

# MANUFACTURE AND TEST OF A SMALL CERAMIC-INSULATED Nb<sub>3</sub>Sn SPLIT SOLENOID

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## Abstract

A small split solenoid wound with high- $J_c$  Nb<sub>3</sub>Sn conductor, constituted by a 0.8 mm Rod Re-stack Process (RRP<sup>®</sup>) strand, was built and tested at CERN in order to study the applicability of: 1) ceramic wet glass braid insulation without epoxy impregnation of the magnet; 2) a new heat treatment devised at CERN and particularly suitable for reacting RRP<sup>®</sup> Nb<sub>3</sub>Sn strands. This paper briefly describes the solenoid and the experimental results obtained during 4.4 K and 1.9 K tests. The split solenoid consists of two coils (25 mm inner diameter, 51.1 mm outer diameter, 12.9 mm height). The coils were initially separately tested, in an iron mirror configuration, and then tested together in split solenoid configuration. In all the tests at 4.4 K the coils reached a current higher than 95 % of their short sample limits at the first quench; in split solenoid configuration the maximum field values in the coils and in the aperture were respectively 10.7 T and 12.5 T. At 1.9 K the coils had premature quenches due to self field instability despite the rather high RRR of the two coils (190 and 270). This phenomenon at 1.9 K, predicted by our theory [1], was confirmed by strand measurements.

## INTRODUCTION

In the framework of the High Field Magnet Program, CERN is developing an undulator for the lead ion beam in the Large Hadron Collider (LHC) and a wiggler for the Compact Linear Collider (CLIC) damping ring. These magnets are based on a single high- $J_c$  Nb<sub>3</sub>Sn wire. In order to explore the feasibility of using such conductor, a small split solenoid was built and tested at CERN. In particular, the main goal of this experiment was to study the applicability of: 1) ceramic wet glass braid insulation without epoxy impregnation of the magnet; 2) a new heat treatment devised at CERN and particularly suitable for reacting Rod Re-stack Process (RRP<sup>®</sup>) strands produced by Oxford Superconducting Technology (OST). This paper briefly describes the split solenoid and the experimental results obtained during 4.4 K and 1.9 K tests.

## MAGNET DESCRIPTION

The split solenoid consists of two small coils (Coil A, Coil B, see Fig. 1) wound with a 0.8 mm Nb<sub>3</sub>Sn RRP<sup>®</sup> strand produced by OST. To build the coils, the glass braid covered wire is varnished with a wet ceramic and wound around a stainless steel tube. The glass braid and the ceramic filler guarantee the turn-to-turn electrical insulation and prevent the strand motion within the coil. One end of the tube is connected to a stainless steel disc

that houses two Cu supports for the two coil terminals, see Fig. 1. The Cu supports are electrically insulated from the stainless steel disc through a ceramic layer. After heat treatment the coil terminals exceeding the Cu supports are cut, the remaining terminals and Cu supports are spliced to a 14 kA NbTi Rutherford cable through tin soldering and, four voltage taps are applied to measure the voltage across the coil and the voltage across the superconducting splices. Then a bronze annular support is inserted around the coil, and the coil is assembled with its iron half-yoke. The outer radius of the bronze annular support is equal to the outer radius of the stainless steel support (see Fig. 1).

At this point the coil can be either assembled with another coil to form the split solenoid, or assembled with an iron block to test the coil in mirror configuration. More details regarding the magnet manufacture are in [2].

In order to react the two coils and to have a sufficiently high Residual Resistivity Ratio (RRR) of the stabilizing copper without depressing the critical current density at high fields of the RRP<sup>®</sup> strand, the following heat treatment, devised at CERN, was used: 1) increase the temperature to 205 °C at 25 °C/hr and hold 205 °C for 72 hrs; 2) increase the temperature to 400 °C at 50 °C/hr and hold 400 °C for 48 hrs; 3) increase the temperature to 695 °C at 50 °C/hr and hold 695 °C for 17 hrs; 4) decrease the temperature to room temperature at 50 °C/hr. The coil A was heat treated in argon atmosphere at the INFN-LASA laboratory (Milan) while the coil B had a vacuum heat treatment at the University of Geneva. A strand sample for critical and stability current measurements (short sample A) and a 1 m long straight strand for RRR measurements were heat treated together with the coil A. In the furnace with the coil B, only a strand sample for critical and stability current measurements (short sample B) was inserted. The short samples A and B were wound and heat treated on grooved cylindrical Ti-Alloy barrels (ITER barrel).

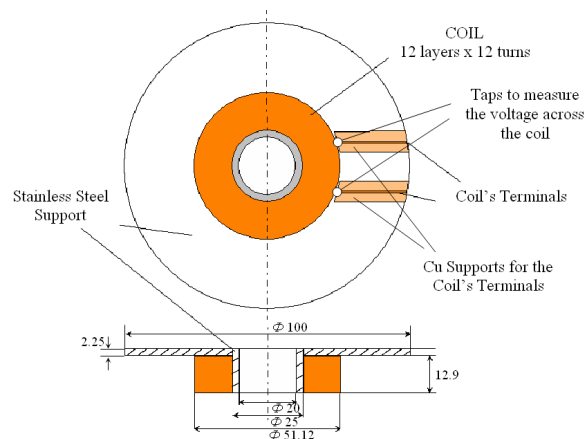


Figure 1: Drawing of one coil – dimensions are in mm.

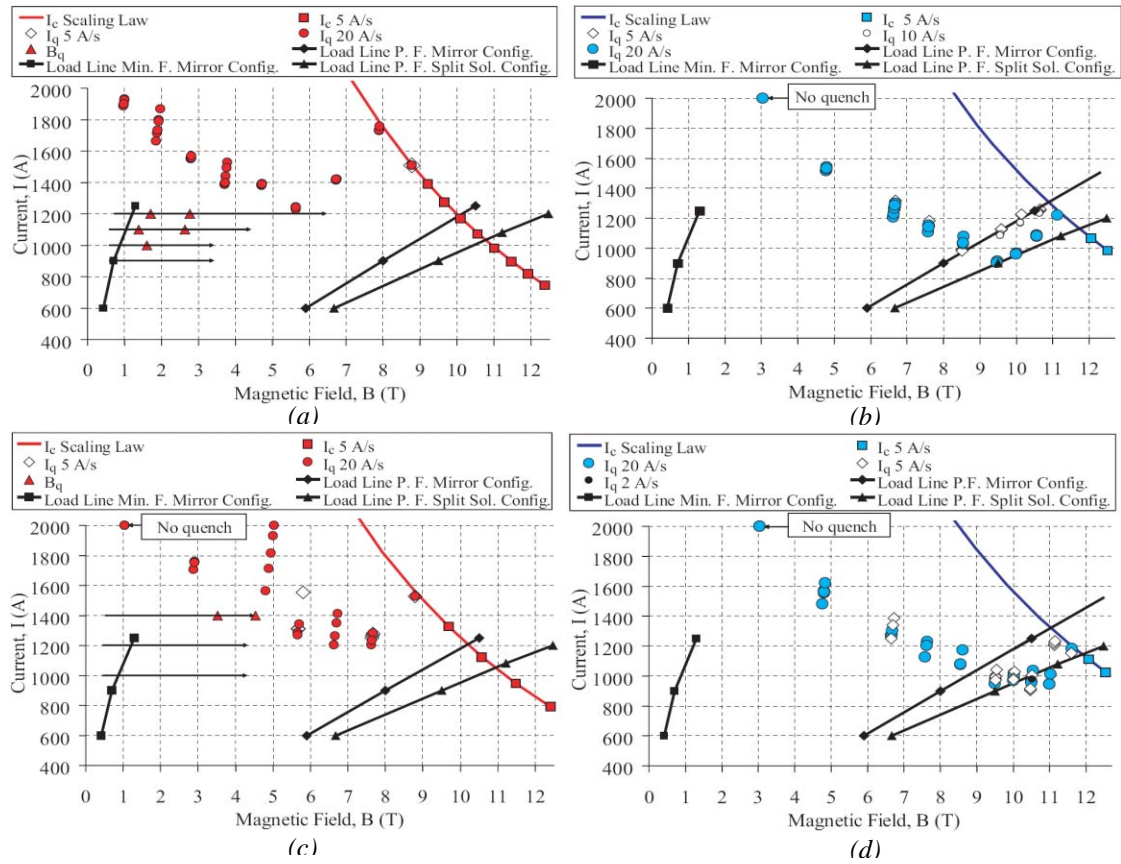


Figure 2: Short sample test results as function of the peak magnetic field: (a) sample A at 4.4 K; (b) sample A at 1.9 K; (c) sample B at 4.4 K; (d) sample B at 1.9 K; during V-H measurements the magnetic field ramp rate is equal to 5 mT/s.

### SHORT SAMPLE TESTS

The critical and stability currents of short samples A and B were measured at CERN following the procedure described in [3]. The stability current ( $I_s$ ) is the minimum current at which a strand can have a premature quench due to magneto-thermal instability [1]. The critical current densities of short sample A and B were respectively equal to 2850 A/mm<sup>2</sup> and 3030 A/mm<sup>2</sup> at 12 T (applied magnetic field) and 4.4 K.

Fig. 2 a) and 2 b) show the test results of short sample A plotted as a function of the peak field in the strand (taking in to account the self field produced by the wire). The dots labelled as  $I_c$  and  $I_q$  respectively represent the critical and the quench currents measured during V-I tests [1, 3] and, the dots labelled as  $B_q$  the quench magnetic fields measured during V-H tests [1, 3] (in the plots the arrows indicate the field range covered during V-H tests [1]). V-H measurements were not performed at 1.9 K because their results are expected not to be significantly different with respect to those obtained during V-I measurements [1, 3]. In the plot the calculated load lines of the coils in mirror configuration and in split solenoid configuration are also showed. For the coil in mirror configuration, two load lines are presented: one describes the relationship between the current flowing in the conductor and the Peak Field (P. F.) in the coil and, the

other, the relationship between the current and the Minimum Field (Min. F.) in the coil. For the coils in split solenoid configuration only the peak field load line is presented because the minimum field in the coil is vanishing. The expected critical current for Coil A in mirror configuration is 1181 A at 4.4 K and 1305 A at 1.9 K, while in split solenoid configuration it is 1028 A at 4.4 K and 1130 A at 1.9 K. Stability measurement show that coil A, both in mirror and split solenoid configuration, should be limited at a current approximately equal to 1000 A due to magneto-thermal instabilities. These instabilities should occur, at 4.4 K, in the very low field region (1 T – 3 T) of the magnet and, at 1.9 K, in a relatively high field region (8.5 T – 9.5 T) [2].

In order to estimate the RRR of sample A, the RRR of two 11 cm long straight samples were measured; their RRR values were respectively 126 and 158.

Fig. 2 c) and 2 d) show the experimental results of sample B plotted as a function of the peak field. The expected critical current for Coil B in mirror configuration is 1201 A at 4.4 K and 1323 A at 1.9 K; in split solenoid configuration it is 1046 A at 4.4 K and 1145 A at 1.9 K. Stability measurements show that, at 4.4 K, coil B should not be limited by magneto-thermal instabilities, while, at 1.9 K, the self field instability should limit the current of coil B at a value equal to 1050 A when the coil is in mirror configuration and, to 950 A when it is in split solenoid configuration [2].

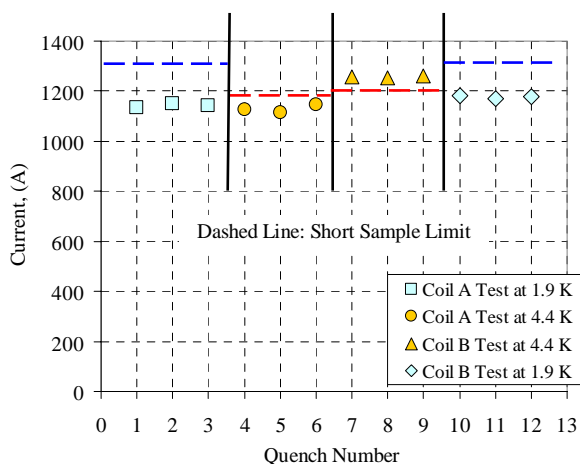


Figure 3: Quench history of Coil A (Quenches 1 to 6) and Coil B (Quenches 7 to 13) in mirror configuration.

### MAGNET TESTS

At first the coils were tested separately in mirror configuration (each coil was assembled with an iron block acting as a magnetic mirror). The coil RRR, defined as the ratio between the coil electrical resistances at 293 K and at 20 K, was measured during the cool down and the warm up and, it was respectively 190 for coil A and 270 and for coil B. The sequence of quenches performed in mirror configuration is summarized in Fig. 3. One can notice that at 4.4 K, the magnet practically reached the short sample limit at the first quench (~95 % coil A; 104 % coil B) showing that, in these coils, the ceramic insulation not only prevents the strand motion but also eliminates the training phenomenon. This is most likely due to the absence of cracks in the ceramic insulation. The peak field in the coil, estimated by a magnetic model and confirmed by magnetic measurements, was 9.8 T in Coil A and 10.5 T in Coil B. The excellent performance reached at 4.4 K also showed the effectiveness of the heat treatments that generated a high critical current density and a high RRR. The high RRR prevented significant reductions of the quench current values due to magneto-thermal instabilities at 4.4 K. These results are especially important if one consider that this strand will be used for magnets with a peak field larger than 12 T; in this case the strand critical current at 4.4 K is lower than 900 A and the magnet will have a large margin with respect to magneto-thermal instabilities. At 1.9 K both coils had limited quench performance as predicted by our theory [1] and by short sample strand measurements.

The two coils were then tested in split solenoid configuration at 4.4 K, Fig. 4. The first two quenches were obtained injecting the current only in one coil (see quench number 1 and 2 in Fig. 4): Coil A had almost the same quench current as in mirror configuration even though the coil critical current was higher, while Coil B had a higher quench current (1380 A instead of 1260 A). Coil A was most likely limited by instability. Finally the

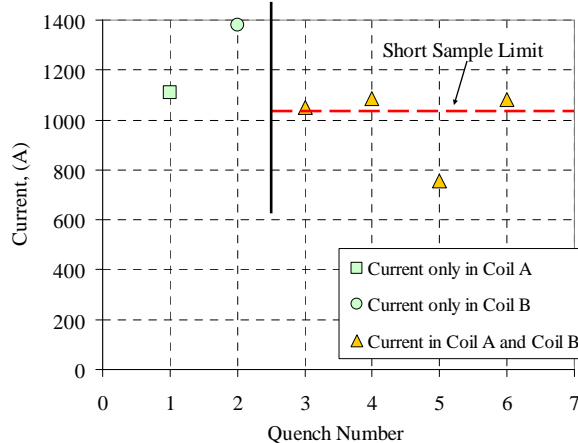


Figure 4: Quench history of the split solenoid at 4.4 K

split solenoid with the two coils connected in series was tested at 4.4 K (see Fig. 4 quenches 3-6) and it reached the short sample limit at the first quench; only four quenches were performed because the split solenoid had a ground problem due to a fault of the electrical insulation between one of the Cu terminal support and the stainless steel support (see Fig. 1). All the quenches occurred in Coil A. More details can be found in [2].

### CONCLUSIONS

The test of a small split solenoid showed that the ceramic developed by CERN can be used to prevent strand motion and to electrically insulate Nb<sub>3</sub>Sn small solenoids. The use of ceramic completely eliminated the training phenomenon. The test also showed that a new heat treatment devised at CERN and particularly suitable for reacting RRP<sup>®</sup> Nb<sub>3</sub>Sn strands allows reaching a  $J_c$  of 3000 A/mm<sup>2</sup> (at 4.4 K and 12 T) with a RRR equal to 270. This high RRR guarantees a stability current equal to 1200 A at 4.4 K for this 0.8 mm RRP<sup>®</sup> strand and it allowed the split solenoid to reach, at 4.4 K, its critical current with a peak field in the coil equal to 10.7 T and a peak field in aperture equal to 12.5 T. At 1.9 K the coils had premature quenches due to self field instability despite the rather high RRR of the two coils (190 and 270). This phenomenon at 1.9 K, predicted by our theory [1], was confirmed by strand measurements.

### REFERENCES

- [1] B. Bordini, E. Barzi, S. Feher, L. Rossi, A.V. Zlobin, "Self-Field Effects in Magneto-Thermal Instabilities for Nb-Sn Strands", IEEE Trans. Appl. Supercond., vol. 18, no. 2, pp. 1309 - 1312, Jun. 2008.
- [2] B. Bordini, R. Maccaferri, L. Rossi, D. Tommasini, "Test Report of the Ceramic-Insulated Nb<sub>3</sub>Sn Small Split Solenoid", CERN internal note - EDMS 907758.
- [3] B. Bordini, "Magneto-Thermal Instability of superconducting strands: preliminary results on a new behaviour observed in Nb<sub>3</sub>Sn strands at 1.9 K", CERN internal note - EDMS 859861.