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A NEW GENERATION NB_3SN WIRE, AND THE PROSPECTS FOR ITS USE IN PARTICLE ACCELERATORS

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ABSTRACT

The US DOE has initiated a Conductor Development Program aimed at demonstrating a high current density, cost effective Nb_3Sn conductor for use in accelerator magnets. The first goal, an increase in current density by 50 %, has been achieved in a practical conductor. The program is focused at present on achieving the second goal of reduced losses. The different approaches for achieving these goals will be discussed, and the status will be presented. Magnet technology R&D has been proceeding in parallel with the conductor development efforts, and these two technologies are reaching the level required for the next step--introduction into operating accelerator magnets. An obvious point for introducing this technology is the LHC interaction region magnets, which require large apertures and high fields (or high field gradients). By upgrading the interaction region magnets, machine performance can be enhanced significantly without replacing the arc magnets, which represent most of the cost of an accelerator. Design requirements generated by recent studies and workshops will be reviewed, and a roadmap for the development of the next-generation interaction region magnets will be presented..

INTRODUCTION

The Large Hadron Collider (LHC), under construction at CERN, will be the world's most powerful particle accelerator, with a luminosity of about 2 x 10^{34} $cm^{-1}s^{-1}$, and a proton beam energy of 7 TeV. As construction of this phase is nearing completion, CERN has initiated a task force to study the feasibility of upgrades to the LHC [1]. Two possible upgrade scenarios for LHC are being evaluated--a luminosity upgrade and an energy upgrade. Both upgrades will require higher performance superconducting magnets, beyond the capability of the NbTi superconductor that was used in the LHC. Several luminosity upgrade options are being considered, with the most likely being a replacement of the existing NbTi interaction region quadrupoles with larger aperture Nb_3Sn quadrupoles. The energy upgrade, from 7 to 14 TeV, will require new arc dipole magnets as well, with a maximum field strength of 15 T to 17 T (depending on the field margin). Another factor that must be considered in the upgrade studies is the higher radiation loads on the magnets, especially in the interaction regions. The higher temperature and enthalpy margins for Nb_3Sn relative to NbTi make Nb_3Sn a more attractive choice. Radiation damage to the magnet insulation is another important factor that must be considered in any proposed upgrade.

The possible superconductor candidates are Nb_3Sn, Nb_3Al, Bi-2212, or MgB_2. At present, Nb_3Sn is the only high field superconductor being produced on an industrial scale, and with properties approaching those required for the LHC upgrades. In order to meet the LHC upgrade requirements, R&D efforts have been launched in Europe and the U.S. to provide the necessary improvements to the Nb_3Sn conductor. Initial results for the U.S. program were presented in [2]. The plans for the European program can be found in [3].

The goal of the U.S. Conductor Development Program, initiated by DOE in 1999, is to provide a cost-effective, high-performance superconductor for the high-field magnets required for the next generation high-energy physics colliders, as well as upgrades at the existing colliders at FNAL and CERN. The target specifications for this conductor were developed in collaboration with the major U.S. HEP laboratory and university groups engaged in high field superconductor development. These specifications are listed in Table 1, and are being taken as a baseline for the LHC upgrade magnet designs. The emphasis is on Nb_3Sn made by industrial partners with large scale production experience in making Nb_3Sn superconductors. At present, two manufacturers, Oxford Superconducting Technology (OST) and Outokumpu Advanced Superconductors (OKAS) are participating in the U.S. program. Both manufacturers are using an internal-tin type fabrication approach, since the bronze approach cannot produce the high Jc values targeted in this program--the limit for bronze process Nb_3Sn is around 1000 A/mm^2 at 12 T. In addition, the bronze process requires wire annealing each 50 % reduction in area, in order to recover the work hardening that occurs in the high Sn bronzes. The main attraction of the bronze approach is that the composites can be hot-extruded and thus the bonding and wire piece lengths are good. Thus, improving the bonding and piece lengths for the internal tin approach is a major goal of this program.

As the program progresses and the emphasis changes, more companies may be added in order to investigate new options. This is a multi-year program with two phases that partially overlap. The first phase (3-4 years) is primarily an R&D program leading to an improved understanding of the factors that influence conductor performance and cost. Using the new knowledge gained from this research as a base, the program will then move into a fabrication scale-up phase where the performance and cost-effectiveness can be demonstrated on production-size quantities. Improvements in the critical current density Jc in the non-copper part of the wire has been the first priority, followed by reduction in the effective filament diameter d_{eff}, and then by lower cost. The conductor for a practical accelerator magnet may require other properties in addition to those listed in Table 1, such as sufficient copper to non-copper ratio to protect the magnet during quench. Because these parameters can be defined only in the larger context of magnet design, and in the interest of allowing leeway for innovation, such parameters are not specified at this time.

Table 1. Target specifications for HEP conductor:

Jc (noncopper, 12T): 3000 A/mm^2
Jengineering(12T): greater than 1000 A/mm^2
Effective filament size: less than 40 microns
Process unit size: scaleable to greater than 100 kg and average piece lengths greater than 10,000 m in wire diameters of 0.3mm to 1.0 mm
Wire cost: less than $1.50/kA-m (12T, 4.2K)
Short heat treatment times: maximum 400 hrs; target 50 hrs for wind and react magnets

IMPROVEMENTS IN CRITICAL CURRENT DENSITY

Jc improvements can be achieved by (1) increasing the volume fraction of Nb_3Sn in the composite, and (2) improving the quality of the Nb_3Sn. Although the first approach was the initial focus of this R&D program, a recent analysis of the results shows that significant improvements have been made in both areas [4]. The teams at both OST and OKAS have produced a series of composites in which the local area ratio (LAR) of the Nb rod/copper matrix has been increased to the practical limit of about 80 % Nb and 20 % Cu (a LAR of 80/20). A series of samples with different Sn contents were then produced by varying the

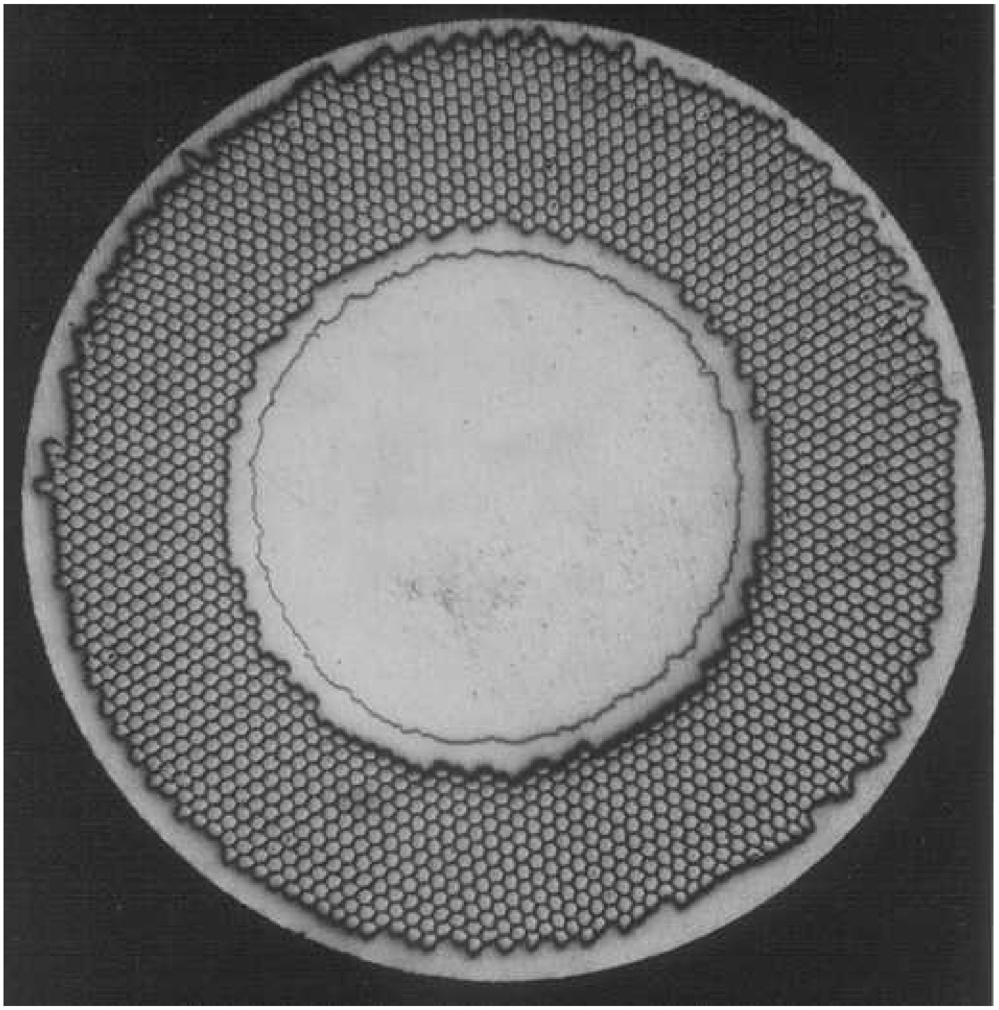

FIGURE 1. Cross section of subelement showing Nb filaments in a Cu matrix, with the central hole filled with Sn alloy.

size of the hole in the center of the Nb/Cu composite rods (FIG 1). Thus, a matrix of Jc vs Nb and Sn content has been produced. The details of the composition optimization studies have been presented [5-6]. The first justification for referring to these conductors as a "new generation" Nb_3Sn conductor comes from these composition studies, which have shown the following. First, the Sn composition of both the Nb_3Sn layer and the remaining bronze matrix is higher in Sn than the conventional bronze or ITER type internal tin conductors.

Further, the Sn content across the Nb_3Sn layer is very uniform and high [4]. Another new observation for these high Sn content wires is that the Nb filaments nearest the Sn core may be dissolved in the reaction step, and new phases may be formed in the reaction step [5]. Finally, and most important, the resulting Jc is a factor of 2-3 higher than the best bronze and ITER-type Nb_3Sn conductors. Recently, OKAS has completed their composition matrix study and report a range of Jc values, ranging from about 1100 A/mm^2 for the low Nb/low Sn compositions to a high of 2700 A/mm^2 for the highest Nb and Sn compositions [6]. However, OKAS has experienced some difficulty in drawing these composites down to the required wire sizes (less than 1 mm). Thus, a high priority goal of the OKAS program is to improve the wire piece lengths.

The initial approach at OST for producing a high Jc Nb_3Sn conductor was the modified jelly roll (MJR). They achieved a Jc of 2900 A/mm2 at 12 T, with reasonable yields and piece lengths [5]. This wire was tested in several dipole magnets built at LBNL, and found to give satisfactory results. These include the dipole RD-3B, which achieved a record field of 14.5 T at 4.2 K [7]. However, the MJR process suffers from some drawbacks, in particular the cost of the Nb expanded metal raw material and some limitations in scale-up options. Recently, OST initiated work on an alternate internal Sn approach, referred to as the Restack Rod Process (RRP). The Nb raw material is in the form of rods, which are less expensive and easier to procure than the expanded metal sheets. Initial results for the RRP process were reported in [5]. Although current testing limitations prevented measurements at 12 T, results extrapolated from higher fields indicated that a Jc value close to 3000 A/mm^2. Further testing at LBNL, with improved sample mounting and testing procedures [8], indicate that the Jc is above 3000 A/mm2 at 12 T (FIG 2). Since this is a new record

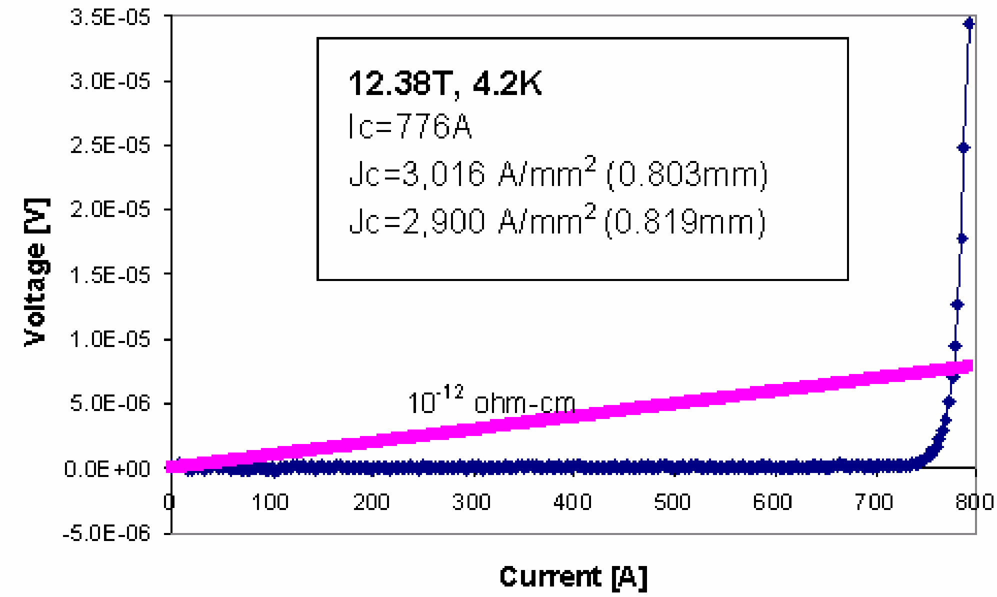

FIGURE 2. Short sample measurement of RRP process wire, showing a Jc value of 3016 A/mm2 at a field (background + self field) of 12.38 T. The V vs. I curve is stable to a level of 60 microVolts/m.

Jc, and a confirmation of reaching the program target Jc, we have made several corrections to the raw data. First, a self-field correction was made, as indicated in FIG 2. Second, a correction for the increased wire diameter after reaction was made, also indicated in FIG 2. This result has been reproduced on several additional billets fabricated at OST [9]. Manufacturability of this new conductor has been established, and OST has delivered over 100 kg of wire for use in the HEP magnet program. Cable has been made and used to wind the coils for magnet HD-1, which will be tested at LBNL in Oct 2003 [10]. As a result of these promising results, OST has announced that this will be their primary manufacturing method for future Nb_3Sn wire orders, and another 100 kg has been ordered for the HEP magnet development program.

EFFECTIVE FILAMENT SIZE OPTIMIZATION

Once the critical current objective of the Conductor Development Program was met, the focus of the programs at OKAS and OST was turned to the issue of reducing the effective filament size, while maintaining good Jc in their processes. Since the filaments coalesce during reaction in these high LAR composites, the effective filament size is determined by the size of the subelement, rather than by the size of the individual Nb filaments. Thus, for the record current density wire discussed above (OST billet 6555), the effective filament size as determined by magnetization measurements is between 90 and 100 microns, for a 54 subelement restack. The number of subelements required to yield a given effective filament size is plotted in FIG 3. Although it is possible to reach the program target size of 40 microns with a simple restack approach, it requires over 200 subelements. The difficulty of producing long wire lengths increases as the number of subelements increases. One factor is the increase in surface area than must be bonded during the cold drawing process. If the alternative hot extruded rod process (see below) is used, there is a limit on the number subelements that is imposed by the minimum size of

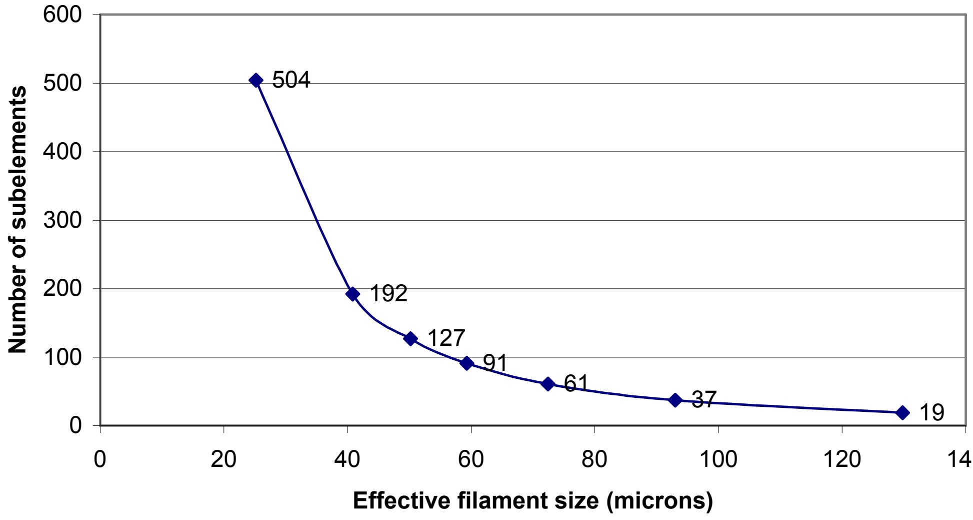

FIGURE 3. Number of subelements required to produce the effective filament size indicated by the abscissa.

Sn rod that can be loaded after extrusion. Another factor is the increased susceptibility to foreign inclusions that may be introduced during the subelement drawing, cleaning, and assembling steps. These issues are being addressed in the OST and OKAS programs, and also at Supergenics, Inc. in a SBIR-funded program [11].

A new method for reducing the effective filament size of the subelements has been proposed by Zeitlin [12]. The method consists of dividing the subelement by means of radial fins of a material that prevents the coalesence of Nb_3Sn. This approach follows earlier work [13], which attempted to subdivide the Nb_3Sn region by replacing Nb filaments with Cu in a radial pattern. However, it was found that, for a reasonable Cu spacing, the filaments still move together and coalesce in the reaction step. Another undesirable effect of this radial Cu channel is that it provides a fast diffusion path of the Sn to the diffusion barrier and in some instances the barrier failed at the ends of the Cu channels due to stress corrosion cracking [6]. A proof of principle test of this new approach using a Ta-40 wt % Nb alloy sheet for the fins has been reported [14]. Following this promising result, OKAS is investigating the possibility of barrier fins in their billet design. A cross section of a billet made by OKAS containing three fins of Ta-40 wt % Nb alloy is shown in FIG 4. Calculations indicate that each fin element occupies only 0.4 % of the subelement cross section; thus, the overall reduction in Jc due to adding fins should be about 0.4 %, multiplied by the number of fins. The Ta-40 wt % Nb alloy was chosen for good ductility, and because earlier studies indicated that the resulting Ta-Nb-Sn compound was a poor superconductor and slow to form relative to Nb_3Sn [15]. Careful metallographic examination by Lee and coworkers [4] show that an intermetallic

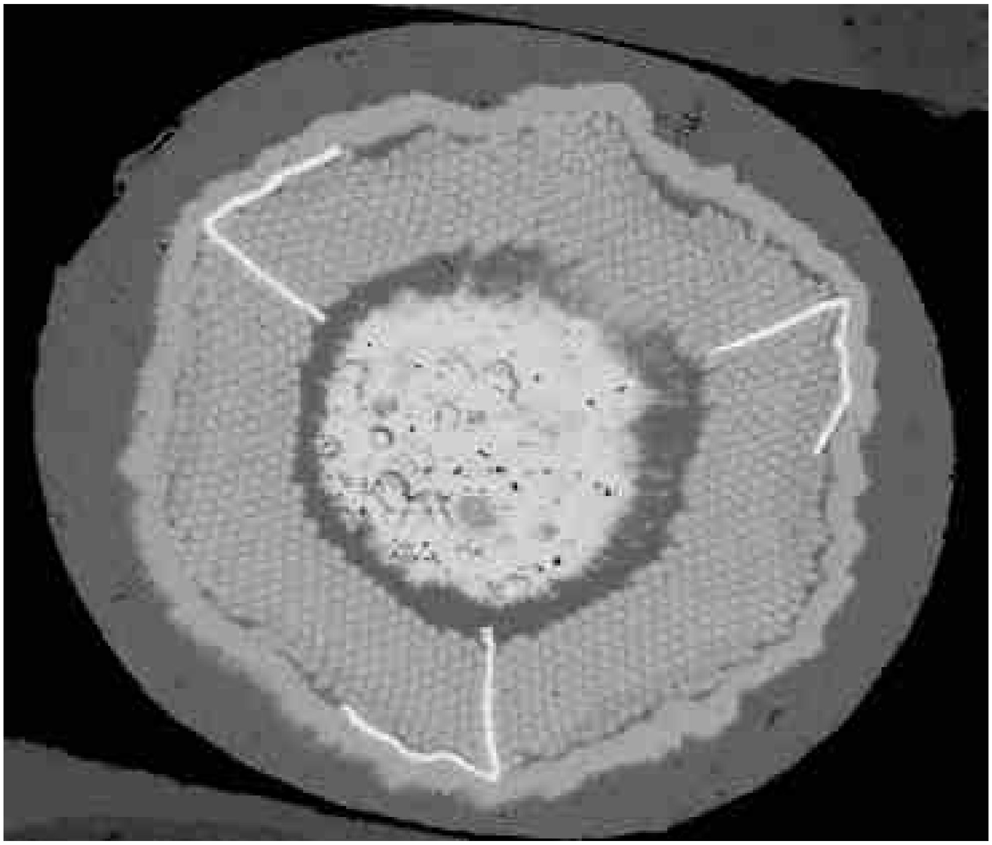

FIGURE 4. Cross section of a wire at 0.25 mm diameter, showing three fins of Ta-40 wt % Nb alloy, added to reduce the effective filament size.

compound does form, especially at the end of the fin which is near the Sn core. However, magneto-optical examination by the same group indicates that flux penetration into the core of the subelement does occur, and thus the fins appear to be non-superconducting (at least under the field and temperature conditions of the magnetooptical experiment). An alternative fin material is pure Ta, which shows much less reaction with the Sn than the Ta-40 wt % Nb alloy. However, it must be demonstrated that the ductility of the pure Ta is satisfactory for use as a fin material. Experiments are underway at OST to investigate this option.

Another method for achieving a 40 micron effective filament size is the powder in tube (PIT) approach. This approach is being pursued by Shape Metal Innovation [16], and in addition, some exploratory work on PIT is being done at Supercon, Inc, supported by the SBIR program [17]. However, present processing and raw materials costs for PIT are a factor of 3 higher than that for either internal tin or MJR process Nb_3Sn. An important part of the Conductor Development Program is the demonstration of the potential for process scaleup and cost reduction, as discussed in the next section.

SCALEUP AND COST REDUCTION

The cost/performance measure for Nb_3Sn wire procured for Fusion and HEP projects has shown a steady improvement over the past 15 years, as shown in FIG 5. However, most of that improvement has been due to the dramatic increase in Jc performance, while the cost per kilogram has decreased slowly. As shown in [18], significant reductions in price can be realized with increased billet size, which reduces the labor cost factor. However, the increased billet size reduces the labor cost only if the resulting rod and wire can be drawn without breakage. Thus, a key factor in selecting a process for scaleup must by the capability to achieve long wire lengths. Shorter than expected piece lengths has been a continuing issue for all companies pursuing the cold restack drawing approach for Nb_3Sn.

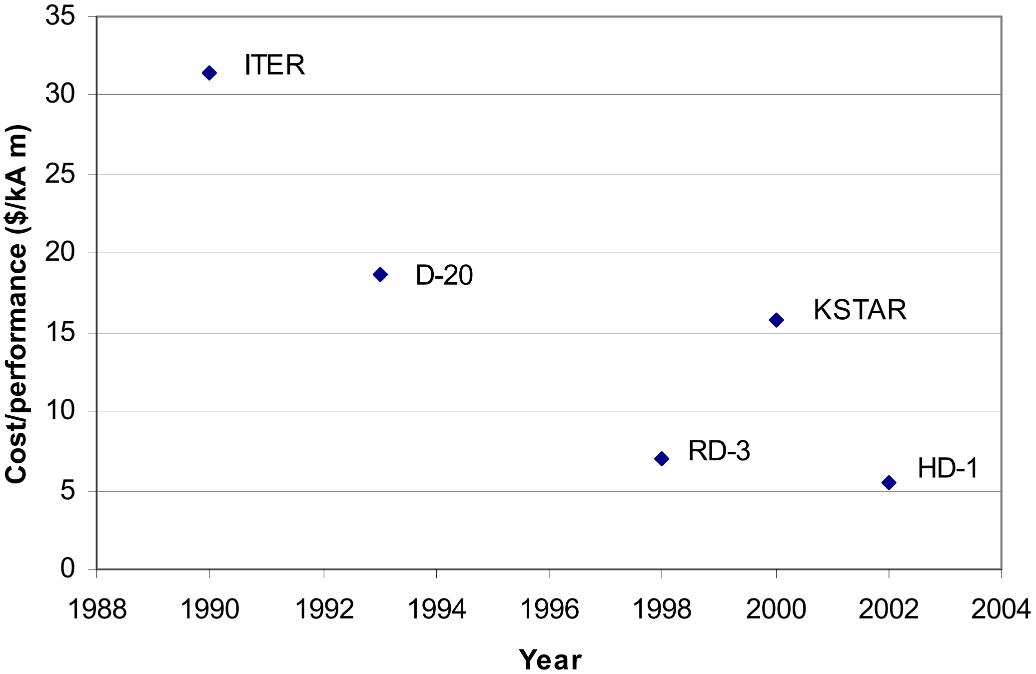

FIGURE 5. Cost/performance improvements of Nb_3Sn used in the projects listed, showing steady improvements for both fusion (ITER, KSTAR) and high energy physics magnets (D-20, RD-3, and HD-1).

The Cu surfaces must be cleaned, etched, and then quickly loaded into the outer Cu tubes for drawing. Few wire fabrication facilities at present have adequate environmental control to insure that the conditions (especially humidity) are maintained constant. Also, scaleup is a challenge, since this means dealing with very long tanks for cleaning and etching the rods, etc. However, OKAS has shown good piece lengths for KSTAR using this approach, and will attempt to scale up the billet and restack rod sizes for their internal tin, cold drawing, process.

An alternative process identified by OST for scaleup is the Hot Extruded Rod (HER) process [5]. An economic analysis of this HER process was prepared as part of the first year contract report. The report concludes that this process should enable the fabrication of Nb_3Sn wire at a cost/performance target of $1.50/kA m at 12 T. The HER process will use the same equipment and a fabrication procedure analogous to that used for production of NbTi. In the first year of this program, OST has demonstrated proof of principle for the new hot extruded rod process. At present, their primary goal has been to optimize wire critical current performance, and the status is presented in [9]. The next step will be to increase the number of subelements in order to meet the effective filament size goal of 40 microns.

The production scale-up efforts should produce a significant quantity of wire that will be available for the magnet fabrication programs at the HEP laboratories. This is an important area of synergism between the conductor development program and the magnet development work. The fabrication approach (or approaches) that has demonstrated the best combination of performance and potential for cost reduction will be selected for scale-up. The final verification of the conductor must be its performance in actual magnets. The success of these two R&D programs (conductor and magnet) will provide the experience and confidence necessary for proceeding with a LHC luminosity upgrade using Nb_3Sn. A future energy upgrade will most likely use Nb_3Sn as well. However, since the parameters of the energy upgrade have not yet been chosen, the possibility of using a higher field conductor such as Bi-2212 will be considered. At present, the field crossover beyond which Bi-2212 may be more attractive is about 16 T.(FIG 6).

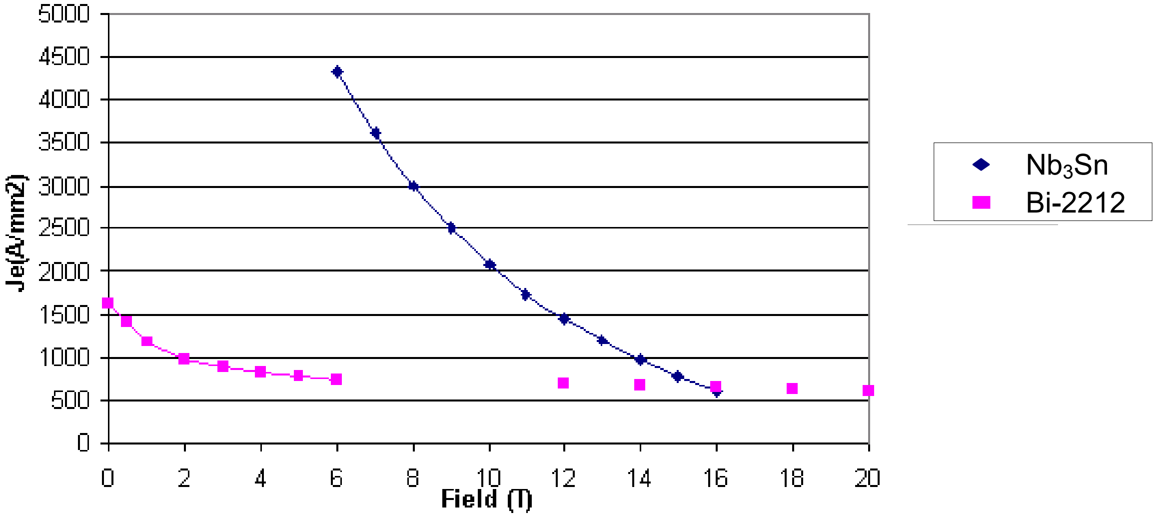

FIGURE 6. Engineering current density vs field for Nb_3Sn and Bi-2212 wires, showing a crossover at a field of 16 T, 4.2 K.

SUMMARY

The first-priority goal of the program, achieving an increase in Jc from 2000 to 3000 A/mm^2 at 12 T, was reached in Nov. 2002 by one of the industrial subcontractors, Oxford Superconducting Technologies. The emphasis has now turned to the next goal--reducing the effective filament size to 40 microns, without sacrificing the gains in Jc. Proof of principle experiments have shown that this goal is achievable. Using the new knowledge gained from this research as a base, the program is moving into a fabrication scale-up phase where the performance and cost-effectiveness can be demonstrated on production-size quantities. These production quantities will be available for use in the magnet development efforts. The quantitative information gained in this program will then be used as part of the ongoing efforts aimed at providing upgrades to existing accelerators such as LHC, as well as cost-effective magnet designs for a next generation HEP collider.

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