Progress on an innovative insulation technique for Nb_3Sn wind & react coils

Rondeaux F., Quettier L., Rey J.M.

CEA, Irfu, SACM, centre de Saclay, F-91191 Gif-sur-Yvette, France.

As an alternative to the conventional insulation technique for Nb_3Sn Wind & React coil, we have developed an innovative one-step insulation technique that directly deposits a ceramic coating on the surface of unreacted Nb_3Sn conductor. A demonstration coil of about 400 turns in 21 layers was designed, built, and tested. It produced a central magnetic field of 5.63 T at 590 A. It was also tested in different levels of a background magnetic field: even after repeated quenches of the coil, the ceramic insulation showed no sign of failure, electrical or mechanical, validating the mechanical cohesion of this insulation.

INTRODUCTION

Although Nb_3Sn is considered the best low-temperature superconductor for high-field magnets, its implementation is not always straightforward. After heat treatment, the material becomes brittle and strain sensitive. As a consequence, most Nb_3Sn coils are produced with the “wind-and-react” technique: the conductor is wound and then heat treated. The technique excludes the use of electrical insulators containing organic materials. After the heat treatment, the coil is transferred into a mould to be vacuum-impregnated with epoxy resin. Transfer, as well as the vacuum impregnation, is risky operation. We have developed an innovative one-step insulation process [1, 2] that directly deposits a ceramic coating on the surface of unreacted Nb_3Sn conductor. The process enables such an Nb_3Sn coil to retain a mechanical cohesion, maintain a proper conductor positioning, and be electrically well insulated.

Previous works have shown that the intrinsic properties, e.g., critical current, RRR, of the wire are not affected by this direct-ceramic-coating process. A small Nb_3Sn solenoid, insulated with this process, has been built and successfully tested in high external magnetic fields. Although it has been possible to reach a maximum stress level of only about 30 MPa in the coil, it has demonstrated that this direct-ceramic-coating process on unreacted Nb_3Sn is applicable to superconducting magnets based on tin-niobium technology [3].

NEW MEASUREMENTS OF THE FIRST DEMONSTRATION COIL

To study the effect of aging on coil, the first demonstration coil, tested nearly two years ago, was tested under the same measurement conditions as those in the first test. Figure 1 shows quench current vs. winding peak field data of the 2004 (triangles) and 2006 (diamonds) tests. The data clearly establishes that there is no degradation of the coil performance, proving that aging does not appear to deteriorate the insulating properties of the ceramic coating, applied with this innovative one-step insulation process.

SECOND DEMONSTRATION COIL

To subject the ceramic insulation to higher stress levels, a new coil, large but compatible with the test facility dimensions, was designed and built. The second coil, with 398 turns in 21 layers, was wound with a “double wire” technique [3]. Figure 2 shows a photograph of the second coil during the winding process.

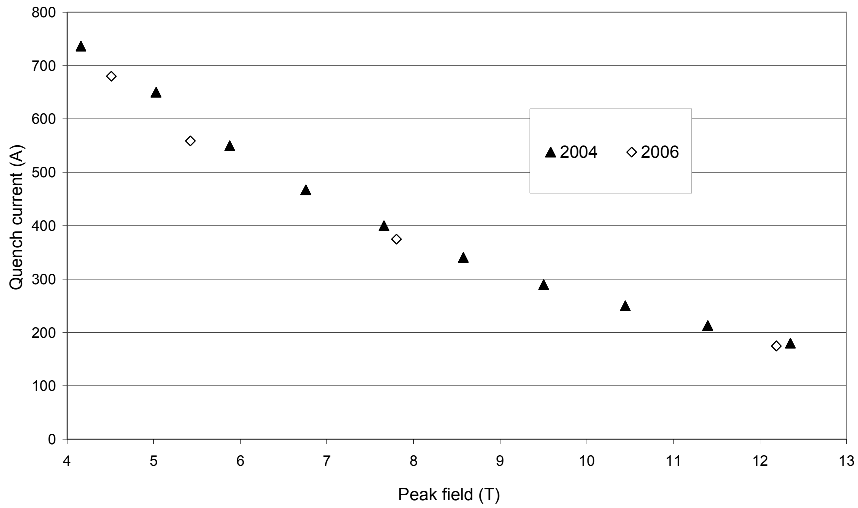

Figure 1 Quench current vs. winding peak field data

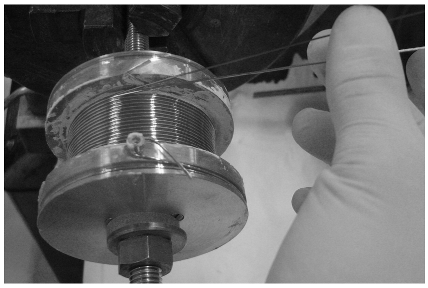

Figure 2 Photograph of the second coil during winding

The coil was mounted in a sample-holder [4] usually used for critical current measurements of VAMAS samples, in the CHRISTIANE test facility. The background field is provided by an NbTi solenoid (CHRISTIANE magnet) capable of generating a central field of 7 T at 4.2 K. The voltage of the Second Demonstration coil (SDC) was measured across the two terminals of the coil. The critical current was determined from the voltage-current curve with an electrical field criterion of 0.1 $\mu V.cm^{-1}$.

NUMERICAL MODELLING

Magnetic field calculation

For a given background field provided by CHRISTIANE magnet, a numerical analysis of SDC was performed using the software Roxie [5]. The analysis computed the coil's quench margin and mechanical stresses within the winding

The calculation was performed by modelling each layer as one rectangular conductor and applying a circulating current corresponding to the number of turns in a given layer. This model takes the interlayer insulation into account but neglects the inter strand insulation. Table 1 and Table 2 show the parameters, respectively of, the CHRISTIANE magnet and Second Demonstration coil.

Table 1 Parameters of CHRISTIANE magnet

Inner diameter (mm)	100.6
Outer diameter (mm)	195.3
Total height (mm)	192.7
Central field (T) at I = 414 A	7

Table 2 Parameters of Second Demonstration coil (SDC)

Inner diameter (mm)	20
Outer diameter (mm)	71.78
Total height (mm)	30
Number of turns per layer	18 to 20
Number of layers	21
Nb3Sn wire diameter (mm)	0.825
Critical current (A) @ 4.2 K and 7 T	> 405
Copper/Non-copper ratio	1.37

Two different magnetic configurations were investigated. In the first case (labelled "Case A"), both magnetic fields, CHRISTIANE and SDC, are in the same direction. In the other case (labelled "Case B"), the respective fields are in the opposite directions. With no external field, the Lorentz forces are induced in the SDC by the interaction of its current and self field. With the used model, orders of magnitude for only radial hoop stresses are evaluated.

In Case A, the SDC is globally in tension in the radial direction. In this configuration, the maximum field occurs in the innermost radius of the SDC. Figure 3 shows a field map computed for Case A, when CHRISTIANE magnet and SDC create respectively central fields of 7 T and 2.39 T.

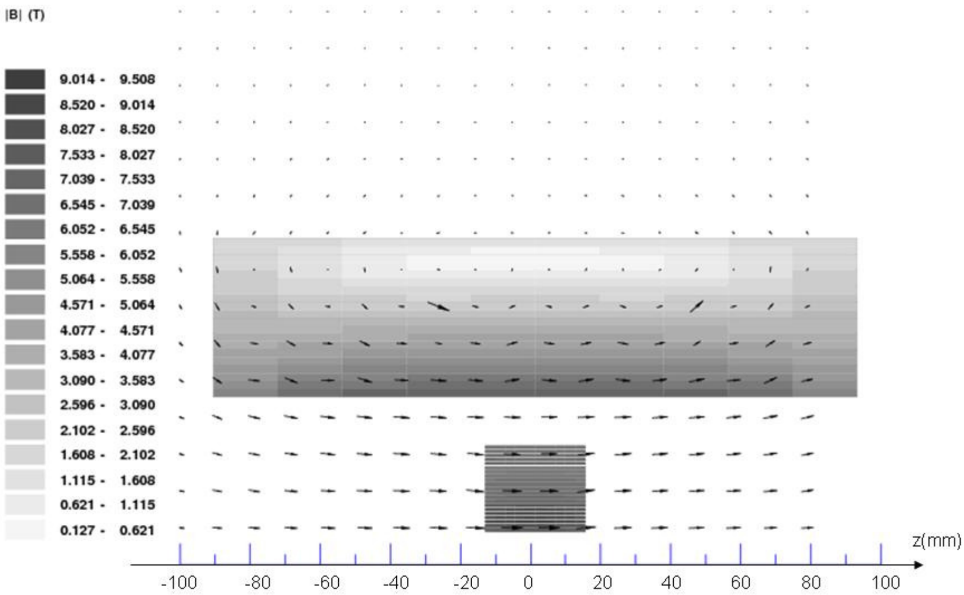

Figure 3 Field map, comprising field vectors, in Case A , with CHRISTIANE magnet and SDC generating central fields, respectively, of 7 T and 2.39 T.

In Case B, two different conditions can exist:
- Case B1: the maximum field occurs in the outermost radius of the SDC
- Case B2: the maximum induction occurs in the innermost radius of the SDC

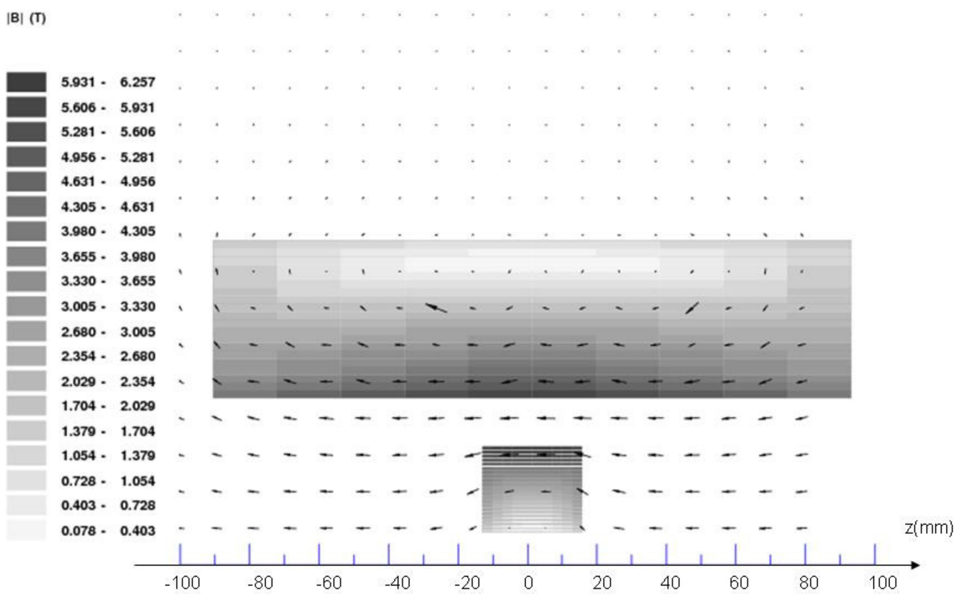

Figure 4 Field map in Case B1 , with CHRISTIANE magnet and SDC generating central fields, respectively, of -5 T and 5.49 T.

In Case B1, the combined Lorentz forces point radially inward and the SDC is under compressive stresses when a zero-field point within the winding occurs beyond the average coil radius. Figure 4 shows a field map corresponding to a case in which Christiane and SDC are creating central fields, respectively, of −5 T and 5.49 T.

In Case B2, the combined Lorentz forces point radially outward and the SDC is under tensile stresses when a zero-field point within the winding occurs close to the average coil radius. Figure 5 shows a field map corresponding to a case in which Christiane and SDC are creating central fields, respectively, of −2 T and 6.57 T

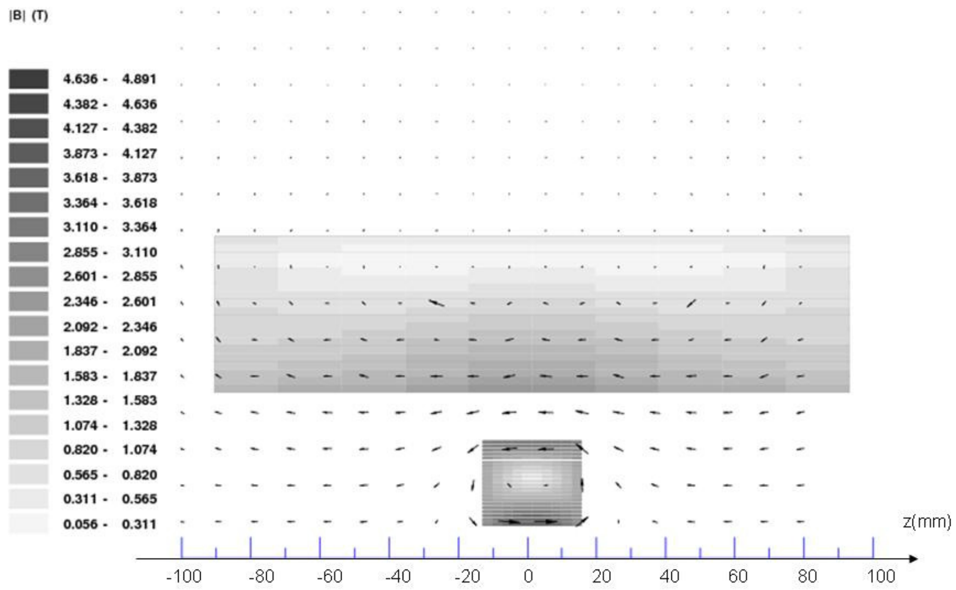

Figure 5 Field map in Case B2 , with CHRISTIANE magnet and SDC generating central fields, respectively, of -2 T and 6.57 T.

<u>Hoop Stress Evaluation</u>

The maximum hoop stress is calculated from the equation B.R.J where J is the overall current density in the winding, B is the peak field, and R is the peak-field radius. As J is the overall current density of the winding in which insulation accounts for 70 % of the winding, the hoop stress computed by this simple equation can be quite conservative, i.e. greater than the actual peak hoop stress.

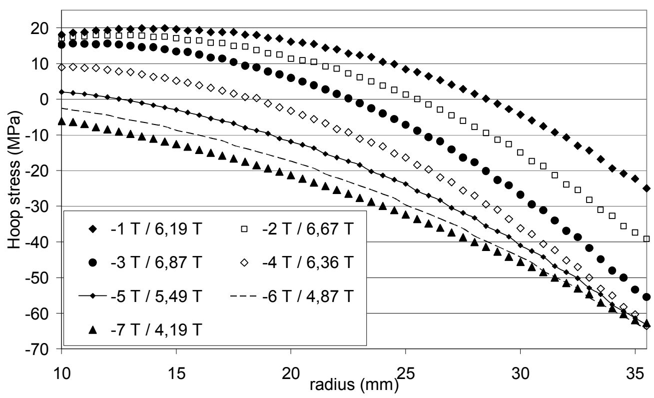

Figure 6 Hoop stress (Mpa) vs. radial location (mm) in Case B for combinations of fields (inset) generated by Christiane magnet and SDC.

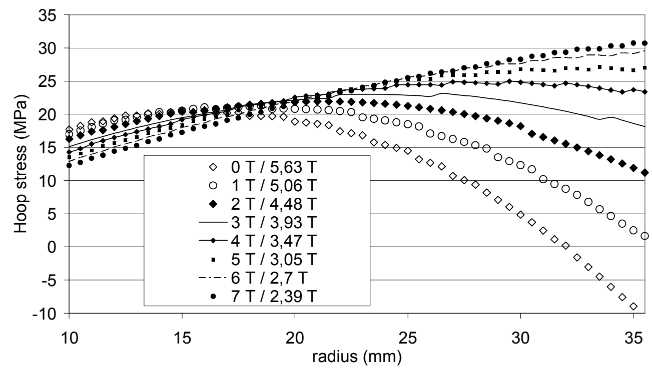

Figure 7 Hoop stress in Mpa versus coil radius in mm (case A).

In Case B, the maximum hoop stress occurs near the outermost radius (Fig.6). According to the zero-field location, the coil is either in tension (maximum field is on the internal radius); either in compression (maximum field is on the external radius)

In Case A, the maximum stresses occur near the external radius as the Christiane field is increased (Fig.7). Thus, the maximum field is always on the internal radius. Up to a Christiane field of 5 T, the curves look parabolic. Above 5 T, they are increasing functions of radial location. The blank-square curve corresponds to the case where the SDC alone is energized: we can see the intrinsic zero-field point for this coil geometry. The coil is globally in tension for each case.

EXPERIMENTAL RESULTS

The main target of the experiment was to verify a good mechanical cohesion of the coil prepared by the one-step ceramic insulation process and to determine its mechanical limits. The effect of the ceramic insulation on the critical current performances of the coil was also investigated. Measurements of critical current were performed with the SDC, energized alone and in an external field in the 0-7 T field range generated by the Christiane magnet. The SDC quenched, for example, at 590 A, corresponding to a combined central field of 5.63 T. Although the SDC was forced to quench more than 50 times, there was no sign of damage to the ceramic insulation. Table 3 shows the computed peak hoop stresses in the SDC in Case B for combinations of magnetic fields generated by Christiane magnet and SDC.

Table 3 Computed Peak Hoop Stresses (absolute values) in SDC for Combinations of Magnetic Fields by Christiane and SDC (Case B)

	Christiane (T)	SDC (T)	Hoop Stress (MPa)
Test 1	-1	6.2	25
Test 2	-2	6.6	39.2
Test 3	-3	6.9	55.5
Test 4	-4	6.4	63.6
Test 5	-5	5.5	63.3
Test 6	-6	4.9	64.5
Test 7	-7	4.2	62.8

In Tests 1 and 2, the SDC is globally in traction. The SDC is in compression in Tests 3-7. In Test 6 we reached a peak hoop stress of 64.5 MPa in compression without any apparent sign of damage to the insulation. This also gives a 64.5 MPa value for the Nb_3Sn wire in longitudinal compression which is a quite unusual way to stress a wire. One can imagine a buckling effect to occur on a bare wire, the ceramic insulation acting in this case as containment for the wire.

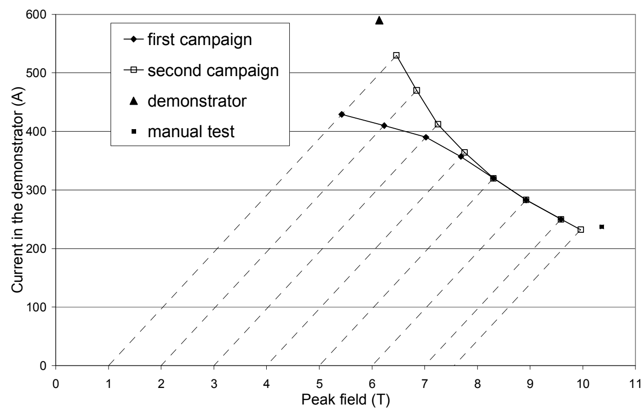

Figure 8 Training effect between the two campaigns for case A

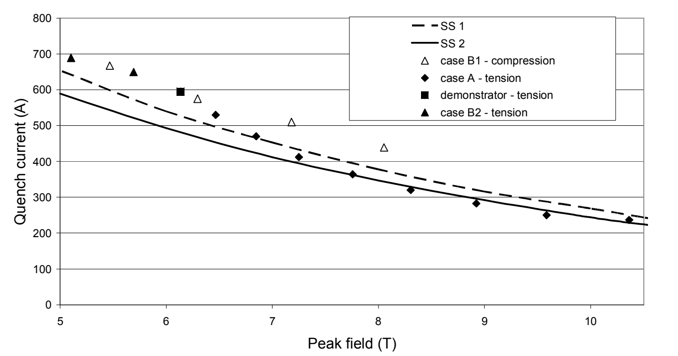

Fig. 9 Quench current vs. peak field plots: solid and dashed lines correspond to VAMAS samples; symbols correspond to experimental values for SDC for different operating conditions.

Figure 8 shows SDC quench current vs. SDC peak field plots in Case A for two test sequences, each increasing field generated by Christiane magnet. The SDC quench current increased during the second test sequence. We thus observed a phenomenon of training: improved quench current with test sequence.

The point labelled as "manual test" in Fig. 8 was obtained under a particular operating mode (Case A) in order to achieve a central field 10 T: the background field was first set to a given value and then the SDC current was increased, thus decreasing the peak field in the SDC. In this manner, a central field of 10 T was achieved. The SDC quench current was compared with the critical current value obtained on short samples (VAMAS type); the two values agree quite well.

Figure 9 shows quench current vs. peak field plots for two VAMAS short samples (labelled SS1 and SS2) and for the SDC under different operating conditions. Agreement between short-sample currents and SDC currents are excellent. This clearly demonstrates that under different operating conditions, the SDC can achieve the maximum current/field performances possible with the superconducting wire without any evidence of degradation to the ceramic insulation.

CONCLUSION AND PERSPECTIVES

A new insulation technique for unreacted Nb_3Sn has been successfully demonstrated with a coil of 400 turns, which created 5.63 T in its centre. A maximum stress level of about 65 MPa in compression and of 30 MPa in tension was obtained inside the coil and the ceramic insulation did not show any appearance of failure, electrical or mechanical. The quench current performances showed no sign of degradation after several quenches.

The results demonstrate that this one-step ceramic insulation process is promising, though the second demonstration coil was subjected to stress levels an order of magnitude less than those reached in real size accelerator magnets (about 150-200 MPa). The results presented here represent the first validation step of this ceramic insulation technique that may be applied for Nb_3Sn magnets. The next step will be to manufacture and test subscale Nb_3Sn racetrack coils, insulated with this innovative technique, within the context of the NED Short Model Coil Project. In parallel, a more complete mechanical model has to be developed, including the real properties of the materials. It will be a way to investigate not only radial, but also axial components of the stresses.

ACKNOWLEDGMENT

The authors wish to thank A.Poulizac and T.Dalla-Foglia for their help in the winding of the demonstrator, J.Laforêt for her contribution in the magnetic computation and JM.Gheller, O.Louchard and L.Kulbicki for their technical support.

REFERENCES

1. Puigségur A., Rondeaux F., Prouzet E., Samoogabalan K., Development of an innovative insulation for Nb3Sn Wind & React coils, Advances in.Cryogenic Engineering. (2004), 50A.266-272.
2. Puigségur A., Ph.D. work presented in jan.2005.
3. Puigsegur A., Quettier L., Rey J.M., Rondeaux F, Prouzet E., An innovating insulation for Nb3Sn Wind & React coils: electrical tests, IEEE Trans. on Applied Superconductivity (2006) 16(2) 1769-1772.
4. Chesny Ph., Fazilleau F., Gheller J.M., A novel short sample mounting fixture for critical current measurements, Advances in.Cryogenic Engineering (2006).51B 1471-1478.
5. Russenschuck S., Roxie: Routine for the optimisation of magnet X-sections, inverse filed calculation and coil end design. Proceedings of the first international Roxie users meeting and workshop CERN, CH (1998).