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Investigation of instability in high Jc Nb3Sn strands

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Abstract—Magnetization measurements show that modern high current-density Nb3Sn 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 Jc Nb3Sn 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, Jc, of Nb3Sn 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 Jc over the non-copper stabilizer area of 3000 A/mm² 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 Jc is a result of strand designs that maximize the area of Nb3Sn 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 Nb3Sn, thus producing large effective diameters of Nb3Sn. 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/mm², 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, Ic, 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. Ic 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 Nb3Sn wires. Ic 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,
assembly and test procedures are described in [7]. High J, Nb3Sn 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 Nb3Sn \( I_c \) tests, the current transfer from the copper leads to the strand is done in the region of uniform central field of the solenoid.

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

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/mm². 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/mm². 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/mm² 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.
previously observed by E. Barzi [9].

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 \(\text{°C}\), 48 h @ 340 \(\text{°C}\), and 150 h @ 650 \(\text{°C}\) 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 BNL cable test facility.

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.

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\text{Fig. 4. A summary of electrical measurements for Sample A. At high fields } I_c \text{ and } I_q \text{ are obtained from } V-I \text{ curves. Notice that } I_q \text{ becomes lower than } I_c \text{ at lower fields indicative of a marginally-stable conductor. } H_q +/- \text{ the quenching fields in the up/down cycle of the applied field, are determined from } V-H \text{ curves. } J_s \text{ is the ”stability threshold” current density which is significantly lower than that at 12 T.}
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\text{Fig. 5. A summary plot of electrical measurements for Sample C. In VI measurements, } I_q \text{ decreased at lower fields indicative of self-field instability. } J_s \text{ measured at } \approx 2900 \text{ A/mm}^2.
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cable was 2200 A/mm². 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/mm². 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_s and large filament diameter Nb₃Sn 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_s strands can be used reliably in high field magnets without being limited by the lack of magnetic stability.

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