BNL-219093-2020-TECH
IEEE2005-1;ASC2004-1

Investigation of Instability in High Jc Nb3Sn Strands

L. Cooley

January 2005

Superconducting Magnet Division
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC), High Energy Physics (HEP) (SC-25)

DISCLAIMER

Investigation of instability in high J_c Nb_3Sn strands

A. K. Ghosh, L. D. Cooley, and A. R Moodenbaugh

***Abstract*—Magnetization measurements show that modern high current-density Nb_3Sn strands made for HEP programs exhibit flux-jump instabilities at low fields, due to their having large effective filament diameters. Such instabilities might be problematic because they can initiate a quench in low-field regions of magnets. We explored magnetization and transport measurements of the most recent high J_c Nb_3Sn strands and cables to probe the instability behavior. In the regime where flux jumps are seen by magnetization measurements, transport current measurements show a threshold for stability. This threshold is significantly lower than the critical current at higher fields, and above this threshold, quenching in the strand could be initiated by ramping the magnetic field. The threshold current depends on the wire size and internal filament design, and is consistent with stability criteria. In cables, quench currents were nearly independent of field after training, and were far below the expected critical currents. Details of these measurements and their implications for testing and use in magnets are discussed.**

***Index Terms*—Electric variables measurements, niobium-tin compounds, stability, superconducting filaments and wires**

I. Introduction

The critical current density, J_c, of Nb_3Sn wires has increased dramatically over the last several years. Oxford Instruments-Superconducting Technology (OI-ST) has developed internal-Sn design, 0.8 mm diameter wires with a J_c over the non-copper stabilizer area of 3000 A/mm^2 at 12 T and 4.2 K [1]. Cables produced from these strands have enabled the achievement of 16 T in model accelerator dipole magnets [2]. Such a high J_c is a result of strand designs that maximize the area of Nb_3Sn in the "sub-elements". This usually requires a high content of alloyed Nb filaments and large tin cores and individual sub-element barriers of pure Nb. Also wires are reacted for long periods of time at temperatures of 650-700 °C. During this reaction, the filaments coalesce to a solid mass with significant conversion of the barrier to Nb_3Sn, thus producing large effective diameters of Nb_3Sn. This in turn produces large magnetizations at low fields and the occurrence of magnetic instabilities, which is seen as flux-jumps in magnetization measurements [3,4]. An example of this is shown in Fig. 1 for a 2985 A/mm^2, 0.7 mm strand manufactured by OI-ST

In this paper we describe measurements (first reported at a workshop at Fermilab [5]) which show that these magnetic instabilities can initiate quenches (irreversible transition to the normal state) in these wires carrying transport currents at low fields. A similar instability is also observed in the tests of Rutherford cables.

II. Strand Electrical Test

A. Current-Voltage Sweep

The usual superconductor wire electrical test at 4.2 K consists of measuring the critical current, I_c, by recording the voltage V across a length of specimen (50-100 cm) as a function of increasing current, resulting in a V-I curve. I_c is defined from this curve as the current at which the sample voltage meets an arbitrary criterion, *e.g.* when the resistivity is 10^{-14} Ω-m, as is usual for NbTi wires, or the electric field is 10 μV/m, as is often used for Nb_3Sn wires. I_c is determined as a function of field by performing this measurement with a suitable holder placed in a solenoid. The most widely used holder is the ITER barrel arrangement [6]. For "stable" conductors, the limitation of this test is then dictated by the available field and current. The facility at Brookhaven National Laboratory (BNL) has been used for many such tests of stable conductors, up to a maximum field of 11.5 T and a maximum current of 1 kA. The sample heat-treatment,

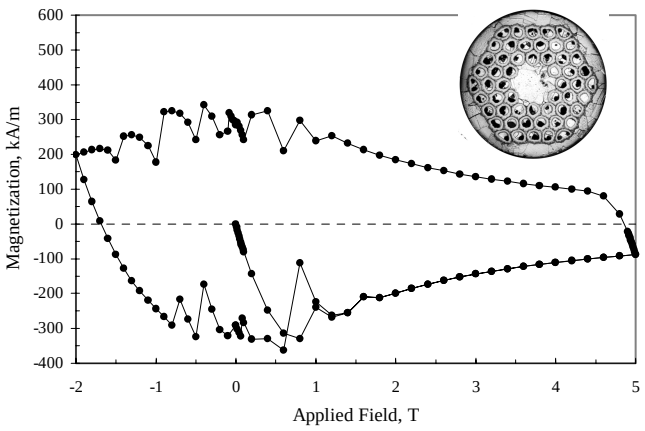

Fig. 1. Volume magnetization vs. field for a 0.7 mm strand. Inset is a cross section of the strand (micrograph reproduced with permission from OI-ST).

Manuscript received October 5, 2004. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

A. K. Ghosh is with the Magnet Division, Brookhaven National Laboratory, Upton, NY 11973 USA (phone: 631-344-3974; fax: 631-344-2190; e-mail: aghosh@ bnl.gov)

L. D. Cooley and A. R. Moodenbaugh are with the Material Science Department, Brookhaven National Laboratory, Upton, NY 11973 (e-mail: ldcooley@bnl.gov, moodenba@bnl.gov).

assembly and test procedures are described in [7].

High J_c Nb_3Sn wires are typically "unstable"; *i.e.* wires tend to quench (irreversible transition to the normal state) before the I_c criterion is reached. In some cases this quench current, I_q, can be significantly below I_c with no detectable development of voltage. This has been referred to as a lack of "self-field" stability [8]. Often, when faced with this situation, the wires are tested successfully at higher fields where I_c is lower [9]. The stabilizer volume and resistivity, the cooling conditions, and the filamentary nature of the composite have a significant effect on this stability. A point to note is that in most holder designs for Nb_3Sn I_c tests, the current transfer from the copper leads to the strand is done in the region of uniform central field of the solenoid.

B. Field-Sweep

An alternate way to approach a quench is to set the current and sweep the field. This was used by Wilson and Walters [10] to study stability of early multifilament composites of NbTi. Sweeping the field is much like what is done in a magnetization measurement, and when a flux-jump occurs, it can create a normal region in the wire which can either recover or grow into a propagating zone and quench the sample. This measurement is more effective in studying "magnetic" instability of a conductor. An example of this is shown in Fig. 2 where the voltage across 110 cm of strand carrying a transport current of 400 A is plotted as the field H is increased from zero in a *V-H* plot. At some field, denoted by H_q, the sample quenches due to a flux-jump event. Transient data loggers are used to record the quench voltage and current in the sample as shown in Fig. 3. Sometimes, voltage spikes are seen in the *V-H* plot without the sample quenching. In these cases, the normal zone due to a flux-jump recovers to the superconducting state. After a quench the current is re-established and the field ramp is continued typically to ~4T. The sample sometimes quenches at higher fields. A similar trace is taken during the field ramping down to zero. Nominally, the field is ramped at 5 mT/s.

C. Stability Threshold Current Density J_S

In this section, we show measurements made on three strands that were manufactured by OI-ST. Samples were all reacted on stainless steel barrels and then transferred to a Ti-alloy barrel for testing in liquid helium. Sample A is a Rod-Restack Process (RRP) wire [1], 0.7mm diameter with a non-Cu fraction of 0.5. The reaction sequence was the following: 48 h @ 210 °C, 48 h @ 400 °C and 150 h @ 650 °C.

The critical current of sample A was first measured at high fields using the *V-I* method. Using the I_c data from 8.5 to 11.5 T, J_c at 12 T was extrapolated to 2690 A/mm2. At 8 T, the sample reached 985 A (the power-supply limit) without developing any onset. Following these tests, while ramping the field down from 8 T, the sample current was maintained at 400 A. A quench occurred at a field of 0.27 T. Subsequently *V-H* measurements were made from 0 to 4 T using different levels of transport current. From repeated *V-H* cycles, a

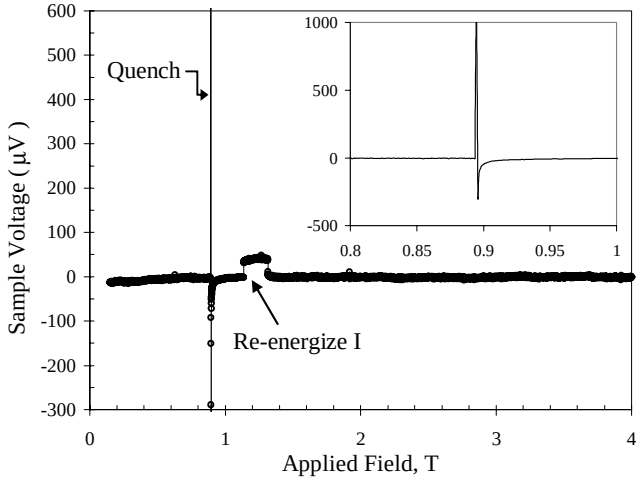

Fig. 2 Voltage measured across 110 cm of sample carrying 400 A. For each measurement, voltage is integrated over 166 ms with a sampling rate of 5.9 Hz. Field is ramped at 5 mT/s. Inset shows an amplified field plot near the quench field H_q.

threshold current of 325 A was found, below which the sample did not quench for either field ramp. It is significant that this "stability-threshold" current density, J_S, is considerably lower than the J_c at the benchmark field of 12 T. These results are summarized in Fig. 4.

Sample B is also a RRP strand at a larger diameter of 0.8 mm. This sample was reacted as follows: 100 h @ 210 °C, 48 h @ 340 °C and 180 h @ 675 °C. J_c (12T) for this conductor was 2810 A/mm^2. In this case, the power supply limit was reached at 10 T. However, at low fields the stability threshold current density was only 1900 A/mm^2. This sample developed more voltage at high fields and also had a higher J_S than Sample A

Sample C is a Modified-Jelly-Roll (MJR) strand [11], 0.8 mm diameter, with non-Cu fraction of 0.39. Magnetization measurements of this sample also showed flux-jumps. Its reaction schedule was similar to that for Sample A. The wire had a lower J_c (12 T) of 1825 A/mm^2 than the RRP strands, and was also marginally-stable in *V-I* measurements. For this wire, quench currents were measured at lower fields and found to be erratic and lower than the limit of the power supply.

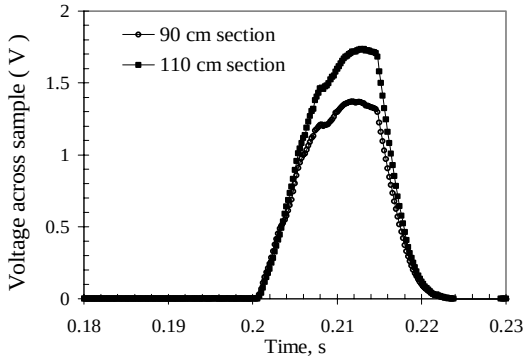

Fig. 3 Example of a quench trace at H_q. Quench starts at 0.201 s. Current is shut-off at 0.215 s. The quench starts within the 90cm section of sample which is wound over the T1-alloy barrel. The 110 cm section is at the end of the Ti-alloy barrel section [7].

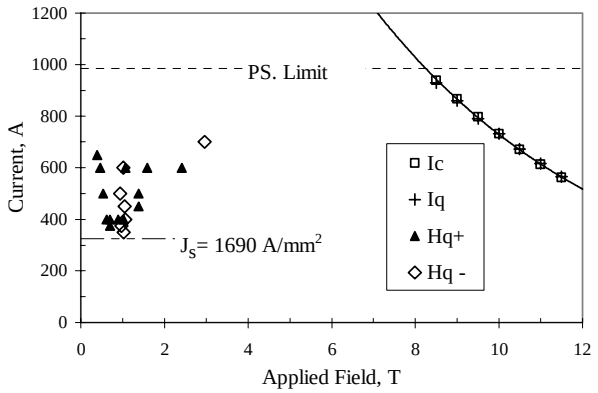

Fig. 4. A summary of electrical measurements for Sample A. At high fields I_c and I_q are obtained from *V-I* curves. Notice that I_q becomes lower than I_c at lower fields indicative of a marginally-stable conductor. H_q+/-,the quenching fields in the up/down cycle of the applied field respectively, are determined from *V-H* curves. J_s is the "stability threshold" current density which is significantly lower than that at 12 T.

Similar unstable *V-I* behavior in MJR strands has been previously observed by E. Barzi [9]. J_s for this wire is higher than the RRP strands on account of its lower J_c, as shown in Fig. 5.

III. Cable Electrical Measurements

30-strand Rutherford cables were fabricated at New England Wire from MJR strand from the same billet as Sample C. For this test, two 1.5 m long pieces were reacted in vacuum (100 h @ 210 °C, 48 h @ 340 °C, and 150 h @ 650 °C in a straight configuration so that no bending strain would be introduced when tested in the short sample holder. Following the reaction, the cable ends were filled with solder over ~15 cm at the return end and ~30 cm at the lead end. The lead-out section of each sample was soldered to NbTi cables which were eventually attached to the current leads of the test holder. The cable samples were vacuum-impregnated with CDT101™ epoxy in a manner similar to that used in magnet coil construction. This bifilar cable composite was assembled in a fixture with a pre-compression of 35 MPa (5 kPSI), and then mounted in the standard short-sample holder of the BNL cable test facility.

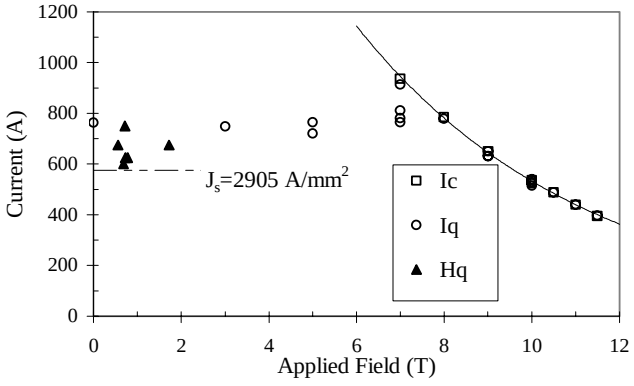

Fig. 5 A summary plot of electrical measurements for Sample C. In *VI* measurements, *Iq* decreased at lower fields indicative of self-field instability. Js measured at ~ 2900 A/mm^2.

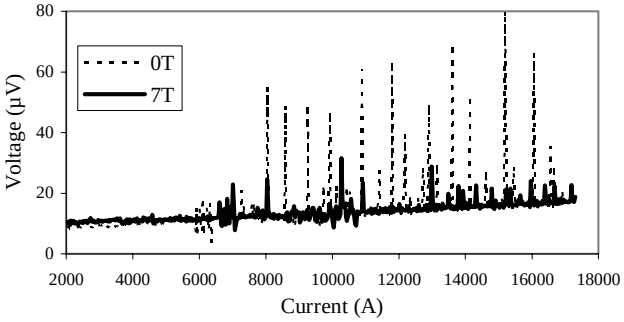

Fig. 6 Voltage across the pair of cable samples as a function of current. The slope in the trace is the return-joint resistance of ~0.5 nΩ. With no background field, the cable reacts only to its self-field which is ~ 1.6T at 17 kA. The magnitude of spikes is higher at 0 T, indicating instabilities are not due to conductor motion.

The test was made in the bore of a vertical dipole magnet to a maximum field of 7 T, with the field applied parallel to the wide face of the cable. The field profile is such that the solder joints at the top are in zero field, while the adjacent 20-cm lengths of the cable lie in a gradient from zero to full field. The 60-cm test section below that has uniform field. Voltage taps were soldered to the edge of the cable at the solder joints and near the margins of the test section.

The current polarity is such that the self-field adds to the applied field. The peak self-field is calculated to be 0.09 T/kA. Details of the test facility and procedures are in [12, 13].

A. Current-voltage test

In a manner similar to that for strands, the cable was first energized with a background field of 7 T. The sample trained up from 13.9 kA to 17.7 kA in 25 quenches. The current of 17.7 kA was significantly lower than what was expected from the strand I_c and the number of strands in the cable. All quenches originated between the solder joints, however many quenches were located in the field gradient region above the test section. Subsequent *V-I* measurements at lower background fields showed no significant increase in the quench current. The *V-I* traces also showed voltage spikes, either from conductor motion or due to flux-jumps. The latter speculation is borne out by the incidence and magnitude of the spikes at zero applied field, as shown in Fig. 6.

The cable test is similar to how a magnet would behave. In this test, as in a magnet, there are always regions of conductor at very low fields where flux jumps dominate and can initiate a quench. We confirm this magnetic instability by the tests described below.

B. Field-Sweep Measurements

In analogy with wire tests, *V-H* traces were made at set currents for field sweeps from 0 to 5 T. Not unexpectedly we find similar quenching at low field. An example of this is shown in Fig. 7, where the voltage across the bifilar cable is recorded as a function of field, while ramping at 5 mT/s.

Fig. 8 summarizes the quench behaviour of this cable. From repeated cycles with various set currents, a threshold current is determined, below which the conductor is stable. J_s for the

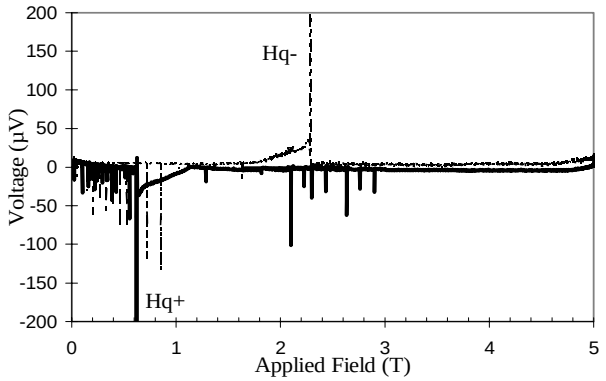

Fig. 7. *V-H* plot for the cable with current set at 14.5 kA. *Hq*+/- are the fields the cable quenches during the up/down cycle. After quench the current is not re-established until the cycle is reversed. Voltage spikes are due to flux-jumps.

cable was 2200 A/mm^2. This value is lower than that observed for the strand, which is probably due to the strand being totally exposed to liquid He and has better heat transfer to the coolant, whereas the cable is potted in epoxy and has worse heat transfer. To check this interpretation, another specimen of Sample C was measured, once while exposed to liquid He on the standard test barrel, and again after wrapping the sample and barrel with fiberglass epoxy to exclude He. J_S dropped from 2855 to 2260 A/mm^2. This indicates that heat transfer to the bath, has some influence on conductor stability.

IV. Conclusions

From adiabatic stability models, it is evident that the high J_c and large filament diameter Nb_3Sn wires would exhibit flux-jump instability. *V-H* measurements, which are analogous to magnetization measurements in the presence of transport current, show a threshold current density below which the conductor does not quench. This J_s is a function of the dynamic stability of the strand which is influenced by heat transfer within the strand and to the coolant bath. The wires and cable described here were all reacted for long times at 650-675 °C. This results in Sn penetrating through the barrier and reacting with the copper, and low *RRR* of the copper stabilizer (*RRR* is the ratio of room temperature resistivity and the residual resistivity at 20 K). *RRR* for samples A, B and C were 2.9, 10.8, and 4.8 respectively. A low *RRR* implies a low thermal conductivity and a reduced stability to flux-jumps. In a follow-on study [14], we find that the *RRR* of the strand has a strong influence on J_S. At an *RRR* of ~ 50, the J_S of sample A increases by more than a factor of two. This is significant, in that by increasing the dynamic stability these modern high J_c strands can be used reliably in high field magnets without being limited by the lack of magnetic stability.

Acknowledgment

We thank A. Werner and R. Sikora for heat treating the conductors, and J. D'Ambra and P. Philipsberg for their help in testing cables.

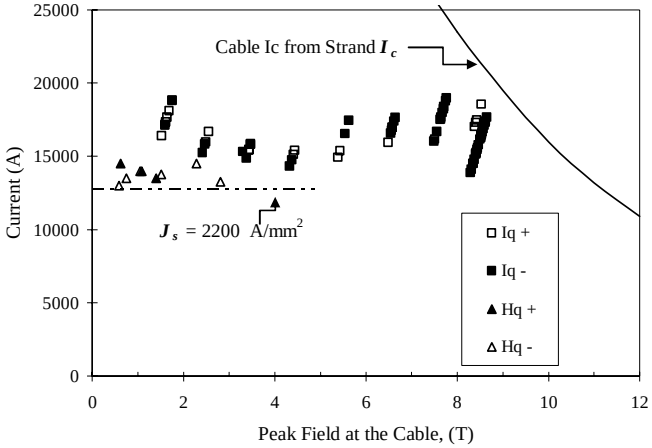

Fig. 8 Summary of cable measurements as a function of the peak field in the cable. Note that there is considerable gradient across the with of the cable due to the self-field generated by the current in the cable. *Iq*+/- are quench currents in *V-I* sweep for field settings which are sequentially increased/decreased.

References

[1] J. A. Parrell, M. B. Field Y. Zhang and S. Hong, "Nb_3Sn conductor development for fusion and particle accelerator applications," *Adv. in Cryo. Eng*., vol. 50, ed. U. Balachandran, pp. 369-375, 2004.

[2] J. A. Parrell, Y. Zhang, R. W. Hentges, M. B. Field and S. Hong, "Nb_3Sn strand development at Oxford Superconducting Technology", *IEEE Trans. Appl. Supercond*., vol. 13, pp. 3470-3473, June 2003.

[3] E. Barzi, P. J. Limon, R. Yamada and A. V. Zlobin,"Study of Nb_3Sn strands for Fermilab's high field dipole magnets", *IEEE Trans. Appl. Supercond*., vol. 11, pp3595-3598, March 2001.

[4] R. B. Goldfarb, L. F. Goodrich, T. Pyon and E. Gregory, "Suppression of flux jumps in marginally stable Niobium-Tin superconductors", *ibid*. pp. 3679-3682.

[5] A. K. Ghosh, L. D. Cooley, A. M. Moodenbaugh, "Investigations of instability in high Jc Nb_3Sn strands and cable", presented at *Workshop on Instabilities in Nb_3Sn Strands, Cables, and Magnets*, April 28-30, 2004, Fermilab, Batavia, IL, (not published).

[6] L. F. Goodrich and A. N. Srivastava, "A simple and repeatable technique for measuring the crtical current of Nb_3Sn wires", in *Proc. 7th Int. Workshop Critical Currents in Superconductors*, Alpbach, Austria, ed. H. W. Weber, 1994, pp. 609-612.

[7] R. Soika, L.D. Cooley, A.K. Ghosh, A. Werner, "Fixture for testing of modern high energy physics Nb_3Sn strands", *Adv. in Cryo. Eng*., vol. 50, ed. U. Balachandran, pp. 67-74, 2004.

[8] M. Wilson, *Superconducting Magnets*, Clarendon Press Oxford, 1983, ch. 7, pp. 140-143.

[9] E. Barzi, "Superconductor and Cable R&D for High Field Accelerator Magnets at Fermilab", paper presented at *Int. Workshop on Progress of Nb-based Superconductors*, Feb. 2-3, 2004, NIMS, Tsukuba, Japan.

[10] M. N. Wilson and C.R. Walters, "Magnetization and stability measurements", *J. Phys. D: Appl. Phys*., vol. 13, pp1547-1561, 1970.

[11] J. A. Parrell, Y. Zhang, R. W. Hentges, M. B. Field and S. Hong, "Nb_3Sn strand development at Oxford Superconducting Technology", *IEEE Trans. Appl. Supercond*., vol. 13, pp. 3470-3473, June 2003.

[12] A. G. Prodell and A, Arn, "A facility for evaluating superconductors above atmospheric pressure at 1.8K", *Adv. in Cryo. Eng*., vol. 43, ed. P. Kittle, 1998, pp. 443-450.

[13] R. Thomas, A. Ghosh, D. McChesney and A. Jain, "Testing and evaluation of superconducting cables for the LHC", in *Proc. 1999 Particle Accl. Conf*. New York, NY, 1999, pp. 3188-3190.

[14] A. K. Ghosh, E. Sperry, L. D. Cooley, A. M. Moodenbaugh, R. L. Sabatini, and J. L. Wright, "Dynamic stability threshold in high-performance internal-tin Nb_3Sn superconductors for high field magnets", accepted for publication in *Supercond. Sci. Technol.*.