ACCELERATOR MAGNET FABRICATION AS RELATED TO STRAND AND CABLE PROPERTIES

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Abstract

The requirements for new accelerator applications are increasing the demand for high performance magnets. Progress in the development of superconducting materials, particularly Nb_3Sn, has encouraged increased activity in several R&D programs world-wide. New techniques for design, analysis and fabrication of magnets using these materials are being developed. This report highlights some of the advantages and challenges of Nb_3Sn for accelerator magnet design and fabrication.

1. INTRODUCTION

Achieving fields above 10 T requires the use of conductor with performance parameters that exceed the limits of NbTi. Possibilities include High Temperature Superconductors (HTS) or the A15 compounds. High Temperature Superconductors have been under intensive study and development for some time. The properties of these materials make them interesting for applications requiring high fields and/or high heat loads, such as interaction region quadrupoles. However, their mechanical properties and cost are still major drawbacks. Until significant progress is made, these materials will probably only be considered for use in cases where performance is essential to meet operational requirements. And even then, mechanical issues such as non-recoverable strain degradation have not been thoroughly studied. One possibility that has some near-term potential is the recently discovered MgB_2 superconductor. It could be considered for low-field, high heat load applications.

The most practical and available A15 material is Nb_3Sn. In a practical geometry, magnets based on Nb_3Sn technology should be able to exceed 14 – 16 T at 4.2 K. Although this material has been around for 40 years, its use and development has been hampered due to its intrinsic brittleness and strain sensitivity. The challenge for magnet designers lies in incorporating it into a realistic magnet where it is subjected to stresses that could exceed 150 MPa. The future need for higher fields has prompted an increased development effort that has recently resulted in significant progress.

2. US/HEP CONDUCTOR DEVELOPMENT PROGRAM

Funding for a new HEP Conductor Development Program was provided in January, 2000 [1]. This program is focused on industrial development, and is administered by LBNL. The purpose of this work is to develop a new, cost-effective superconductor for use in future accelerator magnets, with the following target specifications:

J_c (non-copper, 12T, 4.2K): 3,000 A/mm^2

$J_{engineering}$(12T): greater than 1,000 A/mm^2

Effective filament size: as small as feasible, while compatible with the J_c and cost-effectiveness requirements

Process unit size: scaleable to greater than 100 kg and average piece lengths greater than 10,000 m in wire diameters of 0.3 mm to 1.0 mm

Wire cost: less than $US1.50/kA-m (12T, 4.2K)

Short heat treatment times: maximum 400 hours; target 50 hours for wind and react magnets

This is envisioned as a multi-year program with two phases that may partially overlap. The first phase (2-3 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 evolve towards a fabrication scale-up phase where the performance and cost-effectiveness can be demonstrated on production-size quantities. This program has been underway for about 3 years, and has achieved considerable technical success. One of the key parameters, critical current density, has been increased from the 2000 A/mm^2 level to over 3000 A/mm^2 at 12 T. A comparison of conductor performance properties is shown in Fig. 1.

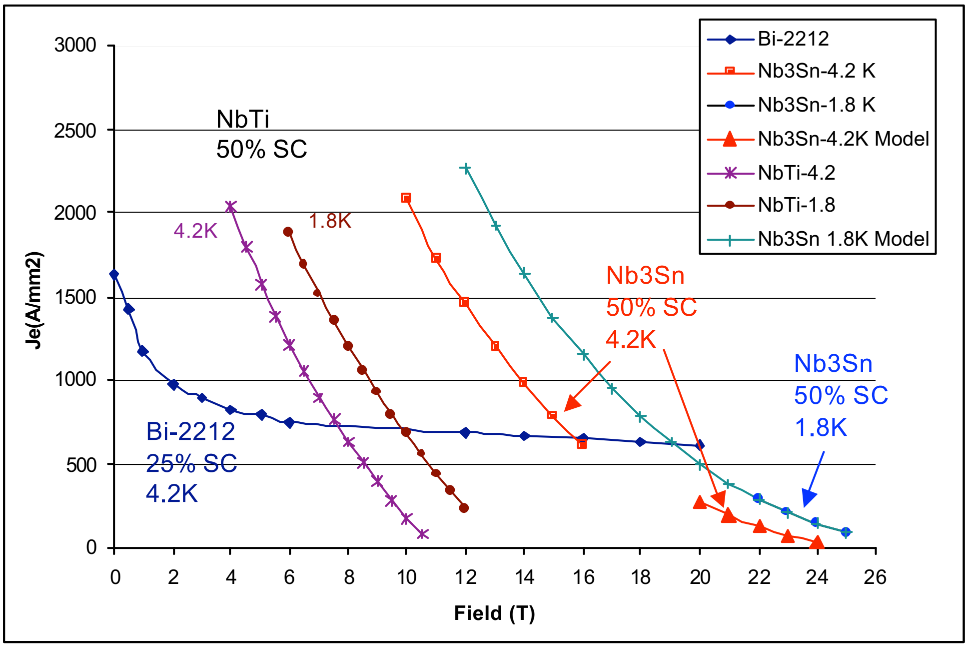

Fig. 1. Conductor Performance Comparison

Nb$_3$Sn has some excellent properties; high current density at high field and a much higher thermal margin than NbTi. This potential has been demonstrated up to 16 T so far [2]. In achieving this field and associated stress level, many mechanical issues had to be overcome. New designs and fabrication techniques have been developed taking into account the intrinsic properties of the strand and cable both before and after reaction. Nb$_3$Sn has a higher sensitivity to cabling degradation and the effects resulting from the degradation have significant influence on magnet performance. Developing the superconducting compound is a diffusion process and leads to issues not found in NbTi. Barriers, designed to prevent diffusion of tin into the copper, which can result in a low residual resistance ratio (RRR), are extremely fragile. In addition, barrier breakage can lead to coalescing of the filaments and a large effective filament diameter. These difficulties are enhanced by the desire to make the barriers as thin as possible, particularly in the high performance strands.

Along with excellent performance properties, Nb$_3$Sn is also known for brittleness and strain sensitivity. The large temperature range (1000 K – 4 K) and high field applications which impose large stresses, calls for careful analysis, appropriate design choices and new fabrication techniques. There are several implications for long magnets that will need to be studied as part of the overall development plan for this technology.

On the positive side, it has been demonstrated in LBNL's HD-1 block magnet [2], that stresses up to 150 MPa do not degrade magnet performance. With the information available at this time it seems prudent to avoid situations of non-uniform compressive stress and to minimize tension as much as possible even though a reacted strand is in axial compression and some current density might be regained by placing the strand in tension. Cables and coils are complex structures and it is not clear if there is any positive effect on overall performance. An example of a design choice is, noting that strain degradation increases with magnetic field, to separate the high field and high stress regions of the magnet. One still needs to be wary of high stress during assembly and cooldown though. One should also be aware that strain sensitivity depends on the strand substructure. Each strand geometry should be evaluated individually. While recent results regarding stress limits are encouraging, more work needs to be done to determine a reasonable working range for magnets.

Field quality is just starting to be addressed. The thicker insulation currently used for coil fabrication and the large thermally-induced movements, make coil size and uniformity control more difficult. Though there is still much to be gained by reducing filament size, it is clear that Nb_3Sn will still suffer from large intrinsic magnetization affects. Fermilab has made progress on both fronts in their cos-theta dipole program [3, 4]. A series of magnets has shown that field qualty is more reproducible than originally expected and passive shield has been used to significantly reduce magnetization.

3. FABRICATION METHODS

Nb_3Sn requires heat treatment at 650^0 C for 60 - 100 hours, followed by epoxy impregnation to support the brittle cable and provide insulation. And stress should be limited to between 150 and possibly up to 200 MPa during all stages of fabrication and operation. There are two fabrication methods for Nb_3Sn coils; wind and react and react and wind. These two processes differ up to the point just prior to impregnation.

3.1 Wind and React

Cable considerations

The more extreme case, and unfortunately more favorable for magnet design, is to use a large cable with a small bend radius. As mentioned above, Nb_3Sn strands are more susceptible to degradation and the consequences are more severe. The trade-off between degradation and mechanical stability is the primary consideration in determining the cable dimensions. A large cable with small bending radius requires increasing the winding tension, which in turn requires a more mechanically stable cable, i.e. increased compaction and a greater probability of degradation. An example of such a cable is that used for HD-1 [5]. Parameters and winding conditions for this cable are shown in Table 1.

Table 1. HD-1 Cable parameters and winding conditions

Strand diameter	0.8 mm
Number of strands	36
Cable dimensions	1.36 x 15.7 mm (rectangular)
Winding tension Bend radius	18 kg 10 mm
Insulation	S-2 glass (0.107 mm @ 14 MPa)

The cable was initially rolled to 1.41 mm, annealed and re-rolled to the final thickness of 1.36 mm. The annealing serves two purposes; the cable is more malleable, reducing filament distortion and damage and it also "pre-shrinks" the cable, eliminating a large fraction of the length change during reaction. Figure 2 shows a dilatometry measurement made on a strand and the reduction in length change due to a pre-anneal [6].

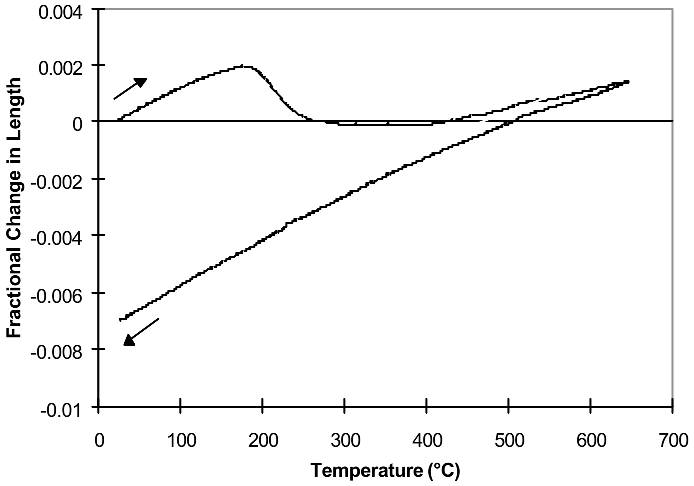

Fig. 2 Length change in Nb_3Sn strand during reaction process

The cable cross section is examined microscopically for barrier cracking and filament distortion which is considered unacceptable. Figure 3 shows an edge of the HD-1 cable.

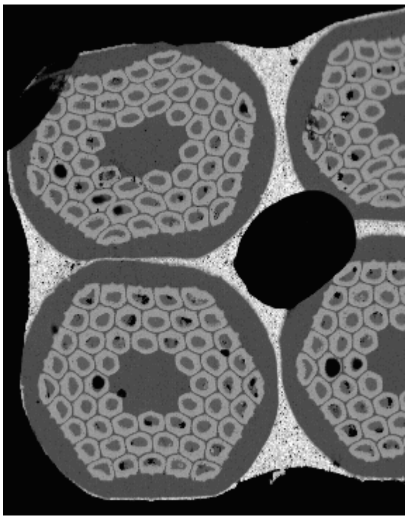

Fig. 3 HD-1 cable cross section

Design and evaluation of Nb_3Sn cables and the relationship to magnet performance is just beginning. Future considerations should include:

Determining the deformation limits of different strands

Cables with a mixture of Cu and superconducting strands

Keystoned and rectangular cables with cores

Cable handling and winding characteristics database

Relate cable parameters to type of strand, width and thickness, core and no core to winding mechanics, i.e. popped strands, winding direction, etc.

With the considerations and minor exceptions stated above, winding the coils is the same as for NbTi. During reaction, the coil is constrained in all dimensions. A pressure of 14 MPa is applied normal to the cable face with moderate compaction in the orthogonal directions. A gap of approximately 1mm/m is used to accommodate coil shrinkage during reaction.

3.2 React and Wind

The react and wind approach is driven by concern over the potential problems in reacting long coils and as the only alternative for winding cols made with HTS, for which wind and react is not an option. The primary limitations are large bending radii, coil sizing (not being able to apply large forces to reacted conductor) and the QC challenge of handling and winding the reacted cable. There are small programs at Brookhaven and Fermilab that have shown some encouraging results [7, 8]. Brookhaven is making "10-turn" coils with Nb_3Sn and HTS and they have plans to fabricate 12 T racetrack coils next year using react and wind. After a couple of fairly successful Nb_3Sn racetrack coils, Fermilab is taking a more fundamental approach by studying the degradation and stability of strands manufactured by different processes. Cable studies look at bending-induced degradation limits, interstrand resistance and cores, and techniques to prevent sintering during reaction. They plan to assess the most promising technologies in small magnets.

4. DESIGN AND ANALYSIS

Each of the coil fabrication techniques results in an epoxy impregnated coil that must be properly constrained without exceeding stresses that could damage the coil during assembly, cooldown and operation. The LBNL design team has developed a design approach that integrates cross section design, generating the coil geometry, CAD and Finite Element Analysis (FEA). Three-dimensional analysis is standard procedure and considered necessary to control and/or limit maximum stress on the conductor. Considerable progress has been made in correlating magnet performance with the FEA models.

5. SUMMARY

Recent work on Nb_3Sn accelerator magnets has given us a point in parameter space that we are comfortable with. Continuing work will tell us how far current constraints and parameters can be expanded. Much more needs to be done to develop the technology for real HEP applications.

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