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Authors

Ambrosio, G.
Andreev, N.
Bartlett, S.E.
et al.

Publication Date

2004-10-04

Critical Current and Instability Threshold Measurement of Nb_3Sn Cables for High Field Accelerator Magnets

G. Ambrosio, N. Andreev, S. E. Bartlett, E. Barzi, C.-H. Denarie, D. Dietderich, A. K. Ghosh, A. P. Verweij, and A. V. Zlobin

***Abstract*—Rutherford-type cables made of high critical current Nb_3Sn strands are being used in several laboratories for developing new generation superconducting magnets for present and future accelerators and upgrades. Testing of cable short samples is an important part of these R&D programs and the instability problem found in some short model magnets at Fermilab made these tests even more significant. Fermilab in collaboration with BNL, CERN and LBNL has developed sample holders and sample preparation infrastructure and procedures for testing Nb_3Sn cable short samples at BNL and CERN test facilities. This paper describes the sample holders, sample preparation and instrumentation, and test results. Several samples made of MJR or PIT strands 1 mm in diameter have been tested. Some samples were unstable (i.e. quenched at low transport currents) at low fields and reached the critical surface at higher fields.**

***Index Terms*—Critical current, niobium-tin, superconducting cables, superconductor instability.**

I. INTRODUCTION

THE best candidate material for the next generation of high field superconducting magnets for particle accelerators is Nb_3Sn. This is confirmed by the fact that only Nb_3Sn is being considered suited for a significant (more than a factor two) LHC luminosity upgrade [1], for the Tesla final focus quadrupoles, for the main dipoles of a Super LHC, and for some VLHC designs [2]. In the last few years the noncopper critical current density (J_c) of commercially available strands has greatly improved, passing the threshold of 3000 A/mm^2 at 12 T and 4.2 K [3]. This opened the door to the fabrication of very high field magnets such as the 16-T HD1 at LBNL [4]. On the other side the rush for a higher J_c resulted in wires with large effective filament diameters and low RRR that compromised the stability of the conductor (due to flux jumps effects) used in several short model dipoles fabricated at Fermilab [5], [6]. Studies of strand stability in low fields [7], and of cable maximum current in self-field (using a superconducting transformer) [8], tests of small magnets [6], and the successful test at Fermilab of a short model magnet fabricated using PIT conductor [9] are contributing to the understanding and the solution of this problem.

The tests here presented constitute an important contribution to this effort. They show, in cable short samples, the same behavior found in Fermilab magnets and point to the cause: conductor instability. This work also favors the development of fixtures and procedures for the characterization of future high-J_c Nb_3Sn cables.

II. TEST FACILITIES

A. BNL Cable Test Facility

At BNL the standard tests are performed at 4.3 K. The test facility is equipped with three 25-kA helium injected leads allowing testing of two samples (made of two cables each) during the same cooldown. The sample holder is placed in the 75 mm bore of a one meter long NbTi superconducting dipole magnet which can produce fields as high as 7.5 T at 4.3 K and ~9 T at 1.9 K [10]. The holder can be positioned such that the field can be perpendicular or parallel to the wide face of the cable. The uniform field region extends over 600 mm. The magnet is energized by a 8.5 kA power supply; a superconducting switch allows it to operate in the persistent mode. Two 15 kA supplies are operated in parallel to supply the cable test current. Details can be found in [11].

B. CERN Cable Test Facility (FRESCA)

At CERN the cable samples are measured in the "Facility for the Reception of the Superconducting Cables" (FRESCA) [12], which has now been operational for about 6 years. In FRESCA cable samples of 2.4 m length can be measured at applied fields up to 10 T, currents up to 40 kA, and temperatures of 1.8–2.17 and 4.3–4.5 K.

FRESCA consists of two cryogenically independent cryostats, both operating with HeII in the lower bath and HeI in the upper bath, both at atmospheric pressure. λ-plates thermally separate the 1.9 K parts from the 4.3 K parts.

The outer cryostat contains the dipole magnet [13] with a bore of 88 mm, reaching 10.3 T at 1.9 K. The magnet is connected through a pair of 18 kA current leads to a 16 kA current supply. The field is uniform over a length of about 600 mm. The sample current leads are connected to a low noise 32 kA power supply by a clamped connection over 12 cm (typical resistance 4 $n\Omega$

Manuscript received October 4, 2004. This work was supported in part by the U.S. Department of Energy. The work at BNL was supported by the U.S. Department of Energy under Contract DE-AC02-98CH10886.

G. Ambrosio, N. Andreev, E. Barzi, and A. V. Zlobin are with the Fermi National Accelerator Lab, Batavia, IL 60510 USA (e-mail: giorgioa@fnal.gov).

S. E. Bartlett and D. Dietderick are with the Lawrence Berkeley National Lab., Berkeley, CA 94720 USA. Contract No. DE-AC03-76SF00098.

C.-H. Denarie and A. P. Verweij are with the CERN, CH-1211 Genève 23, Switzerland.

A. K. Ghosh is with the Brookhaven National Lab., Upton, NY 11973 USA.

Digital Object Identifier 10.1109/TASC.2005.849163

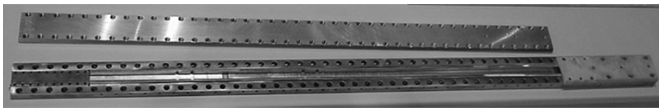

Fig. 1. Sample holder used for test at BNL. The return end splice box is shown on the left. On the right G10 plates cover the copper plates used to joint the Nb_3Sn cables to the copper bus bar used for tests at NHMFL.

using an indium strip). The field can be perpendicular and parallel to the cable face, and inverting the magnet current changes the field direction.

In the following we will use "P-orientation" when the external field is parallel to the self-field between the cables, and "AP-orientation" if it is reversed. No measurement has been performed in perpendicular configuration.

III. SAMPLE HOLDER DESIGNS

The sample holder (SH) used for tests at BNL is shown in Fig. 1. It was designed by P. Bauer *et al.* [14] for developing the React-and-Wind technology by testing cables at BNL and NHMFL. A few parts were modified in order to accommodate thicker cables. The SH consists of a stainless steel case surrounding four cable samples. The two active samples (1220-mm long) are in the center of the cable stack, while two "dummy" cables provide a magnet-like environment and protect the active cables during assembly and pre-stress application. The active cables are joined by a splice at one end (bottom splice), and are spliced to NbTi leads on the other end. All splices are 125-mm long. The Nb_3Sn cables are reacted in a different sample holder, while assembly, impregnation and pre-stressing are performed in this holder. Pre-stress is applied by adding a Kapton layer on top of the cable stack after impregnation. A FEM analysis was performed in order to compute the minimum pre-stress allowing testing at maximum forces with the cables always under compression (35 MPa in P-orientation, 12 MPa in AP-orientation) [15]. Voltage taps were soldered to the thin sides of the Nb_3Sn cables (i.e. in contact with only one or two strands). These solutions were adopted in order to reduce the risk of damaging the brittle Nb_3Sn during pre-stress application.

The SH used for test at CERN (Fig. 2) is based on the same concept (two active cables protected by two "dummy" cables, assembled and impregnated in the same stainless steel case). The pre-stress was applied similarly by adding a Kapton layer after impregnation and pushing the cover against the U-channel using bolts penetrating the FRESCA collars. SnAg soldering was used for all splices and the leads were made of solder-filled LHC-inner-dipole cables. In order to provide adequate cooling of the splices (127-mm long), two channels for liquid helium were created along the sample holder inside the collars. Three 7.6-mm holes per side put each splice in contact with the helium through the 0.2-mm thick ground insulation made of Kapton. Voltage taps were set on the thin sides of the cables and the wires run along the side channels. A FEM analysis was performed also for this sample holder in order to compute the minimum pre-stress required (34 MPa in P-orientation) [16].

This sample holder was designed to test also "unstable" cables that should be completely confined in the field region (see next section for details) allowing for the cooling of splices set in the field region. More details about this sample holder may be found in [17].

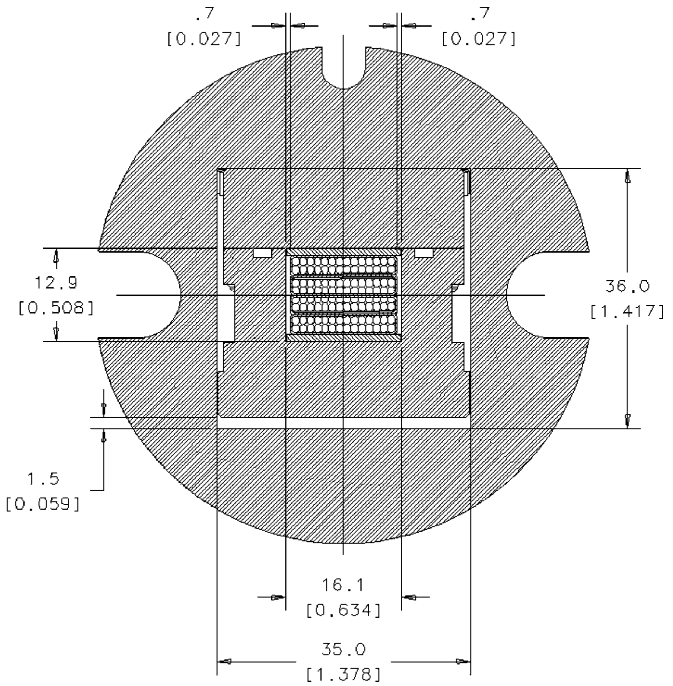

Fig. 2. Cross section of the sample holder for test at CERN inserted into the FRESCA collars (bolts not shown).

TABLE I
SAMPLE CHARACTERISTICS

#	Test	Type	Cond	Φ_{eff} (μm)	RRR	I_c ss† @ 12T 4.2K(A)
1	BNL	Reg	MJR	110	6	700 (virg.)
2	BNL	Reg	PIT	54	81-125*	603 (virg.) 552 (extr.)
3	BNL	Spec	MJR	110	48*	730 (virg.)
4	CERN	Reg	PIT	54	110	597 (extr.)
5	CERN	Spec	MJR	110	9	705 (virg.)

*measured on witness samples.

†Critical current of witness short samples (virgin or extracted).

The Nb_3Sn cables for regular tests are 1725-mm long and a special reaction retort was designed and fabricated at LBNL in order to fit the oven used for Nb_3Sn reaction at FNAL.

IV. DESCRIPTION OF SAMPLES

The sample characteristics are summarized in Table I. Three samples (1 to 3) have been tested at BNL and two (4 and 5) at CERN. All cables had the same dimensions: 28 strands (1-mm diameter), 14.24-mm width, 1.8-mm average thickness before reaction, 0.9-deg keystone angle, 109.8-mm transposition pitch. The strands were made by Oxford Superconducting Technology using the MJR (Modified Jelly Roll) method or by Shape Metal Innovation using the PIT (Powder In Tube) method. The MJR and PIT strands had respectively a copper ratio of ~47 and ~52% and an effective filament diameter of 110 and 54 μm [18]. The MJR cables in samples 3 and 5 had a 25-μm-thick stainless steel core and a thickness 20-μm larger than the other cables. All cables were insulated using ceramic tape and ceramic binder (as the FNAL cos-theta short model magnets) unless otherwise stated. Samples 1 and 3 had a moderate pre-stress of 12 MPa, all other samples 35 MPa.

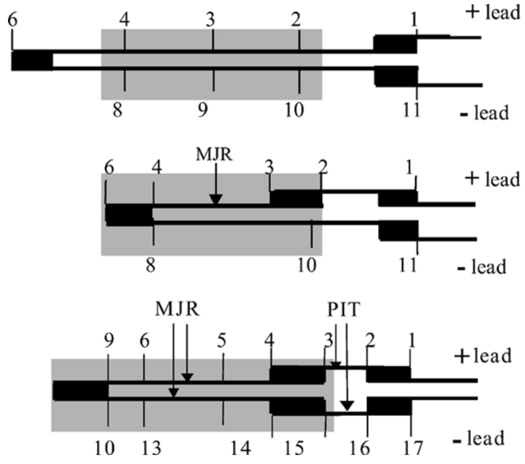

Fig. 3. From top to bottom, schematic of samples 2, 3 and 5, showing cable and splice (black box) positions with respect to the external field (gray box). Samples 2 and 3 are on the same scale. Numbers indicate voltage taps. Sample 1 had the same voltage taps as sample 2 except voltage taps 2 and 10.

Sample 1 consisted of two MJR cables heat-treated following the instructions provided by the vendor (100 h at 210°C, 48 h at 340°C, 180 h at 650°C). Two voltage taps per cable were set 225-mm apart in the uniform field region and a voltage tap was set on the outside of each splice (Fig. 3).

Sample 2 consisted of two PIT cables. It had three voltage taps per cable (two at the ends of the uniform field region, and one in the center) plus those outside the splices.

Sample 3 was a special test with one MJR cable completely confined in the high field region (Fig. 3). The bottom splice was moved upstream and an additional splice was introduced to a stable PIT cable on the other side of the magnet. Holes were drilled on the cover of the holder for splice cooling. The MJR cable used in this test had a shorter than usual final step in the reaction cycle (72 h at 650°C).

Sample 4 was made of PIT cables insulated with S2-glass tape reinforced by ceramic binder, and instrumented with five voltage taps per cable and additional taps for splice resistance measurement. The heat treatment had only one step of 99 h at 675°C. After heat treatment the cables showed signs of tin contamination of the copper matrix close to the thin edge (cable packing factor was 88.5%).

Sample 5 was a special test with two MJR cables completely confined in the high field region (Fig. 3). The bottom splice was moved upstream and additional splices to PIT cables were introduced on the other side of the field region. The splices with MJR cables were set where the field was between 68 and 92% of the maximum field. The MJR cables had a standard heat treatment (i.e. final step: 180 h at 650°C). The PIT cables were insulated as in sample 2.

V. TEST RESULTS

A. *Tests at BNL*

Samples 1 to 3 were tested at BNL between December 03 and April 04 with day per sample at 4.3 K. Samples 1 and 3 were tested in AP-orientation, sample 2 in P-orientation.

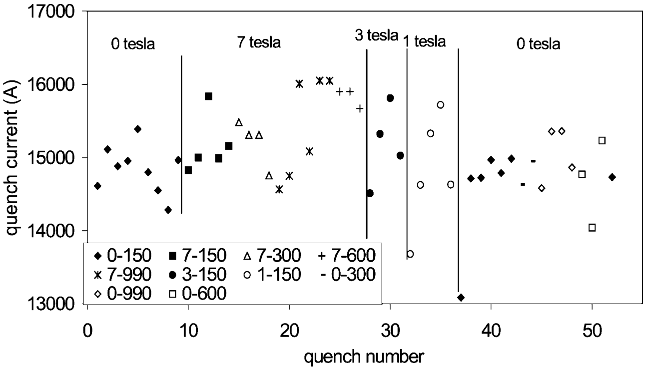

Fig. 4. Quench history of sample 1. The numbers in the labels indicate the background field (T) and the ramp rate (A/s).

Fig. 4 presents the quench history of sample 1. It shows the almost negligible effect of field (0–7 T) and ramp rate (150–990 A/s) on the quench current. In contrast, the field had an important effect on the quench-start location: in low external field (≤ 1 T) the quench-start was randomly distributed among all segments; in higher fields (≥ 3 T) the quench-start still had a random distribution, but it never occurred in the two segments completely set in the field region, as if the quenches were starting only in low field [19].

It can also be noted that the first quench after a reduction of the external field occurred at a current significantly lower than the current of all other quenches at the same field. The RRR of the cables was 6.

The tests of samples 2 and 3 were prematurely interrupted because of quenches in the leads that eventually caused one lead to burn. The maximum current reached by sample 2 was 19 kA in 7 T field. Sample 3 reached almost 20 kA without external field. The RRR of extracted strands reacted with sample 3 (witnesses) was 48. Witness samples of sample 1 and 3 had almost the same critical current at 12 T and 4.2 K (700 and 730 A respectively).

B. *Tests at CERN*

Samples 4 and 5 were tested at CERN in September 2004. The tests took three days per sample, two days at 4.3 K and one at 1.8 K. At the beginning of the test sample 4 was in P-orientation. The field was reversed at the end of the test at 4.3 K, and this new orientation was kept at 1.8 K. Sample 5 was always in P-orientation. The default ramp rate was 150 A/s. All splices in both samples had a resistance below 0.42 $\mathrm{n}\Omega$ with the exception of the bottom splice of sample 5 (0.85 $\mathrm{n}\Omega$). The PIT cables of sample 4 had a RRR of 110, and the MJR cables of sample 5 had a RRR of 9.

The quench history of sample 4 (Fig. 5) shows a long training at 9.6 T from 13 to 21 kA in about 20 quenches. Then the beginning of the voltage rise could be seen in some runs in the field range from 9.9 T to 7 T. The highest quench currents reached in this field range are shown in Fig. 6 together with I_c predicted by measurement of extracted strand witnesses on Ti-Al-V barrels. In these quenches the voltage rose to about half the resistivity criterion (10^{-14} $\Omega\mathrm{m}$). The cable I_c was computed by using a parameterization of the strand I_c (field, temperature and strain) [20] multiplied by the number of strands and taking into account the cable self-field computed in the center of the strand under the maximum total field. The best agreement between cable and strand I_c (shown in Fig. 6) is obtained assuming the same strain

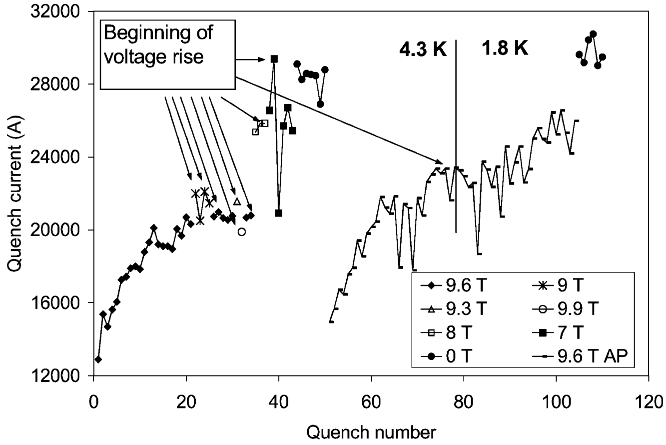

Fig. 5. Quench history of sample 4.

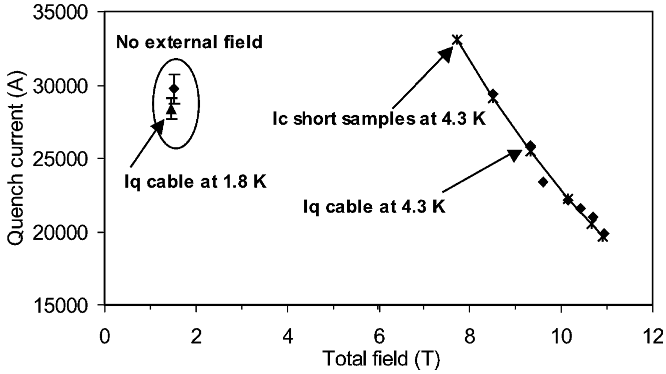

Fig. 6. Field dependence of the quench current of sample 4 compared with the critical current computed from strand short sample measurement. The points show the maximum field on the samples (external+self).

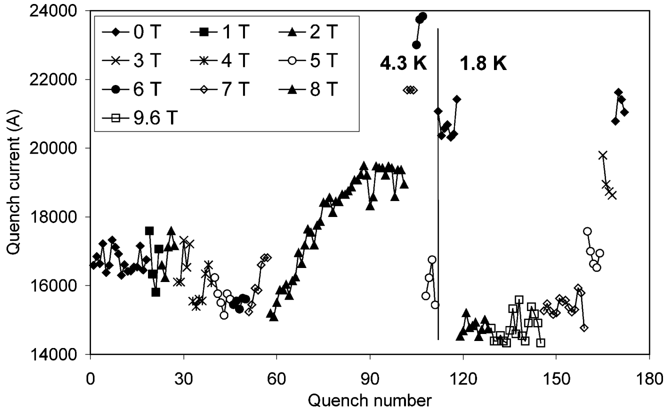

Fig. 7. Quench history of sample 5.

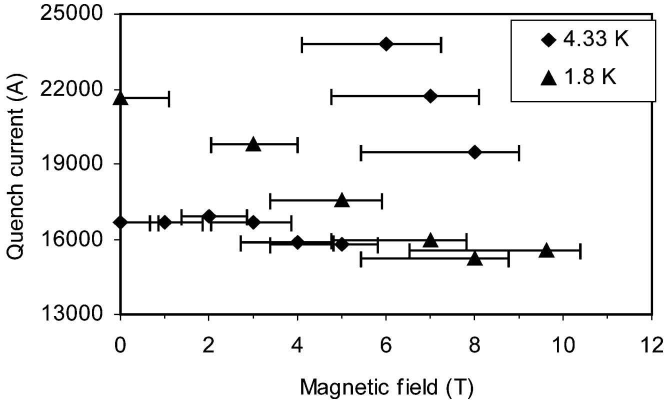

Fig. 8. Field dependence of the quench current of sample 5. Each point shows the background field on the MJR cables when the quench occurred. The bars show the whole field range over the cables (right: maximum due to self-field; left: minimum on the splices).

in the cable and in the witness samples (unlikely but possible if the strands were slightly loose on the Ti-Al-V barrels). In subsequent runs without external field the sample quenched at about 28 kA. The DAQ records at the beginning of these quenches had a characteristic signature consisting of a spike or a large noise in several channels before the beginning of the voltage rise typical of the quench [21].

In the AP-orientation the sample had to be trained again before showing the voltage rise at 23 kA in 9.6 T applied field.

After training, all quenches in external field started in the high field region.

At 1.8 K the training at 9.6 T was interrupted above 26 kA before any voltage rise could be seen. Without external field the cable quenched between 29 and 31 kA.

At 4.33 K and no external field, the MJR cables of sample 5 showed a quench current (Fig. 7) in the range of 16.3 to 17.3 kA, independent of the ramp rate (150–990 A/s). Many voltage spikes (presumably caused by flux jumps) could be seen during all current ramps. The typical spike reached in 50 μsec a maximum of 5 mV and decayed exponentially in 1 ms. Often one or more spikes started before the complete decay of the first. Sometimes they were in different acquisition channels (i.e. different cable segments). Almost all quenches that we have analyzed were triggered by one or more spikes. The segment where the quench started changed from quench to quench, but it was always within the MJR cables. In external fields of 1, 2, and 3 T the samples showed the same behavior with slightly larger quench currents. At 4 and 5 T the average quench current decreased slightly.

At higher fields sample 5 showed signs of training that was completed with 32 quenches at 8 T before reaching a plateau at 19.5 kA. This is lower than the expected critical current (26 kA), and could be caused by the close proximity of the splices to the maximum field region. Decreasing the field the quench current increased up to 21.7 and 23.8 kA at 7 and 6 T respectively. In 6 T external field the minimum field on the MJR cables was 4.1 T (in the splices).

Subsequently the quench current dropped to 16 kA at 5 T (3.4 T minimum field on the MJR), spikes could be seen again, and the quenches started outside the high field region (one time in an MJR-PIT splice).

At 1.8 K without external field, the quench current was limited at about 21 kA. Surprisingly, at high fields (8 and 9.6 T) it dropped below 16 kA. As the field decreased, the quench current increased and again reached about 21 kA without external field (Fig. 8).

VI. DISCUSSION AND CONCLUSIONS

The tests of the PIT cables showed the capabilities and limits of the sample holders and test facilities. At BNL $\mathrm{Nb_3Sn}$ cables were successfully tested up to 17 kA, at FRESCA above 30 kA.

The beginning of the transition that could be seen in sample 4 at FRESCA between 7 and 9.9 T, and the field dependence of the quench current, showed that the sample reached the critical surface (in good correlation with witness sample I_c measurement on Ti-Al-V barrels). The premature quenches at 28–30 kA without external field showed the stability threshold of this sample, which may have been affected by the local tin contamination that occurred during heat treatment.

The tests of MJR cables at 4.3 K showed the instability of these cables at low fields ($B \leq 3.4$ T) and low current (15–17 kA) when the RRR is low (6 in sample 1, 9 in sample 5), and a better behavior ($I > 19$ kA) when the RRR is sufficiently high (48 in sample 3). The dependence of the stability threshold on the RRR is in good agreement with [22]. The stability threshold (15 kA) found in the MJR cables with the lowest RRR (6) is slightly higher than the quench current in Fermilab short model magnets (for instance HFDM-02 [23] had the same RRR and was limited at about 12 kA). Different cooling conditions and/or small variations of the strand characteristics could explain this difference.

The results of sample 5 suggest that at 1.8 K MJR cables with a low RRR are unstable up to at higher fields (6.5 T) than at 4.3 K, and that the stability threshold decreases sharply as the field increases (Fig. 8). In magnets built with this conductor the value of $\Delta I_{q\Delta T}$ (quench current variation when the temperature decreases from 4.2 to 2.2 K) should depend on the slope of the magnet load line. This dependence can be seen by comparing some magnets built at Fermilab using MJR conductor: HFDA-04 ($\cos\theta$ dipole), HFDM-02 ($\cos\theta$ mirror), and HFDA-03B (half turn of a $\cos\theta$ coil) [23] had $\Delta I_{q\Delta T}/I_{q4.2}$ equal to 9, 22, and 32% respectively, and similar I_q at 4.2 K ($I_{q4.2}$).

The cable test facility at BNL is being modified in order to provide a better support of the leads and to avoid quenches in the leads at high currents. The sample holder will be modified accordingly, and the lead splice design will be changed in order to allow a possible quench in the leads to propagate into the sample, preventing the leads from burning.

FRESCA and the new sample holder for $\mathrm{Nb_3Sn}$ cable tests at CERN performed very well. The pre-stress will be increased in future tests aiming at shorter training.

ACKNOWLEDGMENT

The authors thank P. Bauer for his kind help during the modifications of the cable sample holders used at BNL, O. Vincent-Viry for providing the field map of FRESCA, A. Levy and J. Alvarez for the careful sample preparation, and S. Geminian and R. Rota for installation of the sample holders in FRESCA and help during tests.

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