SELF-FIELD INSTABILITIES IN HIGH-J_C Nb_3Sn STRANDS: THE EFFECT OF COPPER *RRR*

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Abstract

High critical current density (J_c) Nb_3Sn conductor is the best candidate for next generation high field (> 10 T) accelerator magnets. Although very promising, state of the art high-J_c Nb_3Sn strands suffer of magneto-thermal instabilities that can severely limit the strand performance. Recently it has been shown that at 1.9 K the self field instability is the dominating mechanism that limits the performance of strands with a low (<10) Residual Resistivity Ratio (*RRR*) of the stabilizing copper. At CERN several state of the art high–J_c Nb_3Sn wires have been tested at 4.2 K and 1.9 K to study the effects on strand self-field instability of: *RRR* and strand impregnation with stycast. To study the effect of the *RRR* value on magneto-thermal instabilities, a new 2-D finite element model was also developed at CERN. This model simulates the whole development of the flux jump in the strand cross section also taking into account the heat and current diffusion in the stabilizing copper. In this paper the main conclusions drown from this study are reported.

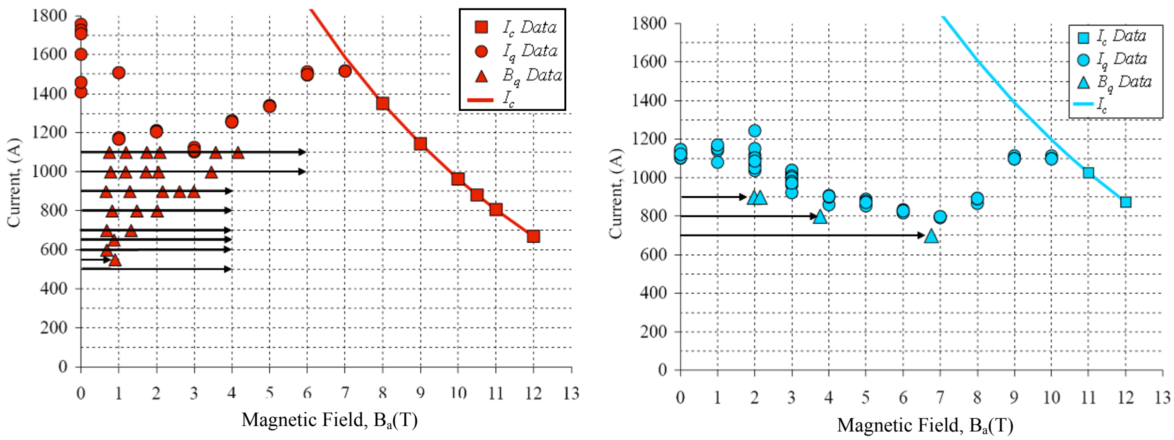
INTRODUCTION

High critical current density (J_c) Nb_3Sn conductor is the best candidate for next generation high field (> 10 T) accelerator magnets. Although very promising, state of the art high-J_c Nb_3Sn strands suffer of magneto-thermal instabilities [1]-[6] that can severely limit the strand performance [6]-[9]. There are two types of magneto-thermal instabilities: 'Magnetization' instability due to the magnetization of the superconducting filaments [1][2] and mainly depending on J_c, on the effective filament size (D_{eff}) and on the Residual Resistivity Ratio (*RRR*) of the stabilizing copper; 'Self-field' instability due to the uneven distribution of the transport current within the strand [3][4] and mainly depending on J_c and the strand diameter. The effect of *RRR* on the self-field instability has not been much studied in high-J_c Nb_3Sn conductor and is one of the topics of this paper.

Magnetization instability has been the primary cause of the limited quench performance (40-70 % of the short sample limit) at 4.4 K of some Nb_3Sn high field magnets built at FNAL [10] and LBNL [9] [11] in the early 2000s. In these magnets the stability current (I_s) of the conductor (i.e., the minimum current at which the conductor can have a premature quench due to magneto-thermal instability) occurred at very low magnetic fields (~0-3 T) and it was significantly lower than the magnet intrinsic critical current (I_c); hence, since in the magnet there are always regions where the magnetic field is low, the magnet quenched when the current reached the stability current value. The low value of the stability current was due to the large D_{eff} (70 - 100 μm) of the conductor, to the high J_c (1700-1900 A/mm^2 at 4.2 K and 12 T) and to the low Residual Resistivity Ratio (*RRR*<10) of the stabilizing copper. At present, the problem of magnetization instability at 4.4 K is contained through optimized heat treatments and cabling processes that guarantee a high *RRR* (>150). Using such approach, the U.S. LHC Accelerator Research Program (LARP) collaboration (which consists of four US laboratories, BNL, FNAL, LBNL, and SLAC, who collaborate with CERN on the Large Hadron Collider) was able to build and test a 1-m-long quadrupole (TQS01) based on a Nb_3Sn Modified Jelly Roll strand produced by Oxford Superconducting Technology (OST) (J_c ~1900 A/mm^2; D_{eff} ~70 μm) that reached more than 80 % of the short sample limit both at 4.4 K and 1.9 K, and did not show evidences of magneto-thermal instabilities [12]. Recently, the LARP collaboration built two 1-m-long quadrupoles and a 4-m-long racetrack based on the more performing Rod Re-Stack Process (RRP®) strand produced by OST (J_c >2400 A/mm^2; D_{eff} ~70 μm): at 4.4 K, these magnets reached more than 85 % of the short sample limit [12][13][14].

In a previous paper [6] it has been shown that at 1.9 K the self-field instability is the dominating mechanism that limits the performance of high-J_c Nb_3Sn strands with a low *RRR* (<10). It was also shown [6] that for RRP® strand with low *RRR*: 1) the minimum quench current due to the self-field instability, that is the self-field stability current ($I_{s\text{-}SF}$), is lower at 1.9 K than at 4.2 K and; 2) at 1.9 K the $I_{s\text{-}SF}$ can be considerably lower than the critical current at 12 T. The self-field instability might be the cause of the limited quench performance at 1.9 K of the latest magnets based on the RRP® conductor built by the LARP collaboration [12][13]. At 1.9 K the quench current of these magnets did not practically change with respect to the 4.4 K case, and this behavior cannot be attributed neither to critical current degradation (the magnets were retested at 4.4 K reaching the previous current values) nor to mechanical instability (often the quench current values at 1.9 K were lower than those obtained at 4.4 K).

At CERN several state of the art high–J_c Nb_3Sn wires have been tested at 4.2 K and 1.9 K to see if the conclusions drawn for samples with low *RRR* can be extended to samples with higher *RRR* values and to study the effects on strand stability of *RRR* and strand impregnation with stycast. The strand samples were heat treated and tested on grooved cylindrical Ti-Alloy barrels (ITER barrel). The wires tested included RRP® strands produced by OST and Powder In Tube (PIT) strands



(a) *(b)*

Figure 1: V-I (I_c and I_q data) and V-H (B_q data) measurement results at 4.2 K (plot *a*) and 1.9 K (plot *b*) for a 0.8 mm RRP® strand with copper *RRR*=8 [6].

produced by ShapeMetal Innovation - European Advanced Superconductors (SMI-EAS).

To study the effect of the *RRR* value on magneto-thermal instabilities, a new 2-D finite element model was also developed at CERN. This model simulates the whole development of the flux jump in the strand cross section also taking into account the heat and current diffusion in the stabilizing copper. In this paper the main conclusions drawn from this study are reported; a more detailed presentations of the experimental results and of the model can be found elsewhere [15].

SELF FIELD INSTABILITY IN HIGH-J_C Nb$_3$Sn STRANDS WITH LOW *RRR*

In a previous study it was found that at 1.9 K magnetization instability does not play a significant role on the quench performance of high-J_c Nb$_3$Sn wire with low *RRR* (<10), indeed during V-H measurements the local minimum of the quench current at low fields (0-3 T), confirmed at 4.2 K (see B_q data in Fig. 1*a*), disappeared at 1.9 K (see B_q data in Fig. 1*b*) [6]. At 1.9 K, the self-field instability is the dominating instability mechanism. A semi-analytical model, supported by experimental measurements, demonstrated that for these strands the self-field instability is characterized by 3 stability regions: an 'high field' stable region where the conductor can reach its intrinsic critical current; an 'intermediate field' region where the premature quench current depends on the severity of the perturbation that initiates the magneto-thermal instability and is higher than a certain minimum, $I_{qMin\text{-}SF}$ *(B)*; a 'low field' region where the premature quench current value does not depend on the amount of the perturbation and a quench can occur as soon as the current is higher than $I_{qMin\text{-}SF}$ *(B)*. Furthermore, the self field stability current $I_{s\text{-}SF}$ occurs in the 'intermediate field' region (~ 3-8 T at 4.2 K and ~ 7-11 T at 1.9 K for the 0.8 mm RRP® strand) and it is lower at 1.9 K than at 4.2 K (see Fig. 2). This conductor behavior could be a serious problem for accelerator magnets based on high-J_c Nb$_3$Sn conductor that have to work at 1.9 K. At CERN the effect of *RRR* on the strand self-field stability was investigated to see if a high *RRR* value can solve this stability problem at 1.9 K; the main results are reported in the next section.

MAIN RESULTS

Testing at CERN seven 0.8 mm 54/61 RRP® strand samples with a similar J_c (>2500 A/mm^2 at 4.2 K and 12 T), it was found that:

1. At 4.2 K in the 'low field' region (0-3 T) the *RRR* value has not a large effect on the self field stability (the premature quench current during V-I measurements [6] increases only few percentages passing from *RRR*=8 to

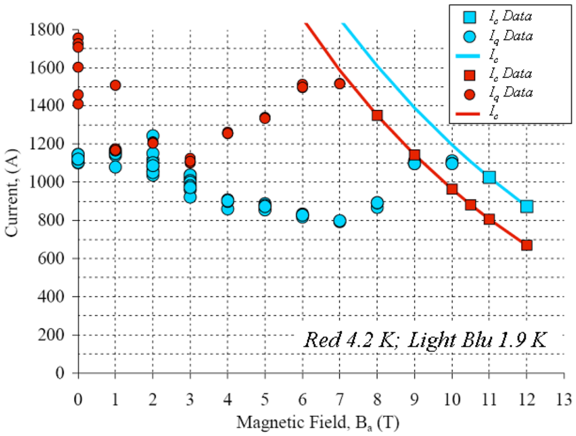


Figure 2: V-I measurements of a 0.8 mm RRP® strand with copper *RRR*=8 [6]: comparison between the results obtained at 4.2 K and at 1.9 K.

RRR=120 or from RRR=140 to RRR=290);

2. At 1.9 K in the ‘low field’ region (0-7 T) the self-field stability significantly improves passing from RRR=8 to RRR=120 (during V-I measurements the premature quench current gets more than 50 % larger), further increasing the RRR does not produce significant effects;
3. In the ‘intermediate field’ region (3-8 T at 4.2 K and 7-11 T at 1.9 K) it was not possible to find experimental evidence, both at 4.2 K and 1.9 K, of the quench performance improvement by increasing the RRR value;
4. In the ‘intermediate’ field region the self-field instability is much more sensitive, with respect to the ‘low field’ region, to the amount of energy released by the perturbation that initiates the magneto-thermal instability; the larger is the perturbation, the lower is the quench current due to the self-field instability;
5. This strong sensitivity in the ‘intermediate field’ region and the difficulty of exposing all the samples to exactly the same perturbation spectrum is most likely the cause of what was observed in point 3;
6. Independently of the RRR value, the minimum quench current due to the self-field instability, that is the self-field stability current ($I_{s\text{-}SF}$), occurs in the ‘intermediate field’ region and is lower at 1.9 K than at 4.2 K;
7. If the energy released by the perturbation that triggers the magneto-thermal instability is sufficiently high, at 1.9 K the self-field stability current ($I_{s\text{-}SF}$) can be significantly lower than the strand critical current (I_c) at 12 T and 4.2 K even for strands with an high RRR value and with $I_{s\text{-}SF}$(4.2 K)> I_c(12 T, 4.2 K);
8. V-H measurements performed at 1.9 K confirmed that magnetization instability does not play a significant role at 1.9 K even in strand with high RRR values;
9. Covering a strand (RRR ~120) with a 1 mm thick layer of stycast did not significantly change the premature quench current values at 4.2 K while it systematically decreased the minimum quench current due to the self field instability of about 10% at 1.9 K in the ‘low field’ region (0-7 T).

The test of a 0.8 mm PIT strand with a J_c equal to 2224 A/mm^2 (at 4.2 K and 12 T) and a RRR=27 showed that this strand is much more self field stable than the previous RRP® strands; at 1.9 K, the self field stability current $I_{s\text{-}SF}$ is almost twice larger than the critical current at 12 T. This improved stability with respect to the RRP® strands is due to the lower critical current density and to the different strand layout. Indeed, the PIT wire had a larger amount of copper in between the superconducting sub-elements, a larger copper to non-copper ratio and a smaller sub-element size with respect to the RRP® strand; all these solutions allow improving the dynamic stabilization of the strand. More details regarding these measurements can be found in [15].

The test at CERN of two round 0.7 mm RRP® strand samples showed that a small local damage of the copper stabilizer can completely jeopardize the dynamic stabilization of a high-J_c Nb_3Sn strand with a high global RRR. The strand for preparing these two samples is the same used by the LARP collaboration for building magnet models [12][13][14] and it was send to CERN by Arup Ghosh (BNL) in the framework of a collaboration between LARP and CERN. The two samples were heat treated together (at the University of Geneva) following the procedure used for reacting LARP magnets; straight samples for RRR measurements were also inserted in the oven. After the heat treatment one sample presented a small copper burst (see Fig. 3). A comparison of the critical and stability current measurements of the two samples at 4.2 K an 1.9 K shows that although this small damage did not degrade the critical current of the sample, it drastically reduced its magneto-thermal stability (the stability current at 4.2 K and 1.9 K gets reduced of a factor of two and it was even lower than the strand critical current at 12 T and 4.2 K). The damage consisted in the local reduction of the RRR and of the amount of stabilizing copper. The huge difference in the stability performance of the two samples is also due to the high global RRR value (a RRR larger than 250 was measured on the straight samples).

A new numerical model for simulating magneto-thermal instabilities was developed at CERN. This model, based on the finite element method, simulates the whole development of the flux jump in the strand cross section also taking into account the heat and current diffusion in the stabilizing copper and the strongly non linear transition of the superconductor to the normal state [15]. The model shows that the self-field instability is significantly dependent on the level of energy of the initial perturbation (the higher the perturbation the lower the quench current). This is true until the current reaches a certain minimum value of the premature quench current, $I_{qMin\text{-}SF}(B)$, below which it seems not to decrease independently from the strength of the perturbation. Furthermore, the lower is the magnetic field, the lower is the value of the perturbation energy beyond which the quench current is equal to $I_{qMin\text{-}SF}(B)$. From this

Figure 3: Picture of a round 0.7 mm RRP® strand that had a copper burst during the heat treatment. The wire is mounted on a Ti-Alloy barrels (ITER barrel).

calculation one can conclude that for a certain perturbation energy, there are three stability regions: a 'low field' region ($0<B<B_{LF}$) where the quench current is practically equal to $I_{qMin\text{-}SF}(B)$; an 'high field' stable region ($B>B_S$) where the conductor reaches its intrinsic critical current and; an 'intermediate field' region ($B_{LF}<B<B_S$) where premature quenches occur but the quench current is higher than $I_{qMin\text{-}SF}(B)$. These stability regions were already predicted by our previous semi-analytical model [6], the novelty being that the values of B_{LF} and B_S depends on the level of energy of the initial perturbation. From the model, one can also conclude that increasing the *RRR* above 120 has not a significant stabilization effect while passing from *RRR* less than 10 to 120 may have a significant stabilizing effect at high fields (at low fields the effect of *RRR* is rather limited). Nevertheless the stabilizing effect of *RRR* at high fields is drastically reduced when the energy released by the initial perturbation is sufficiently high. More details on the model and its results can be found in [15].

CONCLUSIONS

Strand measurements show that at 1.9 K the self-field instability is the dominating mechanism that limits the performance of high–J_c Nb_3Sn wires and the magnetization instability does not play a significant role. For these strands, the minimum quench current due to the self-field instability, that is the self field stability current ($I_{s\text{-}SF}$), is lower at 1.9 K than at 4.2 K; at 1.9 K, even if the *RRR* of the stabilizing copper is high, the $I_{s\text{-}SF}$ can be lower than the critical current (I_c) at 12 T and 1.9 K and, in case of strong perturbations the $I_{s\text{-}SF}$ can be even lower than the I_c at 12 T and 4.2 K. This behaviour could explain the performance of the latest Nb_3Sn LARP magnets based on the RRP® conductor that, at 1.9 K, had equal or even lower quench currents with respect to the 4.4 K case. At 1.9 K, increasing the *RRR* from 8 to 120 is beneficial for the strand self-field stability, while further increasing the *RRR* value does not produce significant effects. Strand measurements also showed that covering the strand with a 1 mm thick layer of stycast reduced the quench current at 1.9 K of less than 10 %.

A new numerical model for simulating magneto-thermal instabilities was developed. This model, based on the finite element method, simulates the whole development of the flux jump in the strand cross section also taking in to account the heat and current diffusion in the stabilizing copper and the strongly non linear transition of the superconductor to the normal state. Preliminary results show that the new model is in good agreement with the experimental data. The model also shows that the self-field instability is characterized by three stability region and in the 'intermediate field' region is strongly sensitive to the perturbation energy that initiates the magneto-thermal instability. Consistently with the experimental data the model predicted that the self-field stability current ($I_{s\text{-}SF}$) occurs in the 'intermediate' field region and if the perturbation energy is sufficiently high (but still much lower than the minimum quench energy) $I_{s\text{-}SF}$ can be lower than the intrinsic critical current at 12 T even with high *RRR* values of stabilizing copper.

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