Magneto-Thermal Stability in LARP Nb_3Sn TQS Magnets

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***Abstract*—In the framework of the US LHC Accelerator Program (LARP), three US laboratories BNL, FNAL and LBNL are developing Nb_3Sn quadrupole magnets for the Large Hadron Collider (LHC) luminosity upgrade. At present CERN is supporting this activity by testing some of the LARP 1 m long 90 mm aperture magnets. Recently two magnets using a shell based key and bladder technology (TQS) have been tested at CERN. These magnets (TQS02c, TQS03a) share the same mechanical structure and use a 27 strand Rutherford cable based on the 0.7 mm RRP strand. The main difference between the two magnets is the strand sub-element layout (54/61 in TQS02c versus 108/127 in TQS03a) and the strand critical current. The TQS03a wire has a lower (18%) critical current, a larger amount of copper stabilizer, and a larger number of superconducting sub-elements with respect to the TQS02c strand. The tests show that TQS02c was stable between 4.3 K and 2.7 K while it was limited by the self-field instability at lower temperatures. TQS03a was not limited by magneto-thermal instabilities and reached 93% of the short sample limit both at 4.3 K and 1.9 K. In this paper the results are summarized and compared with the stability measurements performed at CERN on individual strands.**

***Index Terms*—Instability, magnets, Nb_3Sn, self field.**

TABLE I
CONDUCTOR PARAMETERS OF THE MAGNETS

	TQS02c	TQS03a
Strand		
Type	OST RRP® 54/61	OST RRP® 108/127
# SC Sub-elements	54	108
Diameter	0.7 mm	0.7 mm
I_c(12 T, 4.25 K)[a]	556 A	454 A
J_c(12 T, 4.25 K)[a]	2724 A/mm^2	2558 A/mm^2
Copper content	47 %	54%
RRR	>200	>200
Magnet		
S.S. current[b] 4.3 K,1.9 K	13.9 kA, 15.4 kA	13.2 kA, 14.5 kA
S.S. gradient[b] 4.3 K, 1.9 K	243 T/m, 269 T/m	234 T/m, 254 T/m
Peak field[b] 4.3 K, 1.9 K	12.53 T, 13.76 T	11.96 T, 13.02 T

[a] Measurements performed at LBNL on extracted strands; data are reported without self-field correction.
[b] The Short Sample current (gradient) and the peak field in the magnet conductor are calculated [11] using the critical current measurements performed at LBNL and BNL on extracted strands.

I. INTRODUCTION

In the framework of the US LHC Accelerator Program (LARP), three US laboratories BNL, FNAL and LBNL are developing Nb_3Sn quadrupole magnets for the Large Hadron Collider (LHC) luminosity upgrade [1], [2]. The first step towards this goal is the development of Technology Quadrupoles (TQ); these are 1-meter long 90 mm aperture quadrupole magnets that have been developed at LBNL and FNAL using identical coils but different mechanical structures. The LBNL design is based on a shell structure (TQS magnets) using "keys and bladders" technology [3], [4] whereas the FNAL structure is based on collars (TQC magnets) [5], [6].

At present CERN is supporting this LARP activity by testing some of the TQS magnets. Recently two magnets (TQS02c, TQS03a) have been tested at CERN. These magnets share the same mechanical structure and use a 27-strand Rutherford cable based on the 0.7 mm RRP strand produced by Oxford Superconducting Technology (OST); the main difference between the two magnets is the critical current and the layout of the two wires used to build them. TQS02c is based on the RRP 54/61, a wire constituted by 54 superconducting sub-elements with 46–47% of copper stabilizer. All the TQS02 and TQC02 magnets were built using this RRP 54/61 and were heat treated to have a critical current density in the superconductor approximately equal to 2800 $\mathrm{A/mm^2}$ (4.3 K, 12 T) and a copper Residual Resistivity Ratio (RRR) larger than 200 [7]. These magnets exhibited a stable behavior at 4.3 K but they had limited quench performance at 1.9 K [8] attributed to a self-field instability [9], [10]. TQS03a was built using a different wire, the RRP 108/127, with a lower critical current density (approximately 2600 $\mathrm{A/mm^2}$ at 4.3 K, 12 T), a larger amount of copper stabilizer (Cu content ~54%) and, two times the number of superconducting sub-elements. All these changes, that were introduced to improve the conductor stability at 1.9 K, reduced significantly the critical current (18% at 4.3 K and 12 T) of the RRP 108/127 with respect to the RRP 54/61. More details regarding the conductor used in the magnets are in Table I. The 27-strand cable geometry is exactly the same for the two magnets and can be found in [11].

The TQS02c, previously tested at CERN [8], was retested to study the magneto-thermal stability around 1.9 K. The tests showed that TQS02c reached its plateau current between 4.3 K and 2.7 K while at lower temperatures was limited by the self-field instability. The TQS03a test shows that this magnet was not limited by magneto-thermal instabilities and reached 93% of the short sample limit both at 4.3 K and 1.9 K. In this

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paper the magnets' results are summarized and compared with the stability measurements performed at CERN on individual strands.

II. A NEW TEST FOR THE TQS02C MAGNET

A. *Test Description*

High J_c $\mathrm{Nb_3Sn}$ superconducting strands and magnets can have worse performance at 1.9 K than at 4.3 K (the quench current at 1.9 K can be lower than at 4.3 K). In superconducting strands this behavior is due to the self-field instability [10], a magneto-thermal instability mainly dependent on the strand diameter and critical current. The quench behavior of TQ magnets based on the RRP conductor clearly shows that these magnets are limited by magneto-thermal instabilities at 1.9 K [8].

To understand whether the magneto-thermal instability in the TQS02-TQC02 magnets at 1.9 K is caused by the distribution of the transport current within the strand (self-field instability) or by the persistent currents (magnetization instability [9], [12], [13]), a special test procedure for TQS02c was devised.

From a previous test of TQS02c [8], it was observed that the quench current of this magnet at 1.9 K is about 1 kA lower than the quench current at 4.3 K. Based on this observation, the current of TQS02c at 4.3 K (or at a temperature where the magnet still has a stable behavior) was set to a larger value than the quench current at 1.9 K and held while the temperature was lowered. Using this procedure the magnet should not be limited by magnetization instability because the magnetization in the magnet will not increase while cooling down (the magnetic field is not changing) and the persistent current will not flow at $J_c(\mathrm{T})$ but at $J_c(4.3\ \mathrm{K})$. Furthermore, during this experiment, at a temperature lower than 4.3 K, the magnet should also be more self-field stable with respect to the case where the current is ramped up at a constant temperature because the transport current will flow at a current density $J < J_c(\mathrm{T})$. The test performed using such procedure is named 'cool down experiment' in the next paragraphs and plots.

According to this theory, from this procedure one would expect two possible scenarios: 1) the magnet does not quench during the cool down; 2) the magnet will quench at a certain temperature T_0, and the quench current is higher than the value obtained at T_0 with a regular quench current measurement (ramping the current at a constant temperature). One would also expect not to see partial flux jumps because: 1) the magnet will not be affected by magnetization instability and; 2) flux jumps of the self-field in a magnet are expected to be complete flux jumps that suppress the superconductivity (see Fig. 2 in [9]). The goal of this test is double: 1) to check if the expectations based on the above theory are met; 2) to see if during a cool down experiment a quench can occur. In the latter case the quench could be only due to the self-field instability. In the test plan, a temperature dependence study was also included to investigate at which temperature the instability starts.

B. *Test Results*

Initially three quenches were performed at 4.3 K, ramping the current at 20 A/s (this value will be implicitly assumed in the next paragraphs unless differently specified). After an unexpected room temperature thermal cycle, seven additional quenches at 4.3 K followed showing that the magnet was already trained and the quench current was ranging between 12.2 kA and 12.3 kA with all the quenches confined to coil 23 in the same high field region (the 4 coils were labeled: 20, 22, 23 and 28).

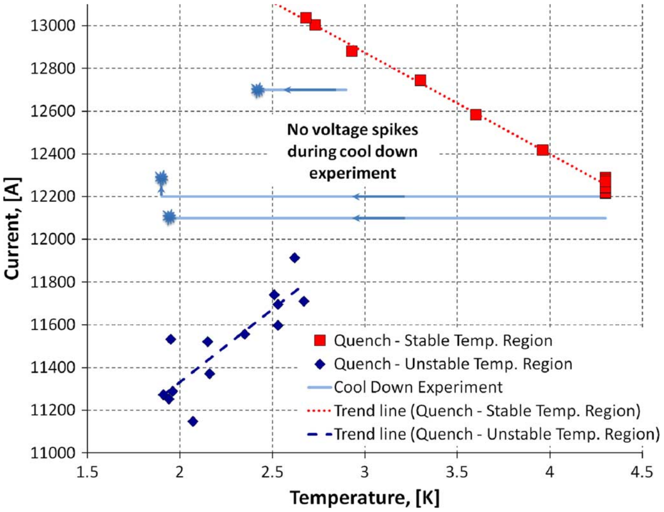

Fig. 1. Quench currents during the new test of the TQS02c magnet.

TABLE II
PROPERTIES OF TESTED 0.7 MM STRAND SAMPLES

Sample ID	I_c @ 12 T & 4.3 K, 1.9 K [A]	B_{c2}^* @ 4.3 K [T]	*RRR*	Billet	# SC. Sub-el.	H.T. Temp. [°C]	Strand Type	Cu/ non-Cu
1	454, 654	21.78	236-264	8781	54	640	Ext.**	0.874
2	510, 700	22.03	296-306	9560			Round	0.83
3	513, 701***	22.76	282-293				Ext.**	
4	484, 670	21.96	246-298	8781			Round	0.874
5	556, 747	23.29	219-225			665		
6	405, 572	21.45	254-281	10400	108	640		1.176
7	487, 657	23.96	120-126			665		

Following these quenches, the cool down experiment was carried out: the bath temperature was reduced from 4.3 K while the current was held constant at 12.1 kA. The magnet quenched 7 hours later when the bath temperature reached 1.95 K (the transition of the helium to the super-fluid state did not induce any quench).

A second cool down experiment was then performed commencing with 12.2 kA at 4 K and subsequently cooling down. This time the magnet reached 1.9 K without quenching. At this point the current was increased at 2 A/s and the magnet finally quenched at 12.293 kA. This measurement was repeated a second time starting from 12.2 kA at 4.3 K and then cooling down. The magnet reached once again 1.9 K and then quenched at 12.26 kA following a ramp at 2 A/s.

A fourth cool down experiment was performed starting from 12.7 kA at 2.9 K. In this case the magnet quenched during the cool down at 2.43 K.

In order to check if during the cool down experiment there were voltage spikes (partial flux jumps), 3 voltage signals ($\mathrm{s1} = \mathrm{coil}\ 23 - \mathrm{coil}\ 20$; $\mathrm{s2} = \mathrm{coil}\ 22 - \mathrm{coil}\ 28$; $\mathrm{s3} = \mathrm{coil}\ 23 + \mathrm{coil}\ 20 -$

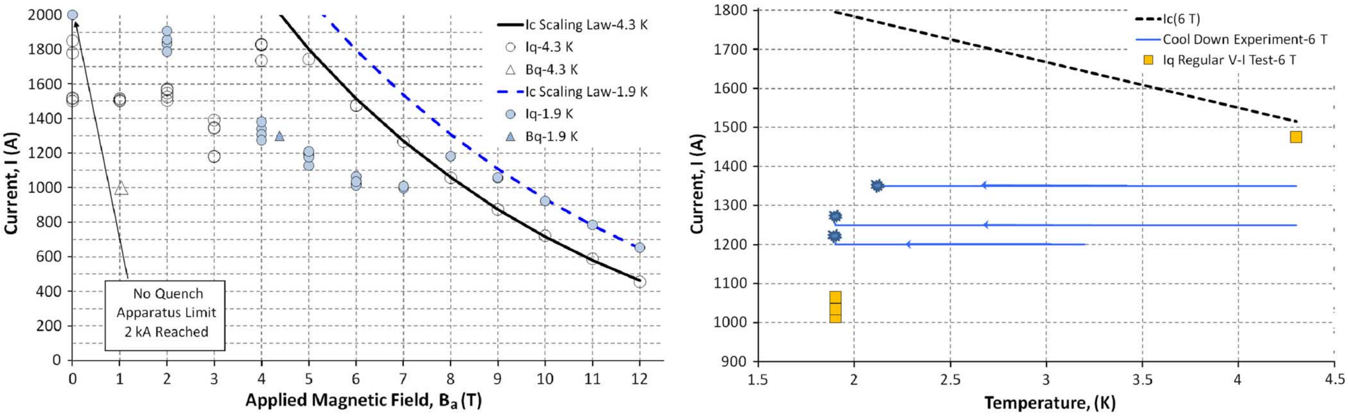

Fig. 2. Critical and stability current measurements in an extracted 0.7 mm 54/61 RRP strand (sample 1 in Table II): the plot on the left shows the V-I (I_q data) and V-H (B_q data) measurements [9] at 4.3 and 1.9 K; the plot on the right shows the cool down experiment performed with a background field equal to 6 T.

coil 22 – coil 28) were monitored with a sufficiently high sampling rate (100 kHz). For the signals s1 and s2 the peak-to-peak noise was lower than 8 mV while for s3 it was lower than 16 mV. During this measurement no voltage spikes were recorded compared with hundreds of voltage spikes that were recorded during regular ramp in TQS02c.

Finally a temperature dependence study using regular quench current measurements was also performed. The magnet had a stable behavior (reaching its plateau current) between 4.3 K and 2.7 K while below 2.7 K the quench current significantly dropped and the magnet became unstable. Fig. 1 summarized the results obtained during the cool down experiments and the temperature dependence study.

The test results met the expectations of the theory showing that: 1) in the temperature region where the magnet is limited by magneto-thermal instabilities, the magnet is more stable using the ‘cool down’ procedure than during the regular quench current measurements; 2) partial flux jumps are not present during the ‘cool down’ experiment.

These results also showed that the magnet can quench during the cool down experiment; these premature quenches cannot be attributed to the magnetization instability as predicted by the theory and confirmed by the lack of voltage spikes. Since it is clear that they are due to magneto-thermal instabilities and the magnetization instability is excluded by the special procedure used, these results are strong experimental evidences that the cause of magnet premature quenches at temperature around 1.9 K is the uneven distribution of the transport current within the strand (self field instability).

III. STRAND MEASUREMENTS

In order to correlate the magnet performance with the conductor behavior seven 0.7 mm RRP strand samples were extensively tested at CERN. The samples were reacted and tested on VAMAS Ti-alloy barrels. Five samples were reacted using the regular LARP heat treatment: 72 hrs at 210°C, 48 hrs at 400°C and 48 hrs at 640°C. Two samples were reacted changing the temperature of the last plateau to 665°C. The strands come from 3 different billets: billet 8781 used in the TQS02c magnet; billet 10400 used in the TQS03a magnet and; billet 9560 used in the LARP cable recently tested at CERN [15] and in the Long Quadrupole magnet (LQ) [15]. More information are summarized in Table II.

Comparing the critical current measurements of Tables I and II one can notice that the critical current of the samples tested at CERN is significantly lower than those of the magnet witness samples. This difference is most likely due to the significant sensitivity of the strand critical current to the temperature value of the 48 hrs plateau at 640°C.

Fig. 2 shows the measurements performed on sample 1 (see Table II). The plot on the left summarizes the ‘classical’ critical and stability current measurements (V-I, V-H measurements [9]) while the plot on the right shows the cool down experiment performed on the strand with a background field equal to 6 T. The cool down experiment performed on the strand confirmed the behavior observed during the same experiment in the TQS02c magnet. More details regarding the test of this strand can be found in [14].

Fig. 3 shows the critical and the quench current obtained from samples 2 and 3 at 1.9 K during V-I measurements (the current is ramped in the sample with a fixed background magnetic field—premature quenches during V-I measurements are due to the self-field instability [9]). Sample 2 is a round wire while sample 3 is an extracted strand. The extracted strand was tested twice, the second time a thin layer of sty-cast was applied on the sample to better bond the strand to the VAMAS barrel and to fill any possible gap between the wire and the VAMAS groves. When the sty-cast was solidified the surface of the strand was cleaned by gently sanding the sample in order to have a direct contact between the strand copper and the helium bath.

Before being tested at 1.9 K the samples 2 and 3 were tested at 4.3 K where it was possible to measure the critical current at least from 12 T down to 9 T. At 1.9 K the samples tested without sty-cast are strongly unstable and the local minimum in the premature quench current value (see Fig. 3) is at higher fields with respect to the results generally measured on similar strands: 8–9 T instead of 6–7 T (see Figs. 2 and 4). Furthermore the quench current value in this minimum is significantly lower: 600–700 A instead of 850–1000 A.

The extracted strand (sample 3) is particularly unstable and it was not possible to measure the critical current even at 12 T. After application of the sty-cast, sample 3 was retested: at 1.9

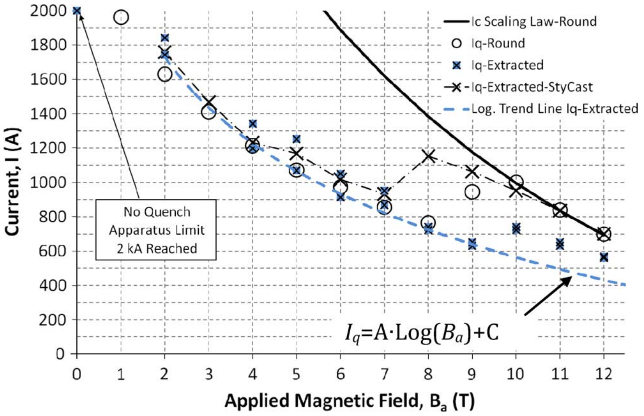

Fig. 3. Quench currents during V-I measurements [9] at 1.9 K for two 54/61 RRP strands: samples 2 and 3 in Table II. For each field at least 5 quenches starting with the sample not magnetized [9] were carried out, in the plot the minimum and maximum quench values are reported for one test (Iq-Extracted) while only the minimum value is reported for the other two tests.

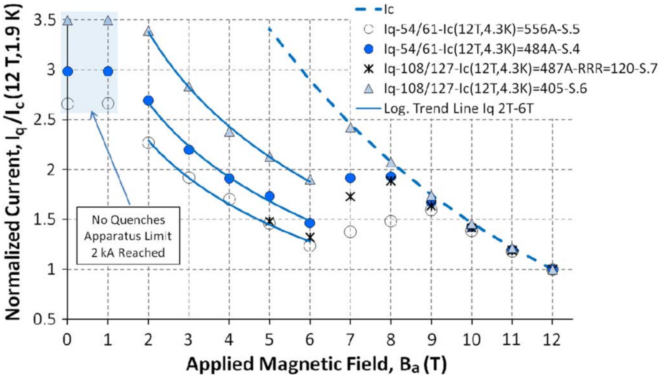

Fig. 4. Quench currents during V-I measurements at 1.9 K normalized versus the strand critical current at 1.9 K and 12 T for 0.7 mm RRP strand samples with different critical current (Samples 5, 4, 7, and 6 in Table II). These samples have a RRR larger than 200 unless differently specified in the legend. In the plot, for each field, only the minimum value of the quench current is reported.

K it was possible to measure the critical current at high fields (11–12 T), and the minimum in the premature quench current moved back from 9 T to 7 T (see Fig. 3). From 7 T to lower fields the quench current was practically the same as during the test without sty-cast. This behavior can be explained by the perturbation theory of the self-field instability [10] assuming that the pronounced instability is due to larger strand micro-motions that are then reduced by using sty-cast as bonding agent. The strand micro-motion acts as a perturbation that initiates the self-field instability.

In Fig. 3, it is also very interesting to notice that in the field region between 2 T and the field where the minimum in the premature quench current is observed, the trend of the quench current can be approximated by a logarithmic curve. If this curve is extended toward higher fields one can observe that the estimated premature quench current in the 12 T field range is about 400 A. This value could explain the quench current of TQS02c at 1.9 K. A shift of the minimum towards the 12 T region might be explained by assuming that the conductor conditions in the magnet are more severe than those experienced during a strand test.

Fig. 4 shows a comparison of the quench current at 1.9 K normalized versus the strand critical current at 12 T for strands with different values of critical current. The goal of this plot is to compare the self-field stability of the conductor; this comparison can be accomplished by analyzing the low field region where the value of the quench current is practically independent from the strength of the perturbation that initiates the magneto thermal instability [10]. In this field region the quench current value is only ruled by the magneto-thermal instability of the conductor and not for example by the goodness of the strand sample mounting. In Fig. 4 the interesting field region is between 2 and 6 T (at 0 and 1 T the samples did not quench because the 2 kA test station limit was reached).

Comparing samples 4 and 5 (full circle marks and open circle marks respectively), 54/61 strands that come from the same billet and have a RRR larger than 200, one can notice that a decrease of about 13% of the critical current (at 12 T, 4.3 K) produces a significant increase of the strand stability (at 6 T the normalized quench current goes from 1.238 to 1.466).

In the plot there are also two RRP 108/127, (sample 6 and sample 7); in particular sample 7 (asterisk marks) has practically the same critical current as sample 4 and similar critical current density as sample 5 (the 54/61 RRP strands). Comparing these three strands (7, 4, 5) at 6 T one can conclude that the 108/127 (sample 7) is more stable than the 54/61 when the critical current density is similar (sample 5) but it is not when the critical current is similar (sample 4). This latest statement has to be further experimentally proved because sample 7, the 108/127 strand, had a lower RRR with respect to sample 4 (120 instead of more than 250). Nevertheless at 6 T the thermal and electrical conductivity of the copper improves only 20% passing from RRR 300 to RRR 120, hence from the results obtained one can expect that with RRR larger than 200 and with similar I_c, the stability at 1.9 K of the 108/127 is not significantly better than that one of the 54/61. Elsewhere [10] it was shown that increasing the RRR above 120 does not improve significantly the self-field stability of 54/61 RRP strands.

By further reducing the critical current in sample 6, a further increase in the stability was observed.

In conclusion the results in Fig. 4 suggest that at 1.9 K: 1) the main parameter in the strand stability (for a fixed strand diameter and a RRR sufficiently high) is the strand critical current; 2) doubling the number of sub-element does not have a drastic effect, although having smaller effective filament size is certainly beneficial for the conductor behavior. Further measurements are necessary to confirm this statement.

IV. TEST RESULTS OF TQS03A

TQS03a has been tested at CERN using a current ramp rate equal to 20 A/s. Initially the magnet was trained at 4.3 K. Only 8 quenches were sufficient to train the magnet that reached 93% of the short sample limit corresponding to a gradient of about 220 T/m. This is an excellent result also considering the relatively small number of quenches that were necessary to train a magnet built using 4 new coils.

The magnet was then cooled at 1.9 K and tested: after 16 quenches the magnet reached 13.452 kA, 92.8% of the short sample limit (237 T/m); although there was still no evidence of the training completion, the measurements at 1.9 K were stopped because the strain gages showed a lack of mechanical pre-stress of the magnet at this level of Lorentz forces. Finally two quenches at 4.3 K were done showing that the conductor was not degraded during the 1.9 K tests. The quench history plot of this test and more details can be found in [11].

TQS03a was the first TQ magnet based on the RRP conductor that was not limited by instabilities at 1.9 K. Stable behavior at 1.9 K was already observed in all TQS01 and TQC01 magnets based on the 54/61 MJR strand by OST but the critical current of the MJR wire was lower and those magnets reached a maximum current of about 12 kA [16]. This MJR strand had a similar geometry as the RRP 54/61 used in the TQS02 and TQC02 magnets and a critical current (12 T, 4.3 K) equal to about 390 A [17]: 1.42 times lower than the current of the RRP 54/61 used in TQS02c (556 A) and 1.16 times lower than the current of the RRP 108/127 used in TQS03a (454 A).

As suggested by the strand measurements, the increased stability at 1.9 K of the TQS03a magnet with respect to the TQS02 magnets is most likely due to the significant reduction of the strand critical current (more than 18%); other beneficial contributions to the magnet stability at 1.9 K are also the larger amount of copper in the strand and the increased number of sub-elements that improve the dynamic stabilization of the wire against self-field instability [10], [18].

V. Conclusion

The TQS02c magnet results obtained during the cool down experiments can be explained by the theory that suggested the new test. The results also showed that the magnet can quench during the cool down experiment; these premature quenches cannot be attributed to the magnetization instability as predicted by the theory and confirmed by the lack of voltage spikes. These results are strong experimental evidences that the self-field instability is the cause of premature quenches of TQS02 magnets at 1.9 K. The temperature dependence study showed that TQS02c reached its plateau current between 4.3 K and 2.7 K while for lower temperatures it is limited by the self-field instability.

The cool down experiment performed on the strand confirmed the behavior observed during the same experiment in the TQS02c magnet. Strand measurements also showed that by increasing the perturbation that initiates the self-field instability, the minimum premature quench current moves towards higher fields and its value decreases. This is consistent with the perturbation theory of the self-field instability [10]. In strands similar to those used in the TQS02c magnet, the trend of the premature quench current at 1.9 K might justify, in the 12 T field region, a quench current equal to about 400 A. This value could explain the quench current of TQS02c at 1.9 K.

Measurements of 54/61 and 108/127 RRP strands with different critical current values suggest that at 1.9 K: 1) the main parameter in the strand stability (for a fixed strand diameter and a sufficiently high RRR) is the strand critical current; 2) doubling the number of sub-elements does not have a drastic effect, although having smaller effective filament size is certainly beneficial for the conductor behavior. Further measurements are necessary to confirm this statement.

The test of TQS03a showed that this magnet, based on the 108/127 RRP conductor with reduced critical current, was not limited by magneto-thermal instabilities and reached 93% of the short sample limit both at 4.3 K and 1.9 K.

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