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Measurement of Critical Current and Instability Threshold of Rutherford-type Nb_3Sn Cables

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***Abstract*—As part of a collaboration between FNAL and CERN, Nb_3Sn Rutherford-type cables made of different wires (MJR and PIT) have been assembled in the sample holder at FNAL and tested at FRESCA (CERN). All cable samples had 28 strands with 1-mm diameter, and a trapezoidal cross-section with 0.9-1 degree keystone angle. All samples were tested at 4.3 and 1.8 K. After the first series of tests both cables were retested with higher prestress. The PIT sample was extensively retested at 1.9 K. During the second run the MJR sample was also tested at constant current in sweeping field in order to characterize its stability. All samples showed signs of instability and several voltage spikes were detected and recorded. Critical current and instability threshold measurements are presented and compared with previous tests and magnet performances.**

***Index Terms*— Critical current measurement, Niobium-Tin, Superconducting cables, Superconductor instability.**

I. Introduction

Nb_3Sn is the best candidate material for the next generation of high field accelerator magnets [1]. The impressive improvements in commercially available Nb_3Sn wires [2] have made possible the design of magnets with performances unreachable with NbTi, and multi-lab programs have been started in order to verify the maturity of Nb_3Sn technology for real accelerator applications [3], [4]. In past years conductor instability limited the performances of several Nb_3Sn magnets [5], [6]. Collaboration between Fermilab and CERN began in 2004 to test cables at FRESCA [7] in order to study this problem and develop reliable cables. A first series of tests on cables made of strands produced with the Modified-Jelly-Roll (MJR) or the Powder-In-Tube (PIT) method was performed in summer 2004 [7]. Both samples have been retested, after increasing their pre-stress, in order to characterize the performance of the PIT-sample at 1.9 K, and to study the instability of the MJR-sample by testing it under sweeping fields at constant current [8]. The FRESCA control system was appositely upgraded for this test.

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II. Description of Samples and DAQ System

Both samples have been described in [7]. Fig. 1 shows the arrangement of cables and voltage taps with respect to the background (BG) field. The PIT-sample consisted of two cables spliced together at the bottom of the test facility, and spliced to NbTi leads on the top. The MJR-sample layout was more complicated in order to keep all parts of the MJR cables in the field region. The bottom splice was set in the field region, and the other end of the MJR cables was spliced in the field region to a PIT cable. These PIT cables were then spliced to NbTi leads out of the field region.

Both samples were instrumented with several voltage taps (Fig. 1). All segments were monitored, and sometimes their signals recorded, using a fast DAQ system (LDS-Nicolet Vision XP) that can save 16 channels of 16-bit data continuously to a 72 GB hard drive at 100 kS/s per channel.

III. PIT-cable Test Results

The PIT-sample was retested over two days in November 2004 in order to evaluate the effect of higher pre-stress (68 instead of 34 MPa) on training and quench performances, and to study the dependence of the quench current versus field at 1.8 K. The whole quench history is presented in Fig. 2 (square markers) together with the quench history of the first test (dash markers). For an easy comparison, quenches performed during the first or second test have the same quench number (i.e. same horizontal position) when they were performed in

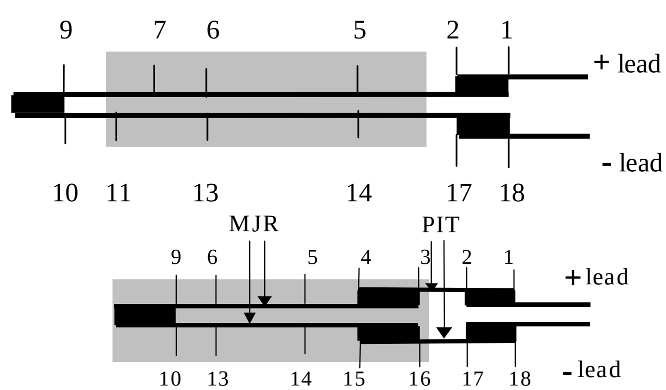

Fig. 1. From top to bottom, schematic of PIT-sample, and MJR-sample, showing cable and splice (black box) positions with respect to the external field (gray box). Numbers indicate voltage taps.

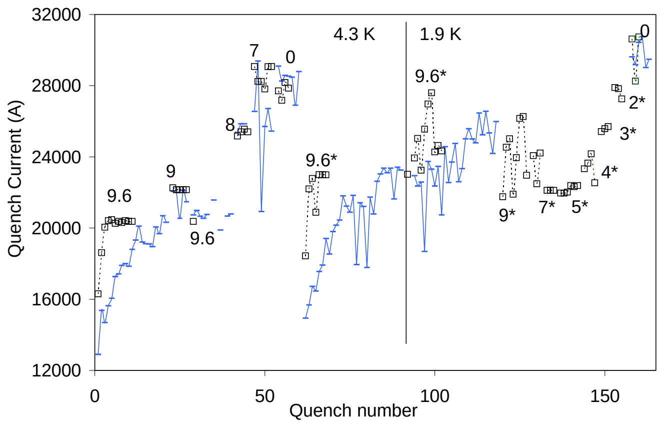

Fig. 2. Comparison of quench history during first (dash markers) and second test (square markers) of the PIT-sample. Numbers indicate the BG field during the second test.

the same conditions (i.e. same temperature, field intensity and orientation). The numbers in the plot show the value of the BG field of the closest set of quenches performed during the second test. The symbol * indicates that the BG field was oriented against the self-field between the cables (parallel in all other cases). The results of the second test show very short trainings (2-3 quenches) at 4.3 K at the beginning of the test (9.6 T) and after the BG field was reversed (9.6*). The average quench currents (I_q) after training are very similar to those measured during the first test showing that the sample again reached short-sample limit [7]. Therefore, doubling the pre-stress greatly reduced the training without introducing any degradation, and 68 MPa will be used as the default value for similar samples. The quenches at 1.9 K show an unexpected behavior that is more clearly presented in Fig. 3. Since the BG field was oriented against the self-field between the cables, its value is very close to the maximum field seen by the sample (defined as the maximum of the average fields on each strand). Fig. 3 shows a decrease of the quench current, with some fluctuations, as the BG field increases from 0 to 5 T. From 7 to 9.6 T the spread of the fluctuations increases with the field. The minimum remains around 22-23 kA and the maximum increases almost linearly.

Fig. 3 suggests that there is a minimum stability threshold [8] (I_s~21 kA) between 5 and 7 T. Because of this minimum the quench current decreases from 0 to 5 T. When the BG

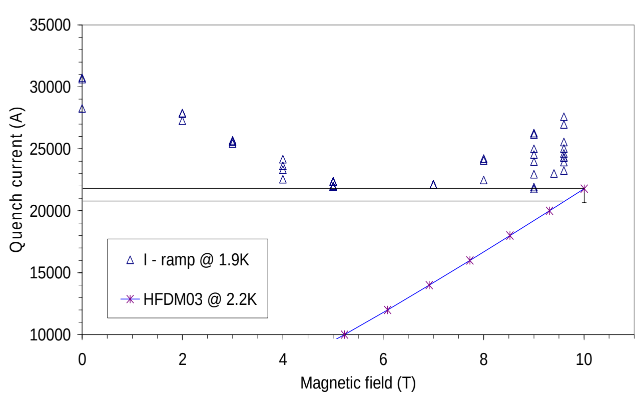

Fig. 3. Quench currents of the PIT-sample at 1.9 K as function of the BG field.

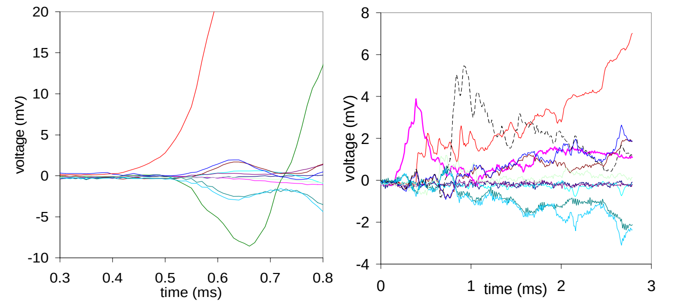

Fig. 4. Voltage onset at beginning of a quench in the PIT-sample during test at 4.3 K with BG field = 7 T (left) and without BG field (right). The ramp rate was 150 A/s in both cases. Quench current was 29386 A (left) and 28575 A (right). Signals show the voltage on different segments.

field is higher than 7 T the part of the sample in the uniform BG field may reach higher currents than I_s (maximum of the fluctuations), but there is always a short section of cables exposed to the field in the range 5-7 T (because the splices are located outside the BG field), and quench may occur at or above I_s in these sections.

Fig. 3 also shows the load line of the maximum field on the coil of HFDM03 (cos-θ dipole coil with iron mirror) [9] wound with a cable of same design and similar PIT strands. HFDM03 heat treatment had a plateau of 170 hours at 655 ºC that yielded an extracted-strand I_c of 589 A (at 12 T, 4.2 K on Ti-Al-V barrel), very close to the I_c of the PIT-sample (597 A under the same conditions) and RRR equal to 84 (110 for the PIT-sample). HFDM03 reached the short sample limit (21 kA) at 4.5 K after 20 quenches with a slow but constant training. In contrast, at 2.2 K it showed some fluctuations of the quench current between 20.8 and 21.8 kA. This behavior at 2.2 K is consistent with the conclusion that these PIT cables (with RRR in the range 80 to 110) had a minimum stability threshold around 21 kA in the 5-7 T range at 2 K.

Fig. 4 shows the voltage onset at the beginning of two quenches at 4.3 K and similar current values (left: 29.4 kA; right: 28.6 kA) but very different BG fields (left: 7 T; right: 0 T). The ramp rate was in both cases 150 A/s. The patterns are very different: on the left there is a sharp voltage rise in one segment; on the right there is a spike in one segment, (V_{max}= 3.9 mV, T~0.5 ms) followed by spikes in two other segments, then the first and third segment recover while the second starts to quench.

IV. MJR-CABLE TEST RESULTS

The MJR-sample was retested at FRESCA during the week 22-26 of August 2005. The BG field was always oriented parallel to the self-field between the cables. At the beginning, standard I-ramps (at 9.6 and 9 T) were performed in order to train the sample and to verify that it had not been damaged by the larger pre-stress (40.5 MPa). The sample after a training quench at 13 kA showed the ramp rate dependence presented in Fig. 5. I-ramps performed at lower BG fields showed ramp rate dependence with some fluctuations at 8 T (Fig. 5), and totally erratic behavior at 7 and 6 T (I_q in the range 16.3-20.3 kA and 15-19.5 kA respectively). I-ramps without BG field gave I_q between 15.5 and 18.5 kA, consistent with the first

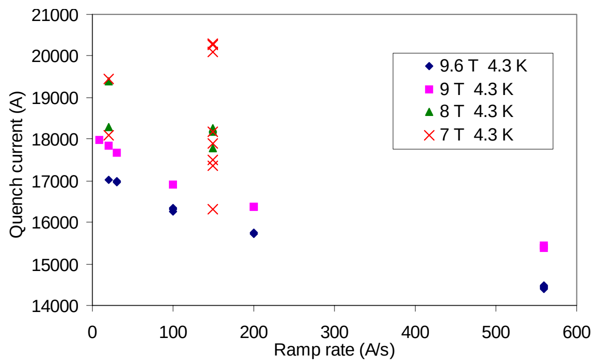

Fig. 5. Ramp rate dependence of the MJR-sample at 4.3 K

test.

The quench current reached at the slowest ramp rates at 9.6 and 9 T is consistent with short sample tests (of virgin wires on stainless steel barrel) assuming 7% cabling degradation and 5.6 K (at 9.6 T) or 5.9 K (at 9 T) temperature. This temperature increase over the bath temperature (4.3-4.4 K) is current dependent and could be the effect of splice heating. The splices of the MJR cables are about 240 mm from the beginning of the maximum BG field. Temperature sensors will be set on the cables in future tests with similar layout.

At the beginning of the study of the sample performance in sweeping field (B-ramps), a series of 8 fast I-ramp quenches was performed before any B-ramp. The goal was to clean the sample of the residual magnetization (history dependent). After several B-ramps performed in this manner, a few were performed without pre-cleaning and results were not systematically different. Therefore it was decided to continue the study without performing cleaning quenches. Since the quenches were occurring at BG fields close to 2 T or higher, it was assumed that the magnetization history was sufficiently erased before the quench. Quench heaters covering the whole sample will be installed during assembly to make samples for studying the effect of magnetic history.

All B-ramps were performed at 1 tesla/minute. Fig. 6 shows the results of B-ramps at 4.3 K. All ramps to higher fields (B-ramp-up) went from 0 T to 6 - 7 T. Markers without error bar indicate ramps when the sample did not quench (the marker is set at the maximum BG field reached during the ramp). Markers with error bar indicates the BG field when the quench occurred, and the bar shows the whole field range on the cable (higher than the BG field because of the self-field, lower in the parts of the cables going to the splices). No quench started from any splice and therefore the splices have not been taken into account when computing the field distribution on the samples represented by the error bar. All ramps to lower fields (B-ramp-down) went from 6 or 7 T to 0 (sometimes to 1 T for a control system problem), and are represented in Fig. 6 in the same manner as B-ramps-up.

Fig. 6 shows also the results of I-ramps performed during the first and second test. Also in this case the markers indicate the value of the BG field and the error bar the range of field on the sample (large when it was not possible to exclude quenches starting from a splice). It can be seen that in this sample B-ramps may cause quenches at lower currents than I-ramps (12.5 kA instead of 15.2 kA), which is consistent with [8]. These B-ramps indicate that the minimum of the unstable region [10] should be between 1.5 and 3 T (consistently with [11]), with I_s slightly lower than 12.5 kA.

Fig 6 shows also the load line of the maximum field of HFDM02 (cos-θ dipole coil with iron mirror) [5] wound from the same cable spool used for the MJR-sample. HFDM02 received the same heat treatment used for the MJR-sample and had RRR equal to 6.3. HFDM02 did not exceed 50% of the estimated short sample limit and showed erratic quenches in the current range represented by the two horizontal lines (11.4 – 12.4 kA). This performance is consistent with the stability threshold seen on the MJR-sample by performing B-ramps.

The results of B-ramps (second test) and I-ramps (first test) performed at 1.9 K are shown in Fig. 7 using the same conventions adopted in Fig. 6. All B-ramps-up went from 0 to 9.6 T, and all B-ramps-down went from 9.6 to 1 or 0 T.

Fig. 7 shows that also at 1.9 K B-ramps give a lower quench current than I-ramps on this sample. Comparison with the 4.3-K results indicates that all 1.9-K quenches were caused by instability, shown by lower currents. An interesting result is that both kinds of ramps show that the unstable region reaches lower currents between 5-10 T than between 0-5 T. They also suggest the presence of a minimum around 6-7 T. Fig 7 shows also the load line of the maximum field of HFDM02 up to the maximum reached during 2.2-K tests. Also at 2.2 K HFDM02 had erratic quench currents (between 14.6 and 14.3 kA) represented in the plot by two horizontal

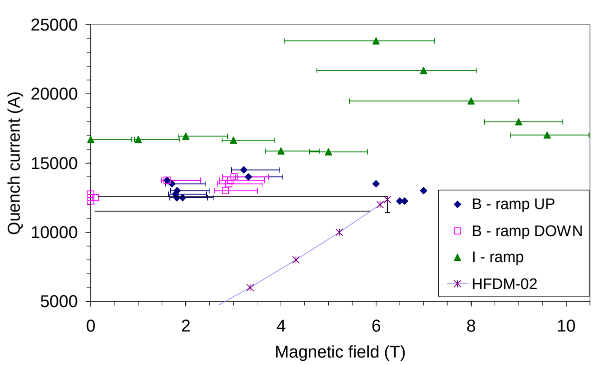

Fig. 6. MJR-sample B-ramp results compared with I-ramp quenches and HFDM02 performance at 4.3 K

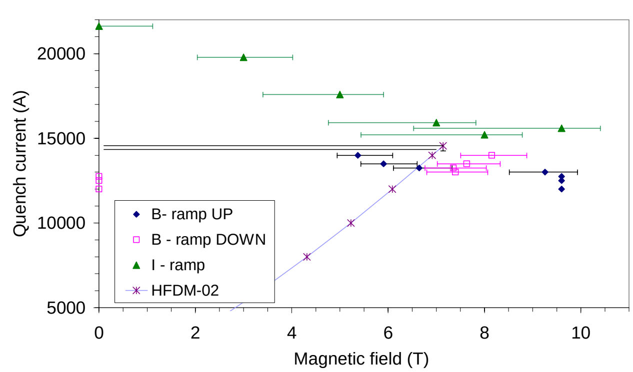

Fig. 7. MJR-sample B-ramp results at 1.9 K compared with I-ramp quenches at 1.9 K and HFDM02 performance at 2.2 K.

lines. In this case the maximum quench current reached by the magnet was just below the minimum quench current measured during I-ramps. Although the comparison between the cable sample and HFDM02 may have been affected by the different temperatures, it suggests that I-ramps can better predict magnet performance at 2.2 K than B-ramps. Another possible interpretation is that the volume of conductor in the unstable region must be sufficiently large to initiate a quench (e.g. larger than the minimum quench volume).

V. Voltage Spikes

A very large number of voltage spikes were detected and recorded, mostly when testing the MJR-sample but also when testing the PIT-sample. Some spikes induced the quench as in the example presented in Fig. 4 (right). The highest spike recorded that did not induce a quench reached 25 mV (in an MJR-PIT splice of the MJR-sample at 4.3 K, 3 T, 16 kA during I-ramp at 150 A/s). The analysis of all kinds of shapes and features of the spikes recorded is still ongoing. Generally speaking it can be said that a "typical" shape is the one shown in Fig 4 (right), but some spikes had very different shapes (e.g. shorter or much longer time), and some correlations between the spike shape and the operating conditions have been seen and will be the subject of further study.

The most noticeable features of the spikes analyzed to date are "propagation" and "coupling". A nice example of both features is shown in Fig. 8 by a spike recorded on the MJR-sample at 4.3 K, 1 T and 17 kA (I-ramp at 150 A/s). The highest signal shows the total voltage on the sample. The other signals show the voltage on the three segments that cover each MJR cable (splices excluded). It can be seen that a spike started simultaneously in both segments close to the PIT-MJR splices propagated through the central segments and then into both segments close to the return splice. This spike traveled along both central segments (500 mm) in 2.4 ms

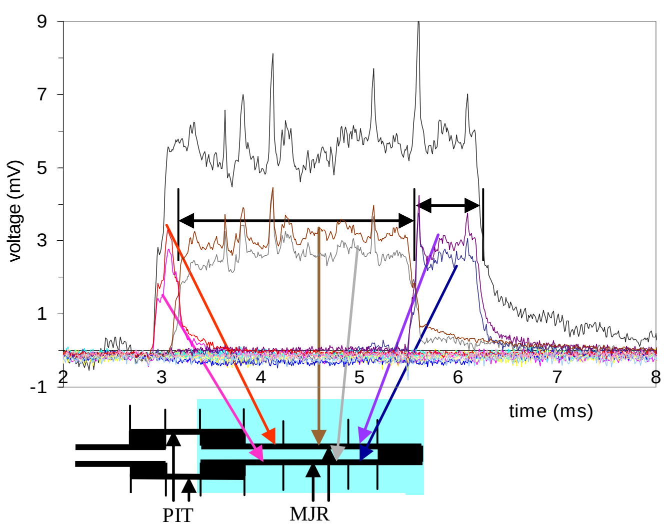

Fig. 8. Propagation of a spike along the whole MJR-sample (splices excluded) at 4.3 K, 1 T. The current was about 17 kA with a ramp rate of 150 A/s. The highest peak is 9 mV, and the time intervals shown are: 2.4 and 0.7 ms.

resulting in a propagation velocity of 208 m/s. Assuming that the spikes propagated at the same velocity in the last segments, they stopped 20 mm before the return splice. Higher velocities have been computed in other cases using the same time-of-flight technique. The highest velocity recorded was 875 m/s during a B-ramp-up at 4.3 K, 1.8 T, and 12.5 kA. This spike propagated in both cables starting from the segment close to the return splice, and traveled along all MJR cables up to the splices with the PIT cables. The highest voltage during this spike was 22 mV. The spike initiated the quench, and the thermal runaway started in a segment close to the return splice after the spike had reached the MJR-PIT splices. Spike propagation has been observed also in strands [12]. In these two cases, as well as in many others, the spike started simultaneously (within 20 μs) in both MJR cables in segments facing each other. This coupling between cables facing each other could be the cause of the fast voltage rise that has often been seen in MJR magnets limited by instabilities, which has been interpreted as multi-turn quenches [13].

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