Title

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Progress and Plans for the U. S. HEP Conductor Development Program

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Abstract— **Although existing accelerators utilize NbTi superconductor, it is likely that any future upgrades or new accelerators will require the use of superconductors with higher critical fields, such as Nb_3Sn. DOE-HEP has initiated a conductor development program aimed at developing a high current density, cost-effective conductor for these new applications. The program is industry-based, with a set of target specifications that were derived from the accelerator magnet requirements. Significant progress has been made to date toward the target specifications, and the results will be presented. Plans for further development, in particular the scale-up tasks required to reduce the conductor cost, will be reviewed.**

Index Terms—**Nb_3Sn, accelerator magnets, Rutherford cable, strand magnetization.**

I. INTRODUCTION

Nb_3Sn is a leading candidate for the next generation of accelerator magnets. Applications under development at present include an upgrade for the LHC interaction region magnets [1] and a next generation high energy collider beyond the LHC [2]. Recently, good progress has been made in demonstrating that very high field accelerator-type magnets can be made using Nb_3Sn, with a new, world record dipole magnet field of 14.7 T reported in 2001 [3]. An important factor in the development of higher field Nb_3Sn dipole magnets has been the parallel development of improved Nb_3Sn conductors. DOE-HEP has initiated an industry-based conductor development program in order to encourage the continued development of high field superconductors [4]. The program, begun in 2000, emphasizes the parameters of prime importance for accelerator magnets. These parameters were developed by the Conductor Advisory Group, whose members include magnet designers as well as materials scientists (see Acklowledgments). In addition to this directly funded program, DOE-HEP is funding a number of complementary SBIR projects that address these issues. A list of target parameters has been developed, and they are shown in Table 1. This paper will summarize the progress toward meeting these goals. More detailed reports for the individual programs will be reported elsewhere in these conference proceedings. The directly-funded DOE-HEP projects are reported in refs [5] and [6], while the SBIR projects are reported in [7]-[9].

II. IMPROVEMENTS IN CRITICAL CURRENTS

The critical current density target is significantly higher than the values required for earlier projects [10], and also higher than the values for material available commercially when this project was initiated. A very aggressive value for Jc was chosen, since this is the primary factor necessary to achieve high fields in a cost-effective manner. This value is realistic from the viewpoint of the *intrinsic* current density in the Nb_3Sn layer, which can be as high as 4000-6000 A/mm^2 at 12T, 4.2K, [11]. Accordingly, a program plan was initiated to work on Jc from three approaches: (1) optimize the conductor composition, (2) optimize the reaction heat treatment, and (3) improve the intrinsic Jc of the Nb_3Sn layer.

Two industrial suppliers of Nb_3Sn are funded at present under this program—Intermagnetics General Corp (now Outokumpu Advanced Superconductors) and Oxford Superconducting Technology(OST). The main emphasis in the first year of the R&D program at Outokumpu Advanced Superconductors (OAS) was on the optimization of the composition of their internal tin composites [12]. The goal is to increase the volume fraction of Nb and Sn, while decreasing the Cu matrix. Obviously, there are practical fabrication issues that limit the degree that Cu can be removed. Thus, the program is focused on production-scale processes and large billets where possible. The dependence of Jc on Nb content and Sn content is shown in Fig. 1a and 1b. The general trend for Jc to increase with both Sn and Nb contents is clear from these data. However, the absolute values and slopes of the Jc vs. composition lines can be affected by other parameters, in particular, the heat treatment. For example, if the homogenization steps are not sufficient, as the Nb filaments are converted to Nb_3Sn, they coalesce and prevent further Sn diffusion so that the outer filaments are not completely reacted (Fig. 2).

Also, in the case of high Sn content composites, the Nb filaments can undergo dissolution and hence Jc will decrease, although the amount of the Nb_3Sn phase has increased [5]. Finally, longer than optimum heat treatments can result in grain growth and a decrease in Jc.

Oxford Superconducting Technology has completed similar composition studies for the modified jelly roll(MJR) process Nb_3Sn and found similar results [5]. After some initial attempts at optimizing the heat treatment, they report a

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maximum Jc (12T, 4.2K) of 2900 A/mm^2. These results, together with recent experiments at OST with a rod-based composite, indicate that the HEP target of Jc = 3000 A/mm^2 is realistic. However, as noted below, it may not be possible to maintain this very high Jc and at the same time meet the other HEP performance target values.

III. EFFECTIVE FILAMENT SIZE

The high current density conductors being developed for HEP, with a high volume fraction of Nb_3Sn, have large magnetization values, which can be expressed as a large "effective" filament size (D_{eff}). After reaction, the individual filaments coalesce (see Fig. 2.); also, in some cases, Nb is used as the diffusion barrier surrounding the Nb filaments, and a reaction layer is formed on the inside of this barrier. This large magnetization presents several potential problems for accelerator magnets. Most important, at low fields, the persistent currents produce local dipole fields that distort the field in the magnet bore. For example, the filament size for NbTi wires typically used in accelerator magnets is 5-6 microns. In contrast, the effective filament size for the Nb_3Sn wires used in the present generation of R&D dipoles is around 100 microns, i.e., the magnetization is a factor of 20 larger from this change alone. Fortunately, accelerator magnet designers have developed methods for correcting the magnetization effects. Recent results from FNAL [13] have demonstrated that ferromagnetic strips placed strategically in the dipole can effectively cancel the superconductor magnetization, even at these high levels. Simple, passive correctors were made using thin iron strips (0.2 mm x 15.85 mm wide) placed between two layers of fiberglass/epoxy tape, wrapped on a mandrel, and cured. This correction system reduced the sextupole variation, during the 1.5 to 4 T up-ramp of the magnet, from 19.4 to 3.2 units, with the corrected sextupole being virtually flat above 2 T. Also, the fact that there was excellent correlation between calculated and measured results indicates that precise corrections can be made for this effect.

Another limitation, which has been known for many years, is the flux jump instability associated with large superconducting filaments. The critical filament diameter, beyond which flux jumps can occur, is inversely proportional to the Jc. Thus, the present case with a combination of filament coalescence and high Jc is a concern from the standpoint of flux jump instabilities. Indeed, evidence of flux jump behavior has been seen in magnetization measurements [14] and, recently, in magnet tests. Using a technique to observe rapid flux changes, two different types of events were observed in the test of magnet RD-3C at LBNL [15]. The first type occurs primarily at higher currents, is short in duration (less than 0.5 ms), and can trigger a magnet quench. This type of rapid flux motion is interpreted as being caused by mechanical motion. The other type occurs at low currents, has a relatively long duration (around 10 msec), and triggers the fast flux detection system but does not trigger a magnet quench. This signal is interpreted as being caused by flux jump behavior. A confirmation that these signals originate from flux jumps was obtained by comparing the signals from two different coils. The coil that contained a conductor with a larger D_{eff} was the origin of all the flux jump signals. Fortunately, these flux jumps occur at lower fields, where the conductor margin is sufficient to prevent a magnet quench. However, this behavior is a concern for two reasons. First, the extent that this local flux redistribution affects the global magnetic field quality is not known. Second, if the Cu matrix volume fraction is reduced, the heating produced by these flux jumps may become sufficient to cause a magnet quench, even when the Jc margin is high.

Several approaches for reducing the effective filament size in Nb_3Sn wires are being pursued. OST has produced composites which have large (physical) diameter filaments at final wire size. The advantage of this approach is that the copper matrix between filaments can be made large enough to prevent filament coalescence, yet a high volume fraction of Nb can be maintained. As a further enhancement, OST has used shaped filaments to increase the interfilament spacing [5]. The composites using this approach have shown good filament isolation, and the filaments can be fully reacted in reasonable time; however, the Jc values at present are disappointing.

Another approach is to "subdivide" the composite. This approach is being used for the MJR conductors made by OST, and, recently, for the internal tin conductors made by OAS [6]. The main issue with this approach is one of optimizing overall performance. Each subdivided element needs a diffusion barrier; thus, a larger fraction of the composite cross section is occupied by barriers. Also, drawability may be affected by the increased number of interfaces that must be bonded together. A different approach to reducing the coalescence is to introduce diffusion barriers within the multifilamentary array. Supergenics, Inc. is pursuing this approach, and has produced a composite that appears promising [8]. However, additional results must be obtained in order to insure that this change can be incorporated without affecting the drawability.

At present, the conductor fabrication approach that shows the best combination of high Jc and low effective filament size is the powder-in-tube (PIT). Two types are being produced commercially by Shape Metal Innovations [16]; a 192 filament conductor with an effective filament diameter of 40 microns and a 504 filament conductor with an effective filament diameter of 30 microns. Current densities in the range 1800-2000 A/mm^2 at 12 T have been achieved, and the material has been used in the 11T dipole built by Twente U. [17]. The PIT wire has two drawbacks at present—the cost per kiloamp-meter is approximately 4-5 times the cost of Nb_3Sn wires made by the internal tin or MJR processes, and the wire shows more degradation due to compaction during cable fabrication. Cable compaction can result in shearing of multiple Nb tubes, which then results in Sn contamination of the Cu matrix and also a loss in Jc. The sources of this increased sensitivity to shear deformation appear to be (1) the low shear strength of the powders in the tubes, and (2) the difficulty of maintaining clean interfaces in the relatively large stack of rods in the bundle and draw processing. Several R&D efforts are underway to reduce the cost of PIT conductors and to improve the sub-element bonding (see discussion in Cost section).

IV. IMPROVEMENTS IN WIRE LENGTHS

Long wire length was listed as a specific requirement in Table I, although this parameter is linked closely with conductor cost as well. We have added wire length as a specific requirement for two reasons: (1) wire breaks often are symptomatic of latent defects which may cause problems in later stages of fabrication, including cabling, heat treatment, or coil winding, and (2) short piece lengths will increase the cost and reduce yield in the subsequent processing step of cabling. Piece lengths are limited by intrinsic factors, such as billet size or drawbench length, and by extrinsic factors, such as defects that cause wire breaks during processing. At present, the wire manufacturers have invested in capital equipment that allows multifilamentary NbTi to be produced in greater than 20 km piece lengths. Also, manufacturing quality control has been improved to the point that these piece lengths can realized in practice. The present status for Nb_3Sn is far from this situation. Finished wire lengths are typically 500-1500 m, and are limited by both intrinsic and extrinsic factors.

The fabrication approach that has allowed the production of long lengths of NbTi superconductor involves the hot extrusion of a large billet containing thousands of Cu-clad NbTi rods. Two different programs are underway that seek to apply this technology to fabricate high current density Nb_3Sn. OST is developing the hot extruded rod (HER) approach, in which Cu-clad Nb rods are co-extruded with salt cores. After extrusion, the salt cores can be dissolved with a water spray and the holes filled with the Sn or Sn-alloy rods. The composite can then be drawn to the desired wire size and reacted to produce Nb_3Sn. Long piece length is achieved, since the various components are diffusion bonded during the hot extrusion stage to produce a strong composite. Another technique is the mono-element internal tin (MEIT) approach, being developed by Supergenics [20]. Cu-clad Nb rods are assembled in a billet and extruded, with a solid Cu core. This core is gun-drilled and loaded with a Sn or Sn-alloy core at the center of the rod. The rod is then cold-drawn to produce a fine wire (0.1-0.3 mm diam.) which is then cabled with pure Cu wire to produce the finished conductor. Both methods should produce a composite that can be drawn to final wire sizes without the breaks that occur in "cold-processed" wires such as the MJR, the PIT, or the bundled and drawn internal tin. In addition, fabrication costs for both methods have been analyzed and both are compatible with the HEP wire cost targets in Table I (see next section).

V. IMPROVEMENTS IN CONDUCTOR COSTS

The improvements made in the cost/performance ratio for Nb_3Sn to date have come mainly in the area of performance. Typical values at present are in the range \$5.50/kA-m to \$7.75/kA/m for internal tin and MJR process, and \$29/kA-m for PIT Nb_3Sn. If these costs are to be reduced further, to meet the HEP target, processing and materials costs must be reduced.

A. Processing costs

A key factor in the development of cost-effective multifilamentary NbTi superconductor has been the adoption of large diameter billets, weighing several hundred kilograms each, which are hot-extruded. One goal of this program is to investigate the extent to which this approach can be adapted for Nb_3Sn. Commercial scale NbTi billets range from 200 to 300 mm in diameter. Consequently, the first step in the scale-up of the Nb_3Sn conductor will use 200 mm diameter billets. During the past year, both OST and OAS have extruded several billets of 200 mm diameter. A cross section of a large filament, HER billet extruded from 200 mm to 64mm is shown in Fig 3. A cross section of a small filament internal tin billet extruded from 200 mm to 51 mm is shown in Fig 4a. Although both programs have produced successful extrusions of 200 mm diameter billets, there have been instances where scale-up has resulted in problems, such as cracking of the rods during subsequent processing (Fig. 4b). Several conclusions with regard to scale-up can be drawn from the results of this first step in process scale-up. Although the room temperature mechanical properties of annealed Cu and Nb are reasonably well-matched, problems in co-extrusion and co-drawing can still occur. Niobium and especially Nb alloys such as Nb-1 wt % Zr work harden at a high rate relative to Cu. Since the Nb cannot be annealed after the addition of Sn to the composite, the fabrication process must be designed with this in mind. Also, the thermal expansion coefficient of Nb is only half that for Cu; this must be taken into account when heating and cooling the composite in order to avoid producing large thermal stresses that can crack the composite rods. Finally, the Sn component is much softer than the other components, and techniques must be developed that accommodate the Sn mechanical properties. These include development of Sn-alloys with improved mechanical properties [18], or by placing the Sn in a favorable location for co-processing, as is done in the MEIT process.

Conductor cost can be reduced significantly by reducing the volume of Cu that is carried along through the extrusion and wire drawing processes. It is necessary to maintain some Cu on the wire for processing reasons, and to provide stability against flux jumps or small motion during operation. However, it appears that the Cu in each strand can be reduced from the 50-60 volume percent level typical of present wires, to 25-30 volume percent and still maintain fabricability. This will reduce the wire cost by about 10-15 %. We propose to provide the extra Cu necessary for magnet protection by adding it at the final stages of conductor manufacturing. Three options are being evaluated: (1) adding pure Cu strands to the cable, (2) adding Cu as a core in the cable, or (3) adding Cu by wrapping a strip or braiding Cu strands around the completed cable [19]. Before any of these options are adopted, the following parameters must be investigated—manufacturability, effectiveness in a magnet environment, and cost. Pure Cu strands have been added directly as strands to the Rutherford-type cables [19], or as strands in a sub-cable that can then be used in a Rutherford cable [20]. Difficulties were encountered in manufacturing the mixed strand Rutherford cable, due to the very different mechanical properties of the two types of strands. Some improvement in cable mechanical stability was achieved by using undersized Cu strands, so that the Cu strands were not deformed and elongated excessively during cabling; however, these cables still exhibited "popped" strands during coil winding. On the other hand, interstrand resistance measurements and coil tests showed good electrical performance [21]. At this time, it appears that the mixed strand method of adding Cu needs more development before it can be considered as an effective substitute for conventional cables.

Several experiments have been completed where the Cu was added as a core to the cable. The most successful cores are bimetallic strips (Cu and stainless steel). The stainless steel component provides tensile strength so that the core does not elongate excessively during cabling, and also provides a high interstrand resistance to reduce coupling losses [21]. This type of cable cannot be used for all applications, since the flexibility for "hard way" bending is reduced. However, it can be used in the common coil configuration, or other racetrack coil designs.

Cables with the Cu added by wrapping strips around the cable, or by placing the strips on the surface of the cable, parallel to the cable axis, have been prepared by hand and interstrand resistance measurements have been made [21]. However, it is uncertain whether a practical manufacturing method can be developed for this approach, and also whether these cables can be wound successfully into coils.

B. Raw Materials Costs

The most expensive raw materials in the Nb_3Sn composites are Nb and Ta. Although Nb is readily available, and the cost of low purity grades such as that used for steel alloying is low ($14/kg), the cost of the fine grain, high purity Nb used in superconductors is over $200/kg. Billets of electron beam melted Nb with high purity are now available at a price of $60/kg. The high cost of superconductor grade Nb is due to the expense, and material loss, associated with converting the coarse grain electron-beam-melted Nb ingots into a fine grain size material via hot forging and extrusion. We are evaluating a new process, equal channel angular extrusion (ECAE), which can refine the grain size in a bulk material, at ambient temperatures [22]. Proof of principle experiments are being performed on 25 mm square sections, and cost estimates are being prepared for tooling to process full size billets [23].

Another key component for the high Sn processes is the Sn alloy. Pure Sn is inexpensive, but it is extremely soft and does not co-process well with Nb. Sn alloys with Cu or Ti additions are being used, but they are difficult to prepare and expensive. Likewise, it is useful to alloy the Cu matrix in order to increase the tensile strength, Cu-0.5 wt.% Sn has been used successfully.

The high field properties of binary Nb_3Sn are improved significantly by the addition of either Ti (0.5 wt %) or Ta (7.5 wt %). However, these special alloys are about 50 % more expensive than pure Nb, and are sometimes difficult to acquire. Alternative methods for adding these alloying elements are being evaluated. Ti additions to Sn have been used, and this has two advantages. In addition to the Nb_3Sn alloying effect, the Sn-Ti alloy has improved strength and thus co-processes well with Nb. However, it is difficult and expensive to produce this alloy; unless rapid cooling techniques are used, coarse particles of intermetallic Ti_3Sn are produced. These particles are not reduced during drawing and eventually cause filament and/or wire breaks. Ti additions via a Cu-0.5wt.% Ti alloy were investigated, but this alloy was found to work harden too rapidly. Addition of Ti via a Nb-47wt.%Ti alloy, first reported in [24], appears to be a promising method. Recent tests at OAS indicate that the composite can be processed, and Jc vs. B measurements indicate that the alloying effect of Ti in the Nb_3Sn is achieved.

VI. PLANS FOR FUTURE WORK

The first phase results indicate that the Jc target can be met by several approaches, including the MJR and the rod-based internal tin process. The emphasis has been on improving Jc by optimizing composition and heat treatments. R&D aimed at further improvements in Jc will continue; however, the focus will be on improving the intrinsic Jc of Nb_3Sn. Success in this area will provide the high overall engineering current density needed, and will allow filaments to be spaced so that D_{eff} is reduced.

Although the scale-up and cost-reduction experiments on Nb_3Sn are just getting underway, several processes under development appear capable of achieving the HEP target cost goal of $1.50/kA-m in large-scale production. These scale-up efforts and the development of less costly raw materials will continue, subject to budget limitations.

Magnet tests have demonstrated that Nb_3Sn can be used successfully in accelerator magnets. Thus, the HEP conductor development program will continue to focus on the development of Nb_3Sn. At the same time, the progress on other high field conductors, such as Nb_3Al and Bi-2212 will be monitored, and they will be introduced into the program if they offer some advantages over Nb_3Sn (Fig. 5). The next major step will be the demonstration of Nb_3Sn magnets under accelerator operating conditions. One likely possibility is an upgrade of the LHC interaction region magnets when the first generation magnets require replacement after several years of operation.

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REFERENCES

[1] T. Taylor, "Superconducting Magnets for a Super LHC," Proceedings of the European Particle Accelerator Conf, Paris, June, 2002

[2] D. F. Sutter and B. P. Strauss, "Next Generation High Energy Physics Colliders: Technical Challenges and Prospects," IEEE Transactions on Applied Superconductivity 10, pp33-43, 2000.

[3] R. Benjegerdes et al, "Fabrication and Test Results of a High Field, Nb_3Sn Superconducting Racetrack Dipole Magnet," in *Proceedings of the 2001 Particle Accelerator Conference*, Chicago, June 2001.

[4] R. M. Scanlan et al, "Development of Cost-Effective Nb_3Sn conductors for the Next Generation Hadron Colliders," Advances in Cryogenic Engineering (Materials) 48B, pp. 949-957, 2002.

[5] J. A. Parrell et al, "High Field Nb_3Sn Conductor Development at Oxford Superconducting Technology," paper 5MJ01, these proceedings.

[6] T. Pyon and H. Kanithi, "Development of Nb_3Sn Conductor for Fusion and High Energy Physics,", paper 5MJ02, these proceedings.

[7] S. Pourrahimi et al, "Fabrication and Performance of Multifilamentary Nb3Sn Wires by the Cable-In-Tube Approach," paper 5MJ03, these proceedings.

[8] B. A. Zeitlin et al, "Continued Progress on a Low Cost High Current Density Mono Element Internal Tin Conductor with Integral Barriers Incorporating Ti and Zr Additions in the Nb3Sn," paper 5MJ04, these proceedings.

[9] C. V. Renaud et al, "Status of PIT Nb_3Sn Conductor Development at Supercon," paper 5MJ07, these proceedings.

[10] N. Mitchell et al, "Conductor Designs for the ITER Toroidal and Poloidal Magnet Systems," in IEEE Trans on Magnetics 30, pp 1602-1607 (1994).

[11] D. Dietderich et al, "High Critical Current Densities in Nb3Sn with Engineered Microstructures," in Adv in Cryo Eng 44B, Plenum Press, N.Y., 1998, pp 951-958.

[12] E. Gregory and T. Pyon, "Internal Tin Nb3Sn conductor Development for High Energy Physics Applications," Adv in Cryo Eng 48B, Plenum Press, N.Y., 2002, pp 958-967.

[13] E. Barzi et al, "Field Quality of the Fermilab Nb3Sn Cos-Theta Dipole Models," Proceedings of the European Particle Accelerator Conf., Paris, 2002.

[14] R. B. Goldfarb et al, "Suppression of Flux Jumps in Marginally Stable Nb_3Sn Superconductors," IEEE Transactions on Applied Superconductivity 11, pp 3679-3682, 2001.

[15] L. Chiesa et al, "Performance Comparison of Nb_3Sn Magnets at LBNL," paper 2LC01, these proceedings.

[16] A. den Ouden 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.

[17] A. den Ouden et al, "Applications of Nb_3Sn Superconductors in Accelerator Magnets," in IEEE Trans on Applied Superconductivity 7, pp733-736, 1997.

[18] G. Chase, Phase I SBIR R&D, private communication.

[19] R. M. Scanlan et al, "Fabrication and Performance of Nb_3Sn Rutherford-type Cable with Cu Added as a Separate Component," paper 1LM02, these proceedings.

[20] B. A. Zeitlin et al, "Progress on a high current density low cost Nb_3Sn conductor scaleable to modern NbTi production," Advances in Cryogenic Engineering (Materials) 48B, pp978-985, 2002.

[21] M. D. Sumption et al, "AC Loss of Nb_3Sn-based Rutherford Cables with Internally and Externally Added Cu," paper 5LG01, these proceedings.

[22] K. T. Hartwig et al, "Hardness and Microstructure Changes in Severely Deformed and Recrystallized Tantalum," in Ultrafine Grained Materials, Y. T. Zha et al editors, TMS, pp 152-160, 2002.

[23] K. T. Hartwig, private communication, 2002.

[24] V. Pantsyrnyi et al, "Superconducting Properties of Nb_3Sn Wire with Enhanced Current Density," Trans on Applied Superconductivity 11, pp 3591-3594, 2001.

Table 1. Technical and cost goals for 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 km
Wire cost	Less than \$1.50/kA-m (12T, 4.2K)
Heat treatment times	Less than 200 hrs

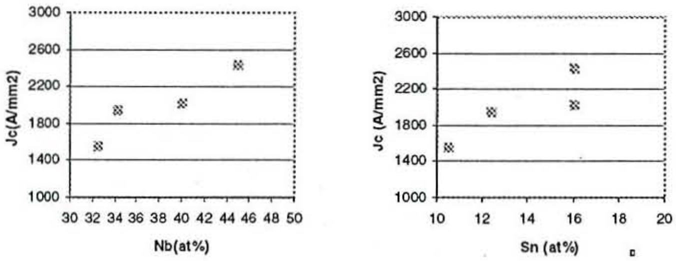

Fig. 1. (a) Dependence of Jc on Nb content, and (b) dependence of Jc on Sn content.

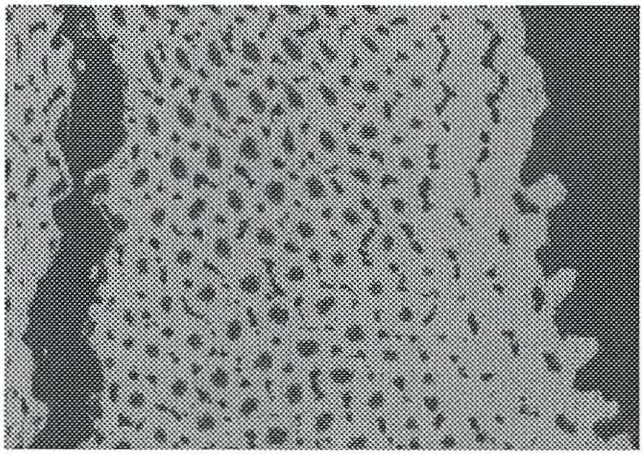

Fig. 2. Multifilamentary array showing the effects of a non-optimum heat treatment. The filaments near the Sn source (right hand side of figure) have coalesced and prevented Sn from diffusing to the outer rows of filaments. This results in a lower than optimum Jc.

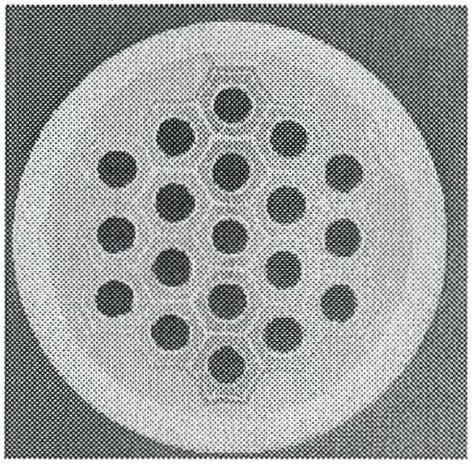

Fig. 3. Cross section (65 mm diameter) of large filament Nb composite made by the HER process. The dark cores are the holes remaining after the salt has been removed by washing after extrusion.

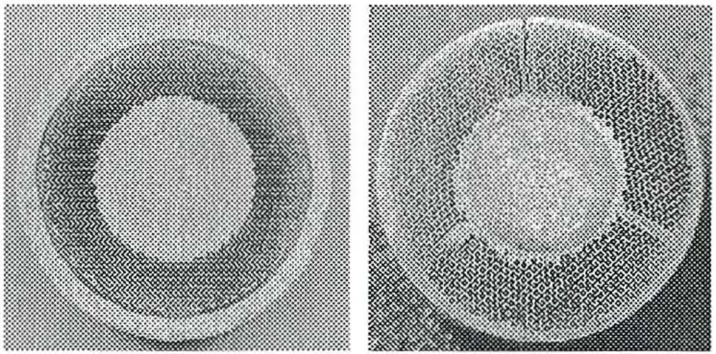

Fig. 4. (a) Cross section of a 1400 filament internal Sn billet extruded from 200 mm to 51 mm diameter, and (b) another internal Sn billet, with Sn core added, which cracked during rod drawing.

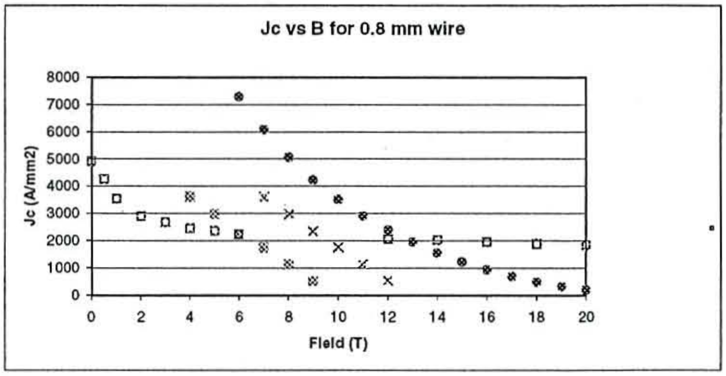

Fig. 5. Critical current vs. field for high field superconductors. The crossover for Bi-2212 and Nb_3Sn is about 13 T on the basis of Jc. However, the practical crossover is still higher, due to the large volume fraction of Ag matrix required in the fabrication on the Bi-2212 wire at present.