process [5], [6]. This is a variation of the hot extrusion process, which is used to produce NbTi billets weighing over 500 kg and has been shown to be very cost-effective. In this instance, a Cu-matrix, Nb-rod composite billet is produced by hot extrusion (Fig 2). Since Sn has a low melting point and cannot be hot extruded, salt is substituted for the Sn and then washed out following extrusion. Then, Sn rods are inserted and the composite is drawn to final wire size. This process overcomes two major problems experienced by all high J_c Nb_3Sn processes: (1) poor bonding of the internal surfaces due to the absence of a hot extrusion step, and (2) scale-up limitations in a rod bundling and cold drawing process.

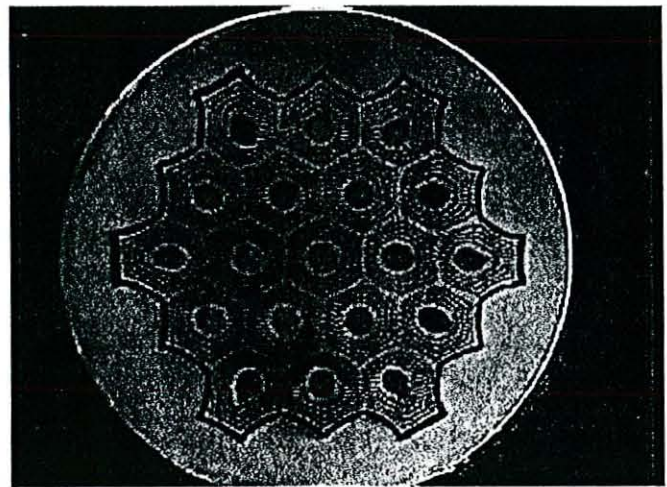


Fig. 2. Hot Extruded Rod Billet with salt packed into the hex-rod centers.

Proof of principle experiments have been completed by OST, and design optimization work is in progress at OST as part of the new conductor development program [7]. In addition to the HER work, OST is performing some composition optimization work using Nb rods cabled with Cu-clad Sn wires. This approach [8] allows a wide range of compositions to be studied, and the optimum Nb-Sn-Cu composition to be selected for HER billets.

The internal tin process is being pursued by IGC through conductor procurement orders, R&D contracts, and a SBIR subcontract [9]. The goals of this program are to (1) optimize the composition to produce the highest J_c , consistent with a reliable manufacturing process, and (2) identify cost reduction tasks for a subsequent manufacturing scale-up phase. The ranges of Nb and Sn compositions under study are shown in Table II. Initial results [10] show that all the composites can be processed successfully as monocoil wire; however, the highest Nb and Sn compositions exhibit some processing problems when fabricated as multicore wire. J_c tests of wires from this matrix are in progress. Preliminary results for a sample of wire from Billet EP2a shows a J_c (12T, 4.2K) = 1900 A/mm². A cross section of a 0.6 mm diameter wire from Billet EP2a is shown in Fig. 3. Analysis of the matrix composition after reaction shows a residual Sn content of 2.65 at%, and some unreacted Nb in the cores of some filaments. EP2b, with more Sn available for reaction, should allow complete reaction of the Nb. Note also that some Nb rods have been removed to subdivide the Nb₃Sn in an attempt to reduce D_{eff} .

TABLE II.
Internal Sn Composition Study Matrix

Billet Number	Nb local area ratio	Nb (at%)	Sn (at%)	Cu (at%)
EP1a	0.53	34.3	12.4	53.4
EP1b	0.53	29.1	16.2	54.7
EP2a	0.81	42.2	14.2	43.6
EP2b	0.81	45.0	16.0	39.0
EP3a	0.73	46.1	15.5	38.4
EP3b	0.73	51.3	17.3	31.4

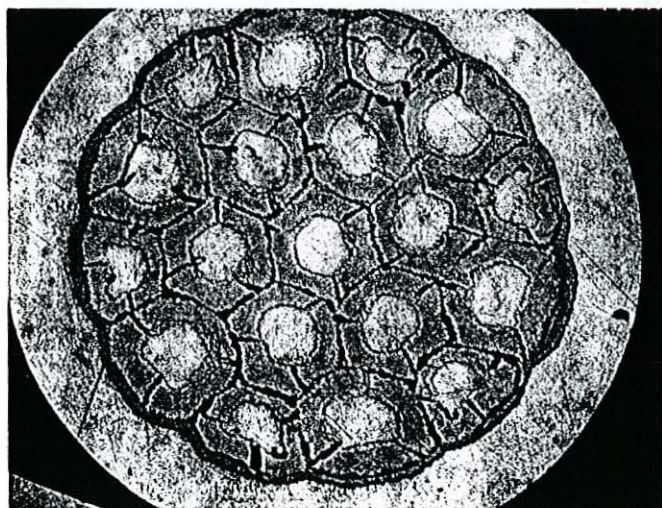


Fig. 3a. Cross-section of a 19 sub-element wire from billet EP2a, after reaction. Wire diameter is 0.6 mm.

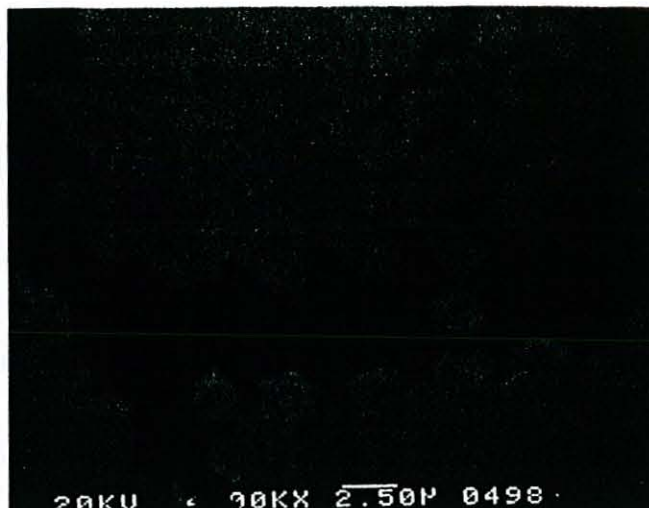


Fig. 3b. Higher magnification photo of the same wire, showing almost complete reaction as well as a significant amount of sintering of the Nb filaments within the sub-element arrays.

B. Nb₃Al

The transverse pressure applied to the conductor at the midplane of a shell type magnet, due to a combination of the applied prestress and the Lorentz forces, is very high. For example, the combined transverse stress reached about 150 MPa at 13.5 T in the LBNL D20 magnet. At this stress level, the J_c for Nb₃Sn has decreased significantly, the order of 20%, and the stress effect becomes more important at higher fields. The effect of stress on J_c is much lower in Nb₃Al, so Nb₃Al is an attractive alternative to Nb₃Sn for high stress, high field applications. Building upon earlier work performed in Japan and the U.S. in support of the fusion magnet programs, several HEP groups have been exploring the feasibility of using Nb₃Al in accelerator magnets. Nb₃Al produced by conventional processing does not provide a high J_c and H_{c2} , so recent R&D is focused on a rapid quench process [11]. A facility for producing rapidly quenched wire in the U.S. has been developed by OSU [12], and precursor wire is being produced under several SBIR projects. Short sample results obtained in both the Japanese and U.S. programs look very promising, with J_c values (for the A15 phase area) over 1000 A/mm² at 15 T. The main challenge is in the production of long lengths of precursor material for processing in the rapid quench apparatus.

Recently, however, new results and changes in magnet design approaches have changed the situation. Results obtained in the common coil program at LBNL [13] indicate that magnets can operate successfully at lower pre-stress levels. This information, together with the demonstration of stress management techniques [14] in dipole magnets, has resulted in a reassessment of the importance of a conductor that is more strain-tolerant than Nb₃Sn. Although a low strain sensitivity material is still a high priority for fusion magnets and perhaps NMR magnets as well, the priority is not so high as formerly believed for high field accelerator magnets.

C. HTS conductors

Although the near term emphasis is on Nb_3Sn , the HTS conductors are of interest for extending the dipole magnet field range above 15-16 T. Bi-2212, in particular, can be fabricated into long lengths of round wire. These round wires have been cabled successfully to produce Rutherford type cables that can be used in react and wind racetrack coils [15]. Until recently, the critical current densities were still too low to be of interest for HEP magnets. However, new results [16] show that J_c values comparable to those for Nb_3Sn can be achieved for fields above 15 T. Also, measurements of the strain dependence of Bi-2212 cables [17] indicate that this material has sufficient strain tolerance to be used in dipole magnets utilizing stress management approaches. Given the rapid pace of J_c improvements for Bi-2212, it seems likely that the J_c will improve even more in the next few years. However, the main detriment to large-scale use remains the cost of this material relative to NbTi and Nb_3Sn . Costs are high due to the small scale of production, as is the case for Nb_3Sn , but in addition, Bi-2212 conductor cost is high due to the raw materials cost of the Ag matrix. Alternatives to Ag, or methods of greatly reducing the amount of Ag, are necessary developments to make Bi-2212 a cost-effective conductor.

YBCO coated conductors are receiving much attention for other applications, due to its higher operating temperature. This conductor may offer advantages for high field dipoles as well. However, for the near-term, this program will focus on conductors that have high J_c and have been fabricated in long lengths.

Figure 4 summarizes the current state of the art for the wires under consideration for high field dipole magnets. All three approaches being pursued for Nb_3Sn are producing wires with J_c (12T, 4.2K) above $2000 A/mm^2$. Although the composition of the Nb_3Sn is not uniform over the entire reaction layer, J_c values in the A15 layer are approaching $5500A/mm^2$. This result suggests (1) there is still more potential for higher intrinsic J_c values if the layer composition

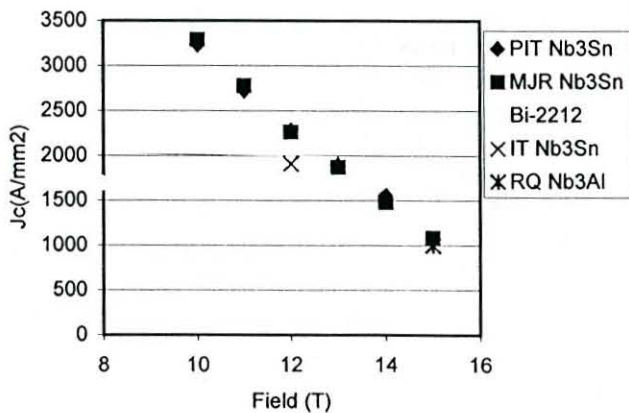


Fig. 4. Comparison of the best J_c values for Nb_3Sn (PIT, MJR, IT), Nb_3Al (average of rapid quench data, based on A15 area), and Bi-2212 (Showa) wires.

can be optimized, and (2) even with the present value of $5500A/mm^2$ in the Nb_3Sn layer, the J_c (non-copper) goal of $3000 A/mm^2$ can be met if the Nb, Sn, and Cu volume fractions are optimized. The J_c data for Nb_3Al indicate the extent that Nb_3Al must be improved in order to be competitive with Nb_3Sn . Assuming a reasonable value for the residual Nb (matrix, plus diffusion barrier) of perhaps 50 % of the non-copper area, the intrinsic J_c of the Nb_3Al would need to be doubled in order to have a conductor comparable to the present Nb_3Sn . Finally, the new J_c data for Bi-2212, extrapolated to higher fields, indicate a crossover with Nb_3Sn at a field of around 14 T. These data are all relatively recent, and further improvements are likely. Since it may be a decade before construction begins on the next hadron collider the relative positions of the three candidate conductors may change.

IV. EXPERIMENTAL RESULTS--CABLE DEVELOPMENT

The Nb_3Sn accelerator magnet programs rely on a flat, compacted (Rutherford) type cable developed initially for NbTi magnets. Cables of this type have been made successfully from Nb_3Sn ; however, the cabling parameters must be modified to take into account the very different mechanical properties of the Nb-Cu-Sn composites compared with the NbTi-Cu composites. In particular, the high J_c wires described above, when made via a bundling and cold drawing process rather than a hot extrusion process, are susceptible to degradation during cabling due to shear, which can cause severe degradation of the electrical properties. Extensive shearing of the Nb tubes (PIT Nb_3Sn wire) in a highly compacted cable results in Sn contamination of the Cu matrix and a serious drop in J_c . Cables compacted to a safe level and an over-compacted cable are shown in Fig. 5. Additional information on methods of reducing cabling degradation of PIT Nb_3Sn is found in [18].

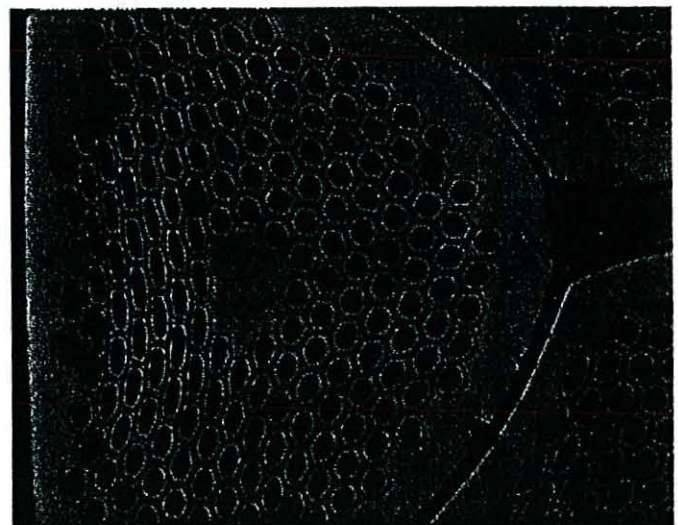


Fig.5a. PIT Nb_3Sn strand at edge of moderately compacted cable, showing deformation without shearing..

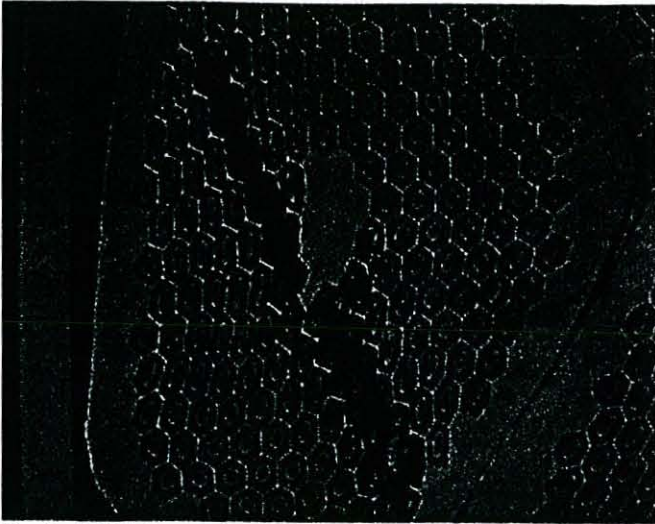


Fig. 5b. PIT Nb₃Sn strand at the edge of a heavily compacted cable, showing severe shearing of the Nb tubes in the composite wire.

Another type of degradation observed in Nb₃Sn cables is I_c degradation as a result of pressure. All cables used in dipole magnets are exposed to some degree of pressure, either as a result of pre-stressing the coils, or as a result of the Lorentz forces when the magnet is energized. I_c degradation can be either reversible, due to the pressure dependence of the intrinsic superconducting properties, or, for high strains, irreversible due to fracture of the Nb₃Sn filaments. In particular, the irreversible damage is of concern since it is progressive with cycling and also since it seems to depend on the type of conductor. For example, the I_c vs transverse strain characteristics appear to be different for cables made from IT wires and MJR wires [19]. Hence, I_c vs strain testing of cables for each type of strand is an important part of a conductor development program. Once the characteristic strain behavior of each type of conductor is known, finite element analyses of the composite strand and cable can be performed to predict magnet behavior [20].

In addition to degradation studies, the cabling work in support of this program is aimed at determining whether copper can be added at the cabling step as a cost-effective alternative to the present method of incorporating the copper necessary for quench protection into the individual strands. Pure Cu strands have been added successfully in a sub-cable, which was then cabled into a Rutherford cable (Fig. 6). Experiments are underway to add Cu strands at the Rutherford cable stage, but these attempts have not been successful to date; the mechanical properties of the Cu and superconductor need to be matched in order to prevent strands from popping out from the cable. A new series of experiments are in progress.

V. COST REDUCTION PROGRAM PLANS

As stated in Table I, the cost/performance goal for Nb₃Sn wire is \$1.50/kA-m compared to the small volume, R&D conductor cost at present of about \$7.00/kA-m. Obviously, it

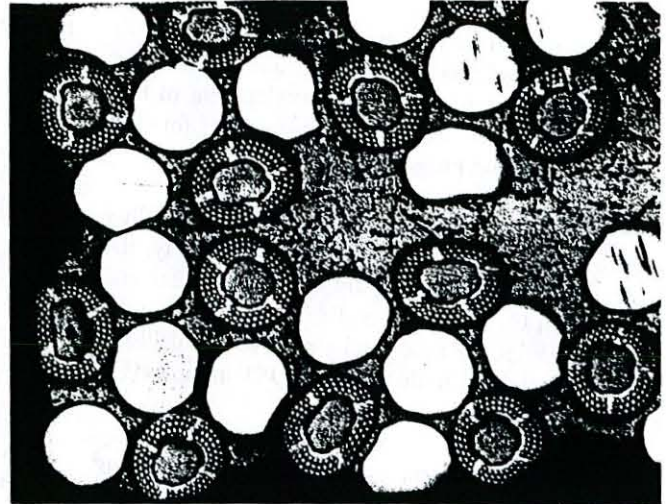


Fig. 6. Rutherford cable made from sub-cables with 4 copper and three superconductor strands. Strand diameter is 0.2 mm.

will be easier to achieve this value if J_c can be increased from the present value of 2200 A/mm² to the target of 3000 A/mm². If this value is met, the cost goal for raw materials and processing steps is then \$1.25/m or \$285/kg for a 0.8 mm diameter wire. The contributions of processing costs and raw materials costs have been analyzed, and the key areas for improvement will now be discussed.

The program goal of \$1.25/m is consistent with a detailed cost analysis performed and presented in another paper at this conference [9]. This analysis was performed for the internal tin process and is based on vendor quotations and extensive experience in the manufacturing of superconductor wire. Although this analysis was based on the internal tin process, it should be applicable to other Nb₃Sn processes as well.

The wire model used as a basis for this analysis consists of a small diameter (0.2-0.3 mm) wire, with a single diffusion barrier and a single Sn core. In addition, a minimum amount of Cu is provided on the core, and additional Cu, if required for protection, is introduced in a 1x6 sub-cable, in the manner shown in Fig 6.

In addition to the process innovations and process scale-up discussed above, it is important to understand and control the raw materials costs. These are discussed below:

1. Sn-Ti Alloy costs. One promising method for introducing Ti as an alloying element to raise H_{c2} and J_c is in the form of Sn-Ti alloy. This alloy must be specially prepared in order to avoid large intermetallic particles of Ti₆Sn₅ that can cause wire breakage. At present, this alloy is fabricated in 22 kg ingots and costs \$185/kg. Fabrication of high quality Sn-Ti alloy on a large scale will be a high priority of the conductor manufacturing scale-up program.
2. Nb rod costs. The present cost of Nb rod at the stacking size of 12 mm diameter is \$200/kg. This cost can be reduced by a process analogous to that adopted for the SSC and LHC NbTi rods, in which the Nb (or NbTi) rods are obtained at large diameter, say 150 mm, loaded into a Cu can and hot-extruded, followed by drawing to the

billet stacking size. This process reduces the loss of Nb and the added cost of special lubricants and dies needed for the direct drawing of Nb rods. Development of this technology is another high priority project for the manufacturing scale-up program.

3. Nb tube costs. The present cost of Nb and Nb alloy tubes are even higher than Nb rod costs. Similarly, the costs can be reduced significantly by co-extrusion and co-drawing with Cu on the outer diameter and inside the tube. The Cu inside the tube can be removed by drilling, or a salt core analogous to that used by OST in their HER process can be used.
4. Diffusion barrier costs. Innovative methods of applying the diffusion barriers at near final size, such as the tube wrapping techniques being developed by Eurys, can reduce costs for the barrier [8]. Also, substitution of NbTa alloy for the Ta, which costs over \$500/kg can result in significant cost savings.

This list of process improvements and raw materials cost savings is not meant to be all-inclusive. Instead, they are presented as examples of the areas that should be developed, and as incentives for others to contribute innovative ideas in this program.

VI. CONCLUSIONS

1. High current density Nb₃Sn shows promise for meeting the performance and cost goals for the next generation hadron collider.
2. In order to realize this potential, better understanding of properties controlling J_c in Nb₃Sn is necessary. The first phase of the Conductor Development Program is focused on achieving these J_c improvements.
3. The cost/performance goal for Nb₃Sn is ambitious, and will require significant scale-up effort to be realized. The subsequent phases of the Conductor Development Program will address these issues.

VII. ACKNOWLEDGMENTS

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