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Superconductor and Cable R&D for High Field Accelerator Magnets at Fermilab

E. Barzi, G. Ambrosio, N. Andreev, P. Bauer, D. Chichili, M. Fratini, L. Elementi, J. Hoffman, P.J. Limon, S. Mattafirri, J.-M. Rey, R. Yamada, A.V. Zlobin

[1]*Abstract*— **This paper presents past results and future goals of the Nb_3Sn strand and cable R&D being performed within the High Field Magnet program at Fermilab. Research tools include a reaction site for Nb_3Sn, a Short Sample Test Facility, a Scanning Electron Microscope, and a 28-strand cabling machine. Strands of various designs and diameters produced with the Internal Tin, Modified Jelly Roll, and Powder-in-Tube methods, and several Rutherford-type cables were studied.**

I. INTRODUCTION

Within the High Field Magnet (HFM) project at Fermilab, cosine-theta and common coil dipole magnets for a Very Large Hadron Collider (VLHC) [1] are being developed and studied [2,3]. For a nominal field of 10-12 T and reliable operation margins, the superconductor of choice should meet the following requirements [4]: the non-Cu critical current density in the strand, J_c, should be greater than 3000 A/mm^2, the superconductor effective filament diameter, d_{eff}, smaller than 40 μm, and the residual resistivity ratio (RRR) of the Cu stabilizer at least 100.

Intermetallic compound Nb_3Sn in strand form is currently the material closest to such goals, thanks to its high J_c of 2600 A/mm^2 (the maximum yet achieved in a round strand by Oxford Superconducting Technology, OST), high critical temperature, T_{c0}, of 18 K, high upper critical field, B_{c20}, of about 25-28 T (24-26 T at 4.2 K), and commercial availability. As a comparison, the ductile superconducting alloy NbTi used in present accelerators has a T_{c0} of 9.5 K and a B_{c20} of 14 T (that reduces to 10-11 T at 4.2 K). However, the need of heat treating the Nb/Sn composite to form brittle Nb_3Sn imposes a completely different technology in magnet fabrication with respect to NbTi magnets. The wind & react approach was chosen for the cos-theta dipole, and the react & wind technique is being explored in the common coil dipole.

Fermilab strand and cable R&D program encompasses the study of Nb_3Sn strands of various designs and technologies, and Rutherford-type cables based on Nb_3Sn. At this time, the most promising technologies for Nb_3Sn appear to be Internal Tin (IT) by Intermagnetics General Corporation (IGC), Modified Jelly Roll (MJR) by OST and Powder-in-Tube (PIT) by ShapeMetal Innovation (SMI). All of them show progress towards the above requirements. Strands with diameters from 0.3 to 1 mm produced using these methods were purchased and tested. Cables of 28 to 60 strands of various diameters and structures (single strands or assemblies of sub-strands), with aspect ratios from 7 to 17, packing factors from 85 to 95%, with and without a stainless steel core were developed and studied. Optimal parameters were determined with respect to mechanical and electrical properties, including critical current degradation, react-and-wind or wind-and-react techniques, interstrand resistance, etc. This paper summarizes the results of such R&D effort at Fermilab.

II. INFRASTRUCTURE

To investigate new superconductors, a reaction site for Nb_3Sn and a Short Sample Test Facility were set up at Fermilab. These include three furnaces and a 17T/15T solenoid in a 2.2K/4.2K LHe dewar equipped with a variable temperature insert. These facilities have been in operation for the last four years with continuous reaction and testing of more than 400 samples per year. More recently, a high-resolution optical microscope and a scanning electron microscope (SEM) were installed. Strand characterization and optimization are performed by testing the critical current, I_c, the n-value and the magnetization as a function of magnetic field, B, by measuring the RRR, and by microstructural studies and chemical analyses. In addition, an experimental cabling machine with up to 28-strand capacity was purchased, installed and commissioned at Fermilab this year. This allowed further advances in strand and cable studies, which were performed in collaboration with LBNL and industry.

III. CRITICAL CURRENT DENSITY

The J_c of Nb_3Sn is controlled by a few parameters, such as the volumetric fraction of Nb_3Sn that can be packed in the non-Cu part of a strand and the flux pinning mechanism. These parameters require optimization. However, the I_c of the original virgin strand gets reduced during magnet fabrication. For the wind & react technique, both strand plastic deformation during cabling, and cable compression during magnet fabrication and operation contribute to I_c degradation. This latter factor is due to J_c sensitivity of Nb_3Sn to strain. For the react & wind method, the bending strain introduced during winding produces some additional I_c degradation.

A. *Strand design optimization*

The J_c of IT Nb_3Sn is affected by design parameters such as the Nb filament size, the number of strand subelements, and the amount of Sn and of Nb in the non-Cu section.

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All authors are with the Fermi National Accelerator Laboratory, Batavia, IL 60510 USA (telephone: 630-840-3446, e-mail: barzi@fnal.gov). J.-M. Rey was on leave from CEA Saclay, 91191 Gif sur Yvette Cedex, France.

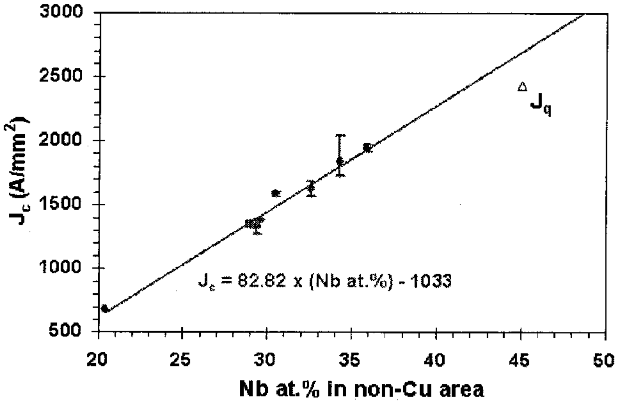

Fig. 1. J_c (12T, 4.2K) as a function of the atomic percentage of Nb in the non-Cu section. The triangle data point represents a quenching current density.

To better understand the effect of filament size during layer growth, a 575°C reaction cycle that provided only partial reaction of the Nb was applied on the same strand drawn down to different diameters [5]. The reacted Nb_3Sn layer thickness was approximately the same for all strand sizes. It was found that during layer growth, the J_c dependence on filament size at 12T had an exponential behavior for all tested strand designs. However, after completion of the reaction at 700°C, the J_c dropped for a filament size below about 1 μm.

A larger number of subelements in the strand appeared to increase heat treatment efficiency in forming the Nb_3Sn A15 phase. This could be inferred by the different times needed by 19 subelement designs with respect to 37 or 61 subelement designs to reach the peak J_c. Whereas the former required 50 to 70 h, the latter needed only 40 to 50 h [5].

The J_c of IT strands is proportional to the atomic percentage of Nb in the non-Cu area of a wire. This is clearly shown in Fig. 1, where the plotted J_c's were produced by different strands having undergone similar heat treatment cycles. At least two observations can be drawn from this plot. Reaching a J_c of 3000 A/mm^2 requires about 50at.% Nb with the present IT technology. Also, the maximum achievable intrinsic J_c can be estimated at around 5000 A/mm^2 by extrapolation to 75at.% Nb in the non-Cu area (*i.e.* the physical limit on Nb content imposed by Nb_3Sn stoichiometry). To judge whether Nb_3Sn can be improved beyond this restriction, the flux pinning mechanisms need further understanding.

B. A model for J_c

Progress towards understanding the flux pinning mechanisms in Nb_3Sn was made with a model for J_c in granular A15 superconductors [6]. It is generally agreed that NbTi and Nb_3Sn show very different scaling behavior with respect to magnetic flux density and temperature. Many authors have attributed this difference to different mechanisms for flux motion: the scaling behavior of NbTi has been associated with pin breaking, while that of Nb_3Sn has been identified with flux shearing. In our model, J_c is determined solely by grain boundary pinning. However, this single mechanism can lead to two different scaling laws because of the anisotropy of the pinning forces. This model predicts that the J_c(12 T) of Nb_3Sn could be improved by a factor of 4 to 5, as shown in Fig. 2, by finding a way to increase the transverse flux pinning contribution (typical of NbTi) with respect to the longitudinal one that prevails in current Nb_3Sn materials.

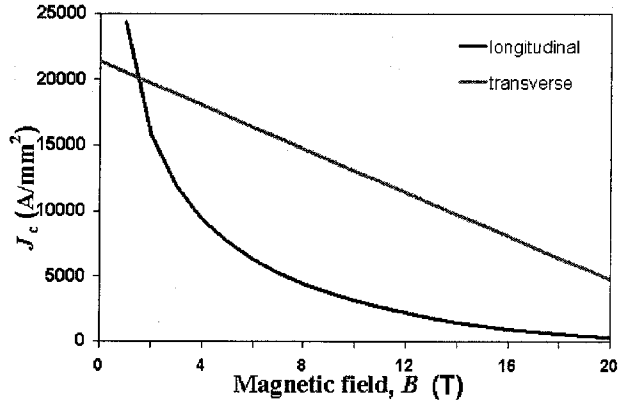

Fig. 2. Critical current density of Nb_3Sn at 4.2 K versus magnetic field predicted by [6] for both 'transverse' and 'longitudinal' pinning.

C. Cabling degradation

For the development and test of the prototype cable for the cos-theta dipole models based on the wind & react approach, Nb_3Sn strands of all three technologies were used [7]. Short samples of 28-strand Rutherford cable (as in Fig. 4, top left) with packing factors (PF) in the 85 to 95% range were fabricated at LBNL, NEEW and FNAL by varying the cable thickness. The results of I_c measurements made on round virgin strands were compared with those made on extracted strands [8]. In the PF range of interest for magnet design (*i.e.* 88-90%), the I_c cabling degradation at 12 T was 7 to 9% for the MJR and IT technologies, and larger for the PIT. However, since this study was performed, SMI allegedly produced a new PIT design with a cabling degradation of 5 to 7% only. The effective cable J_c at 4.2 K and 12 T normalized to the effective J_c of a cable made of undeformed round strands (PF = 78.5 %) is plotted in Fig. 3 as a function of PF. For the MJR and IT technologies, the effective J_c has an almost flat behavior with PF and is always larger than for round strands. A low PF of 88-90% was chosen for the dipole models to avoid excessively sharp edges.

Within the R&D work for the common coil dipole based on the react & wind approach, a two-layer racetrack coil and a

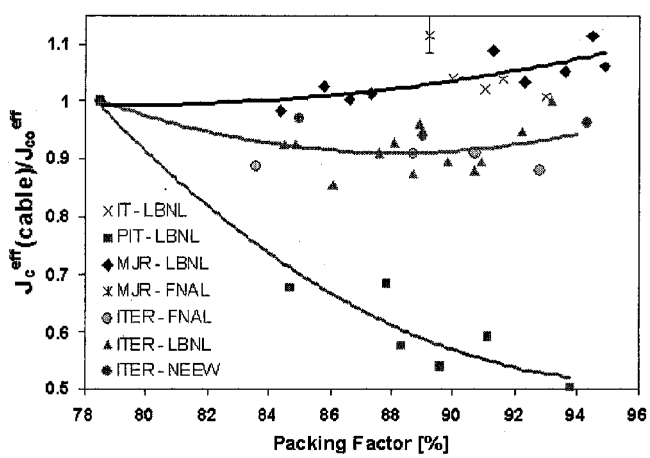

Fig. 3. Effective cable J_c at 4.2 K and 12 T as a function of packing factor for the IT, MJR and PIT Nb_3Sn technologies.

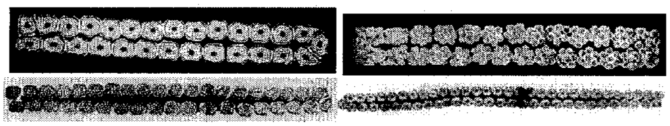

Fig. 4. 28-strand Rutherford cables made at FNAL out of 1 mm MJR strands (top left) and out of '6 around 1' 0.35 mm ITER sub-strands (top right); 41-strand (bottom left) and 60-strand (bottom right) cables made at LBNL out of 0.7 mm IT and MJR strands.

single-layer common coil dipoles are being studied and built. Based on cable studies in which a variety of designs were tried and tested using leftover ITER type strands by IGC, a 41-strand cable was used for the racetrack coil, whereas a 60-strand design was preferred for the common coil model. Fig. 4 (bottom) shows the 41-strand and 60-strand cables that were fabricated at LBNL out of 0.7 mm strands by IGC and OST respectively. The I_c degradation at 12 T due to cabling was negligible for the OST cable, and 11% for the IGC cable [9].

D. Bending degradation

To measure the I_c degradation due to bending, the sample holders used for reaction have a smaller diameter than those used for measurements, and include a conical part [10]. The results of I_c tests made on unbent strands were compared with those made on IGC and OST wires with maximum bending strains of about 0.2% and 0.4%. Based on these data, for react & wind magnets with a minimum bending radius of 90 mm (*i.e.* maximum bending strain of about 0.2% for a 0.7 mm wire), the bending degradation at 12T can be expected to be less than 7% for the OST material and less than 5% for the IGC material [9].

Bending degradation was also measured on ITER cables. The cables were reacted while bent on a 290 mm diameter reaction spool, and straightened before impregnation and measurement. Results were compared with those of unbent samples. An excellent correlation between strand and cable tests was found for cables whose strand layers bent independently [11].

E. Degradation due to transverse pressure

The effect of transverse pressure on the I_c of Nb_3Sn ITER cables was measured at the cable test facility at NHMFL [11]. The cable sample holder is designed to securely hold cable samples in place while applying a transverse stress up to 180 MPa on the cable broad face. The I_c appeared to linearly decrease with pressure, with the effect being reversible. At a field of 11 T, the I_c degradation was about 10 % for a pressure of 100 MPa. Results did not depend on the preexistent strain in the material.

Testing the I_c of superconducting cables under compression is a means to assess the performance of the final magnet. However, these cable tests are complicated and expensive. A fixture to assess the superconducting performance of a Nb_3Sn strand within a reacted and impregnated cable under pressure was designed and built, and is currently being commissioned at Fermilab [12].

IV. MAGNETIZATION AND STABILITY

Accelerator magnets need excellent field uniformity and stability. Even if the persistent current effect can be reduced

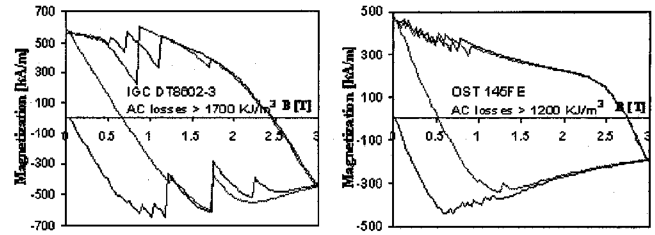

Fig. 5. Magnetization curves per non-Cu volume for the IGC strand used in the racetrack coil (left) and for the OST strand used in the common coil (right). Non-Cu losses are given for 3-0-3 T loops [9].

with passive corrections [13], due to stability problems this is possible to the required level only for superconductors with a d_{eff} of less than 30-40μm. The d_{eff} is calculated directly from magnetization loops performed between 10 and 13 T with a balanced coil magnetometer [14], by measuring $\mu_0\Delta M$ and the critical current, I_c, at 12 T. For present 1 mm high J_c strands, the d_{eff} ranges from about 50 μm for PIT, to 100 μm for MJR [7], and to even larger values for IT [9]. Magnetic instabilities (flux jumps) due to large d_{eff} are assessed by magnetization loops between 0 and 3 T (Fig. 5). Flux jumps were found to depend also on the reaction cycle [7]. The effect of large flux jumps in IT strands on magnet quench performance was observed experimentally during the racetrack model tests [15].

V. COPPER STABILIZER

The RRR, defined as the ratio of the Cu resistivity at room temperature over its residual resistivity, is a means to measure strand Cu purity, which is important for strand stabilization and magnet quench protection. Typical values for the present technologies are of about 200 for PIT and IT. For MJR, the RRR depends strongly on the Nb barrier thickness, ranging from about 20, to 60, to 160 for barrier thickness values of 3, 4.2 and 6 μm respectively. A low RRR indicates damage of the internal structure of the strand and Sn leakage into the surrounding Cu stabilizer. The RRR was found to depend on the heat treatment cycle and, in some instances, to be affected by cabling [8].

VI. REACTION CYCLE

The reaction cycle required to produce the superconducting Nb_3Sn phase is a critical step in the manufacturing process of a magnet and a time consuming operation involving expensive tooling. The reaction cycle for Nb_3Sn strands had been optimized at relatively low temperatures (<650°C) due to restrictions on the conductor insulation. The resulting reaction times for IT and MJR strands were rather long, in the 300 to 600 h range. Development of high temperature insulating materials has allowed increasing reaction temperatures, thereby reducing times, without a significant degradation of the strand performance. Thanks to numerous optimization studies [5], the duration of the original thermal cycles suggested by the companies was reduced by a factor of 2 to 4 by increasing the maximum temperature to 700°C and replacing the low temperature steps by a slow ramp rate.

During heat treatment, several metallurgical phases are created and eliminated in the course of the Sn diffusion through the copper matrix and the Nb_3Sn formation. In order

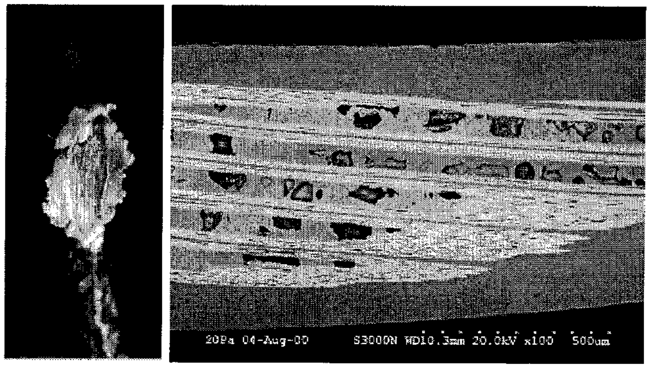

Fig. 6. Copper burst in a Nb_3Sn wire (left) and large fraction of voids produced after reaction in a MJR strand (right).

to optimize the reaction cycle, a thorough understanding of these processes is necessary. Attention has to be paid to both the superconducting performance and the prevention of thermally induced damage, like local inhomogeneities due to overpressure that may cause wire bursts (Fig. 6, left) and tin leakage. Pure Cu-Sn models were designed and fabricated to investigate formation of the η and ε phases of the Cu-Sn phase diagram. By measuring the layer growth of each phase with time and temperature, its diffusion coefficients and activation energy were calculated [16].

The feasibility of winding partly reacted cables to reduce the magnet manufacturing time was also explored. MJR and ITER Nb_3Sn strands were partially reacted to convert the Sn to the η and ε phases, thus suppressing the risk associated with liquid Sn. Then they were plastically strained to determine the amount of cabling and/or winding degradation. After completion of the reaction cycle at 700°C, the I_c was measured and compared with that obtained using the uninterrupted cycle. No I_c degradation was observed with preliminary heat treatments at 210°C and 400°C [16].

All Nb_3Sn technologies display a large fraction of voids after reaction, as shown in Fig. 6 (right) for a MJR strand. Reducing these voids may increase the J_c and reduce J_c strain sensitivity [17], as long as the formation of voids inside the strand is not related to successive phase transition during the Cu-Sn interdiffusion process.

VII. NB_3SN ANISOTROPIC EXPANSION

It is known that Nb/Sn composite strands expand after reaction due to formation of the Nb_3Sn A15 phase. In round strands this expansion is isotropic. However, an anisotropic volume expansion was observed in the first Nb_3Sn cos-theta models. While the cable width did not change significantly, the thickness increased by more than expected. To check the hypothesis that the plastic deformation impressed during cabling would release itself during heat treatment, Nb_3Sn strands of different technologies were rolled down to various sizes. The resulting thickness and width of the deformed strands were measured before and after heat treatment and compared with cable measurements. The thickness expansion was always larger than the width expansion for both strands and cables. Furthermore, the amount of volume expansion appeared to depend on the strand technology and to be a function of the Nb-Sn content [18].

VIII. CONCLUSIONS

High field accelerator magnets based on Nb_3Sn superconductor, with different designs and fabrication techniques, are the core of the Superconducting Magnet R&D at Fermilab. Superconducting strands and cables determine magnet performance and cost, and are substantial to high field accelerator magnets. Several designs of Nb_3Sn strands of different diameters produced using the IT, MJR, and PIT methods were studied. Heat treatment optimization has allowed a reduction of reaction times by a factor of 2 to 4. Another option to reduce the magnet manufacturing time is to partially react cables before winding. It was found that this could be done without any I_c degradation. The impact of the strand design on the J_c was also better understood and quantified. A model for A15 conductors that suggests that the high field J_c of Nb_3Sn could be improved by a factor 4 to 5 was realized. Rutherford-type cables of various designs made of different Nb_3Sn strands were developed and studied. The effect of cabling degradation was measured for all the above Nb_3Sn technologies. The effects of cable bending and compression were evaluated on strands and cables. The progress in our R&D to produce accelerator magnets with field in the 10-12 T range is substantial, and might lead to reach this goal in a few years from now.

IX. REFERENCES

[1] Design study for a staged Very Large Hadron Collider, Fermilab-TM-2149, June 4, 2001.

[2] D. Chichili et al., "Fabrication of the shell-type Nb_3Sn dipole model at Fermilab", *IEEE Trans. Appl. Sup.*, v. 11, No. 1, March 2001, p. 2160.

[3] G. Ambrosio et al., "Design and development of single-layer common coil Nb_3Sn dipole magnet for VLHC", Paper RPPH079, PAC 2001.

[4] G. Ambrosio et al., "Superconductor requirements for the HFM Program at Fermilab", FNAL TD-99-073, Dec. 15, 1999.

[5] E. Barzi et al., "Heat treatment optimization of Internal Tin Nb_3Sn", *IEEE Trans. App. Sup.*, v. 11, No. 1, March 2001, p. 3573.

[6] J. McDonald and E. Barzi, "A model for J_c in granular A-15 superconductors", *IEEE Trans. Appl. Sup.*, v. 11, No. 1, 2001, p. 3884.

[7] E. Barzi et al., "Study of Nb_3Sn strands for Fermilab's high field dipole models", *IEEE Trans. Appl. Sup.*, v. 11, No. 1, March 2001, p. 3595.

[8] E. Barzi et al., "Strand critical current degradation in Nb_3Sn Rutherford cables", *IEEE Trans. Appl. Sup.*, v.11, No. 1, March 2001, p. 2134.

[9] E. Barzi et al.,"Study of Nb_3Sn strands and cables for Fermilab's common coil dipole models", CEC/ICMC'01, Madison, WI, July '01.

[10] G. Ambrosio et al., "Study of the react and wind technique for a Nb_3Sn common coil dipole", *IEEE Trans. Appl. Sup.*, v. 10, No. 1,'00, p. 338.

[11] P. Bauer et al., "Fabrication and testing of Rutherford-type cables for react and wind accelerator magnets", *IEEE Trans. Appl. Sup.*, v. 11, No. 1, March 2001, p. 2457.

[12] E. Barzi et al., "A device to test critical current sensitivity of Nb_3Sn cables to pressure", CEC/ICMC 2001, Madison, WI, July 2001.

[13] V. V. Kashikhin and A. V. Zlobin, "Correction of the persistent current effect in Nb_3Sn dipole magnets", *IEEE Trans. Appl. Sup.*, v. 11, No. 1, March 2001, p. 2058.

[14] C. Boffo and E. Barzi, "Magnetization measurements at the SSTF", FNAL TD-99-036, 1999.

[15] G. Ambrosio et al., "Development and test of a Nb_3Sn racetrack magnet using react and wind technology", CEC/ICMC'01, Madison, WI, July 2001.

[16] J.-M. Rey et al., "Effect of partially reacting Nb_3Sn before magnet winding on the strand critical current", CEC/ICMC'01, Madison, WI, July 2001.

[17] D. R. Dietderich et al., "Critical current of superconducting Rutherford cable in high magnetic fields with transverse pressure", *IEEE Trans. Appl. Sup.*,V. 9, 1999, p. 122.

[18] N. Andreev et al., "Volume expansion of Nb_3Sn strands and cables during heat treatment", CEC/ICMC'2001, Madison, WI, July 2001.