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Author

Scanlan, R.M.

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Conductor Development for High Field Dipole Magnets

R. M. Scanlan, D. R. Dieterich, and H. C. Higley, Lawrence Berkeley National Laboratory, Berkeley, CA., USA

Abstract-- Historically, improvements in dipole magnet performance have been paced by improvements in the superconductor available for use in these magnets. The critical conductor performance parameters for dipole magnets include current density, piece length, effective filament size, and cost. Each of these parameters is important for efficient, cost effective dipoles, with critical current density being perhaps the most important. Several promising magnet designs for the next hadron collider or a muon collider require fields of 12 T or higher, i.e. beyond the reach of NbTi. The conductor options include Nb₃Sn, Nb₃Al, or the high temperature superconductors. Although these conductors have the potential to provide the combination of performance and cost required, none of them have been developed sufficiently at this point to satisfy all the requirements. This paper will review the status of each class of advanced conductor and discuss the remaining problems that require solutions before these new conductors can be considered as practical. In particular, the plans for a new program to develop Nb₃Sn and Nb₃Al conductors for high energy physics applications will be presented. Also, the development of a multikiloamp Bi-2212 cable for dipole magnet applications will be reported.

I. CONDUCTOR FOR FIELDS BELOW 10 T

NbTi is the conductor of choice for accelerator magnets for fields below 10 T. This has been due to availability, cost, long piece lengths, and performance. A series of superconducting accelerators, starting with the Tevatron [1], HERA [2], and more recently, LHC [3], and RHIC [4], have relied on NbTi. In addition, the SSC planned to use NbTi, and significant advances in performance as well as conductor reliability and cost resulted from the SSC R&D program [5]. For example, the conductor J_c specification (5.0 T, 4.2 K) was increased from 1800 A/mm² for the Tevatron to 2750 A/mm² for the SSC. The best values for fine filament NbTi actually exceeded the SSC specification, with values of large size billets exceeding 3000 A/mm² and R&D efforts producing values over 3700 A/mm² [6].

Near the end of the SSC R&D phase (1986), several groups focused on pushing NbTi to new limits via the artificial

pinning center (APC) approach. Rather than rely on a cold work and precipitation process to produce alpha-Ti phase precipitates which act as flux pinning centers, the APC approach seeks to introduce a fine dispersion of second phase particles by mechanical processing. This research showed great promise, especially for increasing the J_c values at low and moderate fields. Samples prepared at the Univ. of Wisconsin showed J_c values exceeding 5000 A/mm² at 5 T [7]. Commercial attempts also showed early promise. Supercon, Inc. provided APC wire for two magnets at LBNL--a solenoid [8] which reached 8.6 T and a dipole [9] which reached 9.0 T at 1.8 K. Supercon also delivered some APC NbTi conductor to a magnet manufacturer for evaluation in MRI magnets [10]. However, at this time, the early promise of APC NbTi has not been realized in any large-scale application. This is partly a question of timing--the LHC project was into production and the SSC project was cancelled before the APC material could be fully commercialized. Also, some of the cost advantages of the APC approach have not been realized due to the high cost of some components, such as thin Nb sheet. Although some groups in Japan remain interested in APC NbTi for low field AC applications, the accelerator magnet frontier has moved on to higher fields and interest in NbTi in general is not high.

A similar scenario holds for the ternary alloy NbTiTa. Basic studies [11] and some early commercialization efforts showed promise. An R&D program was initiated at Fermi National Accelerator Laboratory to develop the ternary alloy for the Tevatron interaction quadrupoles, but the effort was stopped when it was shown that the binary NbTi conductor could produce the required field gradient. Interest in the ternary was revived at FNAL at the beginning of the LHC high gradient quadrupole program when the requirement was for a very high gradient (above 250 T/m) and high operating field. However, this requirement has been relaxed to about 220 T/m--a value that can be reached by the binary NbTi alloy. Also, the optimization of the ternary alloy for high field performance was hampered by problems in getting ternary alloy material. At present, no significant R&D aimed at optimizing NbTiTa for High Energy Physics applications is continuing.

II. CONDUCTOR FOR FIELDS ABOVE 10 T

For fields above 10 T, a new approach to magnet design and fabrication is required, since all the materials available--Nb₃Sn, Nb₃Al, Bi-2212, Bi-2223, and YBCO, are brittle

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compounds and thus require special handling and processing. Two magnet fabrication alternatives are being considered. In the first, "wind and react", the coils are wound when the conductor components are still ductile, i.e. before the reaction step where the brittle superconducting phases are formed. This method has been used for a number of dipole magnets [12,13,14]. However, it requires the development of special insulation and coil structural components that can withstand the high reaction temperatures associated with the formation of the superconducting phases. For Nb_3Sn , with a reaction temperature in the range of 650-700 C, this requirement can be met with fiberglass insulation and structural materials such as stainless steel. However, Nb_3Al may require a somewhat higher reaction temperature for optimum properties, e.g. 800 C, and a different insulation is required. Moreover, the Bi-2212 and 2223 options require even higher reaction temperatures and in addition must be reacted in an oxygen atmosphere, which puts more restrictions on both insulation and structural choices.

In light of these difficulties, new magnet designs are being developed which are more "conductor friendly" than the designs developed using NbTi conductors. In particular, a new design known as the "common coil" [15] has large diameter ends and may be amenable to a different fabrication approach. In this approach, called "react and wind", the conductor is reacted after conductor fabrication, i.e. wire drawing and cabling, is complete, but before coil winding. The reacted conductor is then wound into the magnet coils, with careful handling and maintaining adequate bending diameters to prevent conductor damage. The react and wind technique has been used to construct small solenoids for NMR applications, where small diameter wires can be used, and also for large fusion magnet coils, where the bending diameters are large and the conductors are robust. However, accelerator magnets have posed a more challenging problem, since the large stored energy precludes the use of small wires, while at the same time, the small magnet apertures, typically 30-50 mm, require the conductors to undergo a tight bend at the ends of the magnets. In the common coil approach, one coil is used to produce the field in two apertures, which can be widely spaced, e.g. 200 mm apart (Fig. 1). This means that the bending diameter at the magnet end is 200 mm rather than 20-30 mm of the traditional "cosine theta" design. A proof of principal test of this design has been completed successfully using a wind and react approach, and a high field version is under construction at LBNL [15,16]. Also, common coil react and wind magnets are being designed by Brookhaven National Laboratory [17] and by a collaboration involving FNAL and LBNL [18].

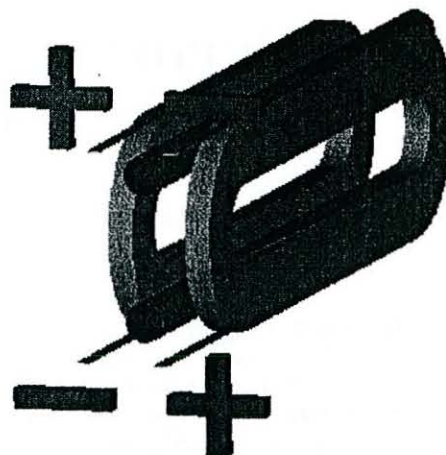


Fig. 1 Schematic of Common Coil Design Showing Large Bending Diameter at the Magnet Ends

A. Nb_3Sn -present status

Of the potential conductors for high field dipole applications, Nb_3Sn is in the most advanced state of development. This is due largely to the investment made by the magnetic confinement fusion programs over the past 20 years, culminating with the ITER (International Thermonuclear Test Reactor) model coil which has just been completed. The ITER program, together with a small but growing NMR magnet business, has provided some financial incentive for the conductor manufacturers. However, with the completion of the ITER program, it has become necessary for the High Energy Physics program to provide increased support for the Nb_3Sn industrial programs. Also, the technical requirements for accelerator magnets are substantially different from the fusion requirements, as shown in Table 1. Here, the ITER specification is listed and compared with key parameters of the two most recent LBNL accelerator magnets--D20 and RD3. Note that the conductors for accelerator magnet application have a very high J_c requirement--over twice that required for the ITER conductor. Note also that the accelerator magnet conductors do not have an ac loss specification at this time. The loss for one wire has been measured [19] and is shown for comparison.

Table 1. Comparison of Critical Parameters for ITER and Accelerator Magnet Conductors

Type	Wire diam. (mm)	Cu volume (%)	J_c (12 T, 4.2K) (A/mm^2)	AC Losses ($mJ/cc,+3T$)
ITER HP1	0.8	60	> 700	< 600
D20 Inner TWCA	0.75	50	1400	----
IGC	0.75	30	877	----
D20 Outer TWCA	0.48	52	1550	----
RD3 Inner	0.8	51	1981	----
RD3 Outer	0.8	60	2190	5000

Three U.S. Laboratories are developing high field Nb₃Sn magnets for accelerator applications, and are purchasing conductor with specifications similar to those listed for RD3. Two manufacturers, Intermagnetics General Corp (IGC) and Oxford Superconducting Technology (OST), are providing conductor for these programs. Most recently, OST has delivered conductor for RD3 with the properties listed in Table 1. This represents the present "state of the art". Although the J_c improvements compared with ITER and also D20 are impressive, most of the improvement is a result of increasing the volume fraction of Nb₃Sn in the conductor cross section with little improvement in the intrinsic J_c of the Nb₃Sn. Recent R&D results on thin film samples indicate that significant intrinsic improvements in J_c are possible [20]. A problem that is associated with attaining higher J_c by increasing the volume fraction of Nb₃Sn is that the tendency of filaments to sinter together during heat treatment is increased, so that magnetization effects become large. The micrograph for the wire used in RD3 is shown in Fig 2 and the magnetization results are shown in Fig. 3. This micrograph shows the reason for the large losses--with this high volume fraction of Nb and Sn in the multifilamentary bundle, the individual filaments are fused together so that the effective filament size is the subelement size, e.g. about 70 micron in this case. This is one of the issues that will be addressed in the Nb₃Sn development program described below. Although this does not have a strong effect on the immediate R&D program, it can be a problem for any proposed accelerator due to the field distortion that results at injection. If the intrinsic Nb₃Sn J_c can be increased, the filaments can be spaced apart so that they do not grow together, and magnetization effects will be diminished.

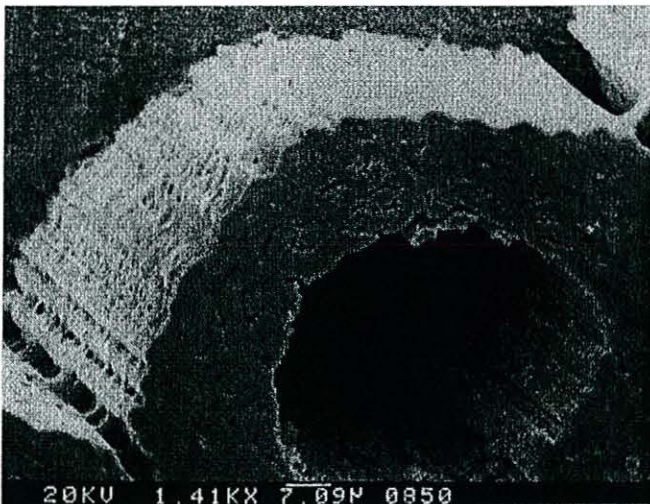


Fig. 2 Nb₃Sn subelement from conductor supplied by OST for RD3. The matrix has been removed by etching to reveal Nb₃Sn filaments which have fused together.

In addition to the magnetization problem, the Nb₃Sn state of the art represented by the RD3 conductor presents two other problems. The first is piece length; the average piece length is 565 m for the inner grade and 357 m for the outer grade conductor. This short piece length reduces the

effective yield of cable, and also increases manufacturing costs for the strands due to the increased labor required. In addition, the high J_c Nb₃Sn is being made in small process batches, e.g. 25 kg, at present. This results in an unrealistically high cost for the Nb₃Sn conductor. These factors are an inconvenience for the R&D programs at present, and will be a serious concern for any large scale accelerator project.

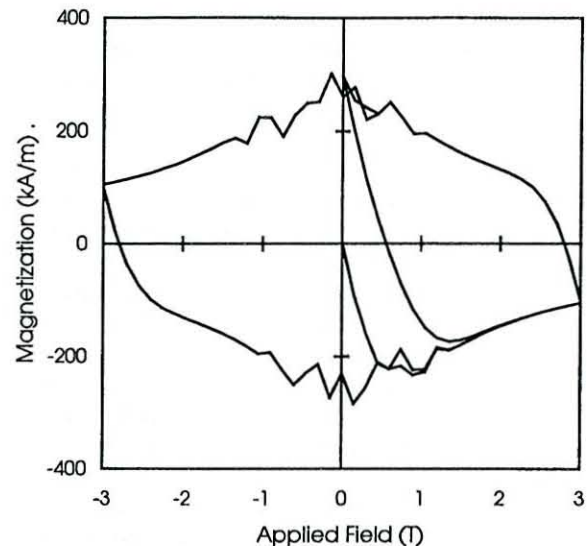


Fig. 3. Magnetization curve for the conductor shown in Fig.2. Note the presence of flux jump behavior at low applied fields. [18]

B. Nb₃Sn-new development program

This situation with Nb₃Sn is prompting work in two areas--a vigorous new conductor development program to improve Nb₃Sn, and a study of the alternatives to Nb₃Sn. The goal of the conductor development program is to bring the cost-effectiveness of Nb₃Sn, as measured by \$/kA-m, to a level comparable to that of NbTi. For reference, the cost of NbTi wire for the SSC was \$1.05/kA-m for inner grade wire at 7 T. In order to meet this goal, the cost of Nb₃Sn strand must be reduced, and the J_c at the magnet operating field must be improved. The critical current goal is 3000 A/mm² at 12 T, which is to be compared with the OST value for the RD3 conductor of 2200 A/mm². The R&D results [20] show that this improvement would occur, for example, if the Nb₃Sn grain size can be reduced from a typical value of 40 nm to 30 nm. The manufacturing challenge is to obtain this improvement while at the same time not affecting the other important properties or the manufacturing costs. The cost goal is to reduce the cost of Nb₃Sn strand from the present small batch R&D price of \$700/kg to a large process unit, high volume price of \$200/kg. A cost analysis based on the raw materials prices and process units comparable to present NbTi manufacturing practice indicate that this cost improvement is reasonable as well.

The new R&D program will have two phases--the first phase will last approximately 3 years and will focus on

intrinsic property improvements and proof of principal experiments on process improvements. Intrinsic property improvements of most interest are J_c , magnetization, and strain effects. Proof of principal process improvements will focus on identifying fabrication processes that will result in longer piece lengths, larger billet sizes, and more cost effective processing. One important guideline for selecting proposals for this phase is that the work should not duplicate the ongoing work being funded by the Small Business Innovative Research (SBIR) program. One of the aims of this program is to supplement the SBIR work by funding projects which cannot qualify for SBIR funds, for example, companies that cannot qualify for SBIR funding due to their size. Another guideline for selecting proposals is that the approaches proposed should have the potential of significant improvements in properties or cost reduction, and not be merely incremental improvements on the established fabrication processes. An example of the type of innovation that can have significant cost improvements is the removal of Cu from the Nb_3Sn strand fabrication process. In the proposed process, basic Nb_3Sn strand is fabricated with only a minimum amount of Cu (some proposals set this minimum at zero). The Cu necessary for protection will then be added in a cabling step as the final process step, rather than adding the Cu early in the fabrication process and then carrying this Cu through the remaining process steps, as is now the case. This new approach has two cost benefits. First, the labor costs are directly related to the volume of material being processed, whether it is superconductor or Cu. Second, the engineering design, and quality control costs are greatly reduced when the strand manufacturer is fabricating only one product, i.e., low-Cu strand. However, several new conditions introduced with this processing approach must be assessed. First, the costs of adding the Cu in a cabling process must be compared with the cost savings generated by this new wire fabrication approach. Second, the effectiveness of the Cu for protection in this new configuration must be evaluated. Current sharing between superconductor and Cu strands must be uniform and the current transfer lengths must be reasonable in order for this new conductor to function properly in a magnet. These issues will be addressed in the proposed conductor development program.

C. Nb_3Al

For very high field dipoles where the transverse stress may exceed 150 MPa, the magnet designer has two choices. First, techniques for limiting the stress on the conductor, called stress management [21], can be employed, albeit at the expense of overall current density and magnet efficiency. Second, Nb_3Al can be substituted for Nb_3Sn . Although Nb_3Al is a brittle intermetallic compound of the same structure type as Nb_3Sn , it has one major advantage: the dependence of the critical current on strain is much less than for Nb_3Sn [22]. For example, at 12 T, after an intrinsic strain of 0.3% has been applied, the critical current of Nb_3Sn decreases to only 60% of its original value, while

Nb_3Al retains 95% of its original critical current under the same conditions. However, at present, the Nb_3Al that is available in long lengths has a J_c (12T, 4.2K) of only 600 A/mm², and thus is not competitive with Nb_3Sn . A new process for fabricating Nb_3Al , called the "rapid quench" process, is under development. However, this process represents significant process control and scale-up challenges. The wires must be heated to near the melting point e.g. 1900 C and then rapidly quenched to retain a bcc phase that has limited ductility. Then, high conductivity Cu must be added for protection and the Nb_3Al wires must be cabled to produce a high current conductor. Finally, the cable must be insulated and wound into a coil, followed by reaction at 750-800 C to produce the superconducting A15 phase, assuming a wind and react process is followed. At present, only 50 m lengths of wire have been produced using this technique, although vigorous programs are underway in Japan [22] and the U.S. [23], to produce long, continuous lengths by this process.

D. Bi-2223 and 2212

Three HEP magnet development groups are investigating the possible application of HTS conductors to high field dipole magnets. LBNL [24], together with industrial collaborators at Intermagnetics General Corp., Oxford Superconducting Technology, and Showa Electric Wire and Cable, are developing a multikiloamp Rutherford-type cable analogous to the NbTi and Nb_3Sn cables used at present. TAMU [25] is developing an armored cable of Bi-2212 strands that can withstand high transverse stresses. BNL [17] is using reacted Bi-2212 and Bi-2223 tape conductors to wind racetrack coils. Although these projects are small and just getting underway, some early results are available in the references cited above.

The goal of the BNL program is to utilize the form of HTS conductor that is most readily available, i.e. thin tapes, to wind racetrack coils. Since the common coil geometry is most amenable to the tape geometry, the BNL program is focusing on this type of magnet. A major problem is magnet protection in this case where the individual tapes at present have an critical current limitation of 100-200 A in fields of 12-15 T. This presents a significant challenge for magnet protection due to the high coil inductance that results when low current conductors are used. Possible solutions to this problem include using multiple layers of tapes in parallel or increasing the current density for the tapes. Ultimately, the BNL program hopes to acquire YBCO tapes in long lengths and with the extremely high current densities demonstrated in short length samples.

Significant progress has been made in producing Rutherford-type cables for accelerator dipole applications. As shown in Fig 4, several types of Rutherford-type cables have been produced. Initially, cables were made with metal cores, since the early wires had limited ductility and the core was necessary to prevent wire breakage at the edges of the cables. As the wire ductility improved, cables with a

thin ceramic core and coreless cables were produced. Each type of cable

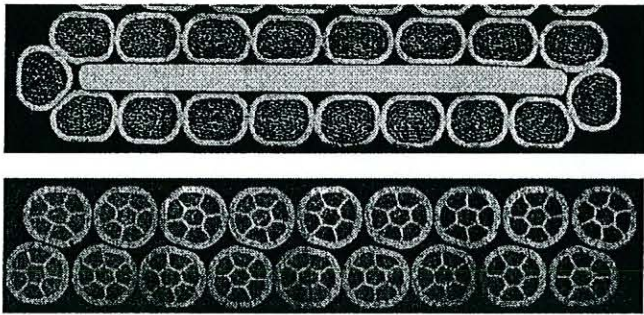


Fig. 4. Two types of Rutherford-type cables made from Bi-2212 strands, the upper using a Nichrome metal core and the lower made without a core.

has some attractive features--the metal core provides some additional strength and may be attractive, especially for react and wind type coils. The ceramic core provides high interstrand resistance and hence low ac losses without the space penalty of the metal core. The coreless cable provides the highest overall current density where ac losses or added strength are not important issues. Progress in attaining high I_c in cables is shown in Fig. 5. The improvement in cable 614A compared with cable 614 resulted from reduced contamination when a ceramic wrap was applied over the Nichrome core. The improvement in cable 685 represents improved wire performance.

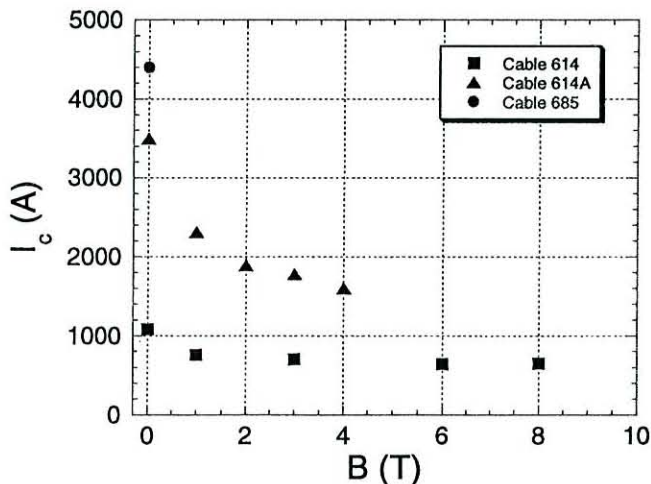


Fig. 5. Critical current vs. field for Rutherford cables. The changes which produced the improved performance are described in the text.

One of the concerns with HTS conductors for application to accelerator magnets is the potential I_c degradation due to the transverse loads that result from the Lorentz forces on the coils. Measurements are in progress to determine the effects of transverse stress on the Rutherford-type cables described above [26]. In addition, this concern is being addressed in the TAMU program with the development of an "armored cable" conductor. Bi-2212 strands are used to form a cable around a central tube (which acts as a spring), and the cable is then inserted into a protective tube. The

combination of the outer structural tube and the inner spring tube prevents the Bi-2212 strands from being subjected to high transverse stresses. Progress on this approach will be presented in another paper at this conference [25].

III. SUMMARY AND CONCLUSIONS

As the focus of accelerator magnet R&D moves beyond the LHC and 10 T, the challenge is to build cost-effective magnets from a new class of superconductors. Although proof of principle demonstrations using Nb_3Sn as a prototypical brittle material have been successful, much remains to be done before the goals of a reliable and cost-effective high field dipole magnet are accomplished. The first task is to improve the intrinsic conductor performance and develop more cost effective manufacturing processes to meet the goals described in Section II. The next task is to develop new magnet designs that can best utilize the brittle superconductors. Finally, these two must be combined to yield the reliable and cost-effective magnet that is the goal of this new program.

IV. ACKNOWLEDGMENTS

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