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Impact of the Residual Resistivity Ratio on the Stability of Nb_3Sn Magnets

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Abstract

The CERN Large Hadron Collider (LHC) is envisioned to be upgraded in 2020 to increase the luminosity of the machine. The major upgrade will consist in replacing the NbTi quadrupole magnets of the interaction regions with larger aperture magnets. The Nb_3Sn technology is the preferred option for this upgrade. The critical current density J_c of Nb_3Sn strands have reached sufficiently high values (in excess of 3000 A/mm^2 at 12 T and 4.2 K) allowing larger aperture/stronger field magnets. Nevertheless, such large J_c values may cause magneto-thermal instabilities that can drastically reduce the conductor performance by quenching the superconductor prematurely. In Nb_3Sn magnets, a relevant parameter for preventing premature quenches induced by magneto-thermal instabilities is the Residual Resistivity Ratio (RRR) of the conductor stabilizing copper. An experimental and theoretical study was carried out to investigate how much the value of the RRR affects the magnet stability and to identify the proper conductor specifications. In this paper the main results are presented and discussed.

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***Abstract*— The CERN Large Hadron Collider (LHC) is envisioned to be upgraded in 2020 to increase the luminosity of the machine. The major upgrade will consist in replacing the NbTi quadrupole magnets of the interaction regions with larger aperture magnets. The Nb_3Sn technology is the preferred option for this upgrade. The critical current density J_c of Nb_3Sn strands have reached sufficiently high values (in excess of 3000 A/mm^2 at 12 T and 4.2 K) allowing larger aperture/stronger field magnets. Nevertheless, such large J_c values may cause magneto-thermal instabilities that can drastically reduce the conductor performance by quenching the superconductor prematurely. In Nb_3Sn magnets, a relevant parameter for preventing premature quenches induced by magneto-thermal instabilities is the Residual Resistivity Ratio (*RRR*) of the conductor stabilizing copper. An experimental and theoretical study was carried out to investigate how much the value of the *RRR* affects the magnet stability and to identify the proper conductor specifications. In this paper the main results are presented and discussed.**

***Index Terms*—Magnet, Nb_3Sn, RRR, stability**

I. INTRODUCTION

HIGH critical current density, J_c, Nb_3Sn wires are the superconductors preferred option for the next generation of accelerator magnets at CERN [1]-[3]. The J_c of recent Nb_3Sn strands have reached values in excess of 3000 A/mm^2 at 12 T and 4.2 K allowing larger aperture/stronger field magnets. On the other hand, such large J_c values may cause magneto-thermal instabilities that can drastically reduce the conductor performance by quenching the superconductor prematurely before reaching its critical current [4]-[13]. Magneto-thermal instabilities cause fast redistribution of the current and of the magnetic field (flux-jumps) within the superconductor. This redistribution, initiated by a tiny increase of temperature, in turn generates heat that can establish an avalanche process quenching the superconductor.

In high J_c Nb_3Sn magnets, one of the main parameters for preventing premature quenches caused by magneto-thermal instabilities is the thermal and electrical conductivity of the stabilizing copper within the Nb_3Sn strands. A large copper conductivity allows a major amount of heat to escape from the region that is experiencing the instability, thus improving the capability of the superconductor to sustain a flux jump without quenching. The copper conductivity at liquid helium temperature is quantified by its Residual Resistivity Ratio (*RRR*): a large RRR value indicates a large conductivity. Nb_3Sn strands that do not suffers of tin leaks during the reaction cycle (necessary to form the superconductor) can have RRR values larger than 300. On the other hand if the heat treatment cycle is too long or some sub-element barrier is damaged, the Sn can diffuse from the superconducting sub-elements into the copper matrix and reduce the RRR to values than can be lower than 10 [4]-[7] ,[10].

Manufacturing companies have difficulties in guaranteeing RRR values significantly larger than 100 for large quantities of high J_c Nb_3Sn strands. Hence it is important to establish the impact of the RRR on the stability of Nb_3Sn magnets. For this purpose, an experimental and theoretical study was carried out at CERN. The critical and stability currents of five different strand samples with similar critical current density but different RRR were tested. All the samples were prepared using the same superconducting high J_c wire. A semi-analytical model was developed to interpret the experimental results and to quantify the effect of the copper RRR. In this paper the main results are presented and discussed.

II. CONDUCTOR INSTABILITIES & MAGNET PERFORMANCE

At a given temperature, the maximum current for a stable magnet is determined by the intersection of the magnet 'load-line' and the line representing the conductor critical current as a function of the magnetic field (see point **A** in Fig.1). If the conductor is affected by magneto-thermal instabilities, the magnet can have premature quenches at a current and peak field that are lower than those expected. Fig. 1 also shows the strand quench currents in the case of magneto-thermal instabilities (instability curves). If the contribute of the strand magnetization is negligible, the premature quench current is dominated by the self-field instability that is a fast redistribution of the transport current within the strand [7],[10],[14]. In Fig. 1 two lines indicate the quench current due to the self-field instability (curves labeled 'SF instability' and 'SF instability with large perturbations'), they differ in the behavior at relative high fields. This difference is due to the different energy of the small perturbation acting on the strand. To trigger instabilities is necessary a small perturbation and the larger is the magnetic field the larger is the perturbation energy required. Hence, at relative high fields, if the perturbation is not sufficiently high the instability does not start and the quench current gets closer and closer to the critical current while increasing the field ('SF instability'

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curve in Fig. 1). ‘Large perturbations’ in this contest indicate perturbations large enough to initiate an instability but with a energy that is in any case much lower than the Minimum Quench Energy.

In the case the magnetization energy is not negligible, the quench current is determined by the redistribution of the transport current and of the magnetization currents (curve labeled ‘SF + M Instability’ in Fig. 1) [7],[10]. This curve significantly differs from the ‘SF Instability’ curve only at low fields where the contribution of the energy associated to the magnetization can be relevant.

A magnet whose conductor is affected by magneto-thermal instabilities can have premature quenches if the minimum of the quench current at low fields (point **C** in Fig. 1) or the quench current defined by the intersection of the Magnet ‘load-line’ with the ‘SF Instability’ curve (point **B** in Fig. 1) are lower than the nominal current value (point **A** in Fig. 1). The current values of the minimum quench current at low fields (point **C**) and high fields (point **B**) for a magnet depend on the RRR value of the copper stabilizer. In the next sections this dependence will be quantified.

III. STRAND MEASUREMENTS

In order to experimentally assess the role of the RRR, the critical and stability currents of five different strand samples were measured. The samples were prepared using the same high J_c Nb_3Sn strand, a 0.8 mm 54/61 RRP® manufactured by Oxford Superconductor Technology. The strand had a copper to non copper ratio equal to 0.92 and an effective filament size of ~ 80 µm (more details about the strand layout in [10]). The samples were wound, reacted and tested on grooved cylindrical Ti-6Al-4V alloy barrels (ITER barrel). They were reacted in vacuum atmosphere using five different reaction cycles that differ for the duration of the high temperature plateau at 695 °C. These durations were chosen in order to obtain different values of the RRR without significantly changing the critical current of the samples. In reality the heat treatment was only one and the different samples were removed from the oven at different time (to remove the samples it was of course necessary to cool down the furnace at room temperature and then ramp it up again at high temperature for the remaining samples). The length of the last temperature plateau together with the RRR values and the measured critical current properties are summarized in Table I. Besides sample 4, all the other samples show a similar critical current density J_c and Kramer field B_{c2}^* at 4.3 K; the J_c slightly decreases by increasing the length of the high temperature plateau (due to the increase of dimensions of the Nb_3Sn grain size [15]) while the B_{c2}^* increases (due to an increase of the Sn content in the superconductor [15]). Sample 4 does not follow this behavior because it was not well supported. The strand was not perfectly in contact to the barrel and during the test the Lorenz forces, pushing the strand towards the barrel, induced a compressive strain that reduced the critical current.

In addition to the critical current measurements, the quench current was measured in the field region were the conductor was unstable. Both V-I and V-H measurements were carried out using the procedure described in [10] and [12]. In V-I measurements, the sample current is ramped up to quench while keeping constant the applied field. Premature quenches during V-I measurements are due to the self-field instability [10]. V-H measurements are carried out by ramping the applied field from 0 T to the quench of the sample while keeping constant the current in the sample; premature quenches during the V-H measurements are due to the combination of the self-field instability with the magnetization instability [7][10]. The main results collected at 4.3 K are summarized in Fig. 2. For the sample 2 (RRR equal to 265), all the results of the V-I measurements are reported: the critical current measured from 12 T to 8 T; the minimum quench current [12] in the field region from 7 T to 1 T where there were always premature quenches. This latest field region was divided in 2 sub-regions: a ‘perturbation region’ where the quench current at a certain field can significantly change from quench to quench because it is strongly dependent on the energy of the perturbation that initiates the instability [12]; an ‘energy region’ where even the smallest perturbation that characterize our system can start a flux jump and the current value at which the quench can occur depends only on the energy associated to the current distribution [12]. In the plot are also reported: the quench current during V-I measurements of the sample 4 (RRR 80) and the minimum quench current during V-H measurements at low fields of sample 4 (RRR 80) and 5 (RRR 30). In the plot the dashed line represent the

TABLE I STRAND PROPERTIES

Sample ID	Time at 695 °C [hrs]	*RRR*	I_c(4.3 K-12 T) [A]	J_c (4.3 K-12 T) [A/mm^2]	B_{c2}^*(4.3 K) [T]
1	20	289±7	800	3068	24.55±0.38
2	30	265±8	778	2982	24.55±0.22
3	50	149±8	773	2963	24.96±0.67
4	70	81±7	732	2806	26.59±1.58
5	100	30±3	759	2909	25.64±0.43

[*] Determined from critical current measurements

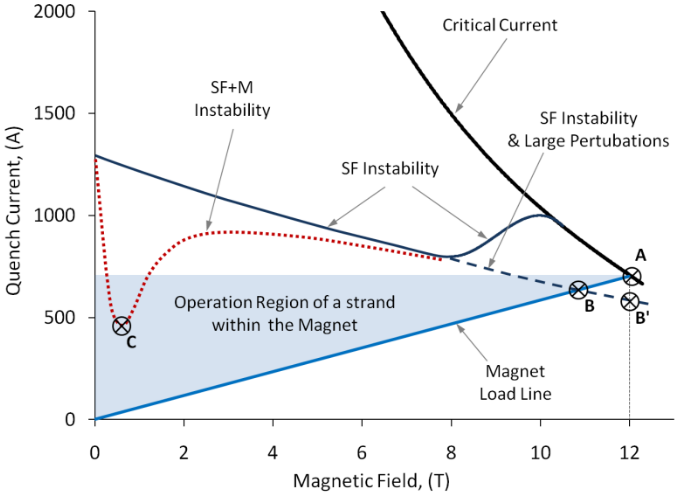

Fig. 1. Sketch representing qualitatively the causes of premature quenches in superconducting magnets affected by magneto-thermal instabilities. In the plot it is reported the current in a strand of the magnet. The acronyms SF and M stand for Self Field and Magnetization respectively.

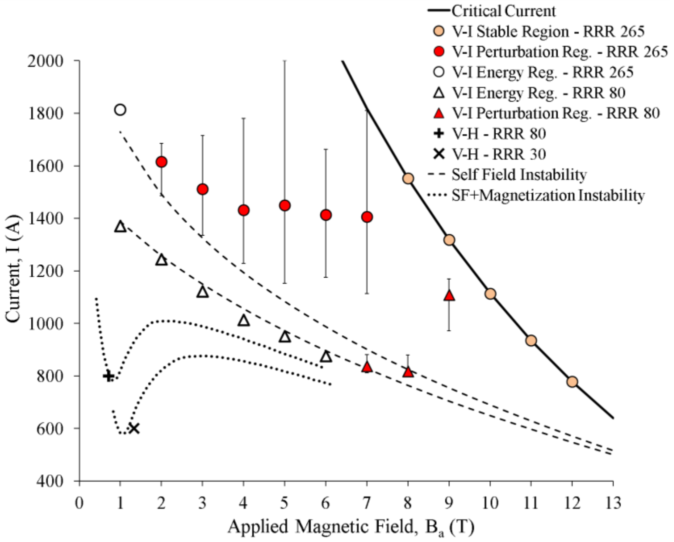

Fig. 2. Critical current and quench current at 4.3 K. The markers represent the experimental results while the dashed lines are the simulation using the proposed semi-analytical model.

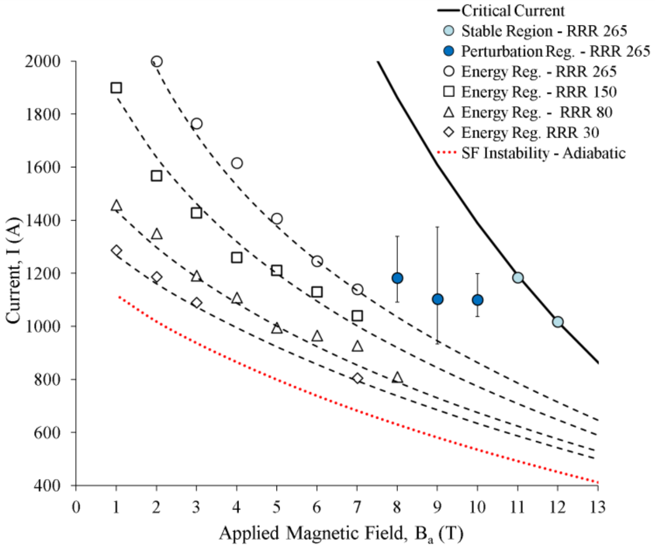

Fig. 3. Critical current and quench current at 1.9 K. The markers represent the experimental results while the dashed lines are the simulation using the proposed semi-analytical model.

results calculated by the analytical model presented in the next section. The other experimental data were not shown for the sake of clarity of the plot and because they did not bring significant additional information. Indeed the behavior of sample 1 (RRR 290) was very similar to that one of sample 2 (RRR 265). The minimum quench current at low fields in the V-H measurements for the samples with large RRR (≥ 149) were higher than 1100 A. The 'energy region' of samples 3 and 5 were limited at fields lower than 2 T. Furthermore, the 'energy region' of all the samples can be clearly observed in the measurements at 1.9 K (see Fig. 3). Indeed at 1.9 K and with the same type of perturbation, the larger J_c and the smaller specific heat of the wire (with respect to the values at 4.3 K) extend the 'energy region' (and the 'perturbation region') towards higher magnetic fields [10][12]. In Fig. 3 the results of the V-H measurements are not reported because, as already observed previously [10][12], the contribution of the magnetization is not that relevant for this strand at 1.9 K.

IV. MODELING

To study the RRR effect, a model based on the Finite Element (FE) method had been already developed at CERN [12]. The FE model, although very powerful, is still computationally heavy and it is more suitable for studying the instability mechanism rather than doing parametric studies. For this reason, it was decided to develop a semi-analytical model capable of simulating the quench currents of an instable conductor also taking into account the stabilizing effect of the copper. The new semi-analytical model is based on the studies carried out with the FE model and on the structure of another semi-analytical model previously developed to study instabilities in the case of wires with very low RRR (<10) [10]. The main difference with the original semi-analytical model is to take into account the heat diffusion from the superconductor to the copper stabilizer during the flux jump. The diffusion mechanism is based on the same hypothesis used in the FE model that are: 1) the instability occurs only over a certain piece length (where the perturbation acts) and then it can propagate longitudinally (assumption supported by experimental studies on voltage spikes [7]); 2) part of the generated heat diffuses out from the region experiencing the flux jump and mostly it diffuses longitudinally in the strand through to the copper. The FE model shows that the RRR does not have a drastic effect on the amount of heat produced by the instability while it significantly helps to slow down the phenomenon allowing a larger amount of heat to be diffused away. For this reason the amount of energy produced by the instability and calculated by the original semi-analytical model was not modified and the time constant of the instability was imposed to be proportional to the electrical conductivity of the Copper. The new semi-analytical model proved to be quite accurate in predicting the quench current of the samples that were tested as it can be seen in Fig. 2 and 3.

A parametric study was carried out, using the properties of sample 2, to quantify the effect of RRR. In particular the quench current at 4.3 K was computed for the minimum in the low field region (point **C** in Fig. 1) and for 12 T in the case of self-field instability and large perturbations (point **B'** in Fig. 1). The results, normalized with respect to the critical current at 12 T and 4.3 K, are reported in Fig. 4. One can notice that for RRR larger than 100, the instability at low field (in the case of the considered conductor) is not a problem for a magnet designed to work at 12 T (or larger fields). On the other hand, the high field instability does not improve much increasing the RRR above 100 (that is partially due to the magneto-resistance effect dominating the electrical and thermal conductivity properties of the copper at high magnetic fields). Finally another study was carried out to estimate the impact of the RRR on the high field instability of samples with different critical current density and of the copper to non copper ratio. A reference strand and 3 different variants were considered. The reference strand had the same property as sample 2 while the other 3 differed from the reference for: 1) the J_c value; 2) the copper to non Copper; 3) the J_c and the copper to non Copper values. The results of the analysis are summarized in Fig. 5. For all the 4 cases an increase of RRR above 100 has not a large impact on the stability.

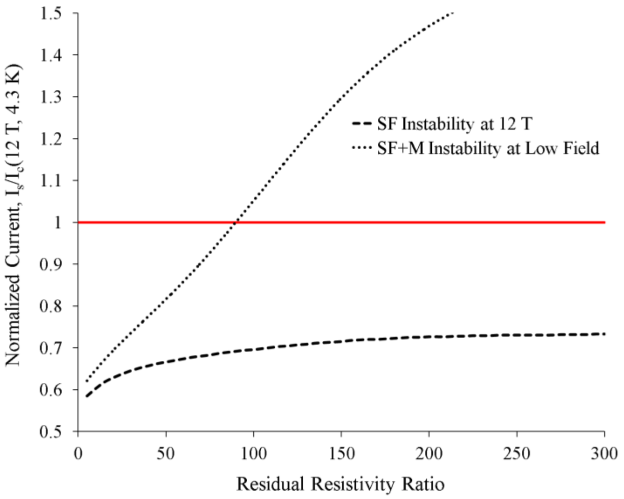

Fig. 4. Ratio between the quench current and I_c(12 T, 4.3 K) as a function of RRR in the case of high field instability at 12 T and low field instability

V. DISCUSSION

The stability studies presented in this paper show that a RRR larger than 100 has not a significant effect on the stability of a high field magnet (> 12 T). This conclusion is based on the analysis of a strongly unstable conductor hence it can be extended to more recent and stable conductors that have smaller J_c, smaller D_{eff} and a larger amount of copper. It is important to remark that even if conductors with RRR larger than 100 are not necessary for new generation accelerator magnets, it is mandatory that the RRR is not significantly lower than 100 in the whole length of the conductor. Indeed it was observed that a strand with an overall RRR larger than 200 and a region few mm long with a very low RRR, behaves as a strand with low RRR in terms of stability. For this reason the strand manufacturer should guarantee a RRR larger than 100 even in the case of mechanical deformation comparable to the worst experienced by the strand during the cabling. Finally one last remark concerns the calculation of the quench current at high fields showed in the plots 3-5. The computed quench current is conservative because it assumes that there is always a sufficiently strong perturbation capable of initiating the instability. This could be not always the case considering that at higher fields and temperatures, larger perturbations are necessary to trigger the instability.

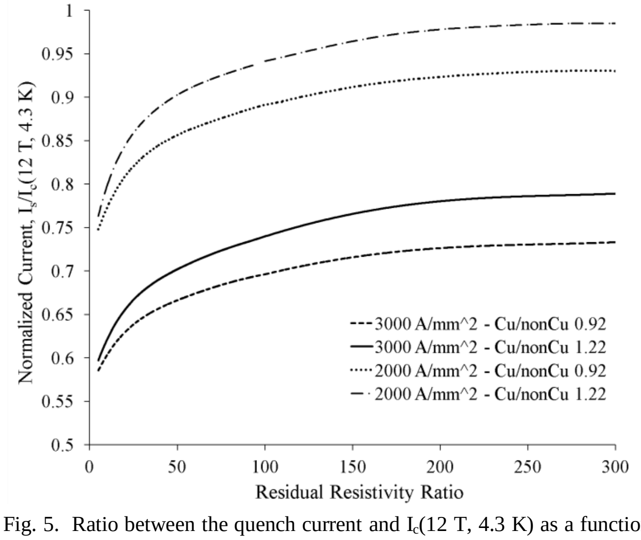

Fig. 5. Ratio between the quench current and I_c(12 T, 4.3 K) as a function of RRR in the case of high field instability at 12 T for different strands

VI. CONCLUSION

The Residual Resistivity Ratio of the stabilizing copper is one of the major parameter to guarantee the magneto-thermal stability of next generation accelerator magnets based on high Nb_3Sn conductor. In the paper, via both experimental and theoretical studies, it is shown how much a large RRR improves the magnet stability. It was found that a large RRR has a significant beneficial effect when the RRR is lower than 100 while, for larger values, the stabilization effect starts saturating. From this study, one can conclude that RRR 100 is a reasonable value to specify as conductor requirement. This constrain should be fulfilled by the strand manufacturing companies in the whole length of the conductor even in the case of samples few mm long with mechanical deformation comparable to the worst experienced by the strand during cabling.

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