An Innovating Insulation for Nb_3Sn Wind & React Coils: Electrical Tests

A.Puigsegur, L.Quettier, J.M. Rey, F. Rondeaux, E. Prouzet

Abstract— **If Nb_3Sn is the best superconductor candidate for the realisation of high field magnets (for 10-11 Tesla), its implementation remains delicate because of the great brittleness of material after the heat treatment necessary for the formation of Nb_3Sn compounds. The conventional insulation for Nb_3Sn Wind & React coils requires performing, after the heat treatment, a vacuum resin impregnation, which adds to the cost and raises failure risk.**

We have proposed a one-step innovating ceramic insulation deposited directly on the un-reacted cable. After the heat treatment, we obtain a coil having a mechanical cohesion, while maintaining a proper conductor positioning and a suitable electric insulation.

We have shown that using this insulation in a coil manufacturing process does not affect the electrical properties of the Nb_3Sn wires. A solenoid of small dimensions (9 * 20 turns on an internal diameter of 22 mm) has produced a magnetic field of 3.8 T at 740 A. It was tested with success in high external magnetic fields: the quench limits have been imposed by the strand and the insulation was not damaged.

***Index Terms*— Ceramic insulation, Superconducting magnet.**

I. INTRODUCTION

IF Nb_3Sn is actually the best superconductor candidate for the realization of high field magnets, its implementation remains delicate.

A long heat treatment of approximately 2 weeks at about 700°C under a flow of inert gas is required to form the superconducting intermetallic compound by a solid state diffusion process. That means that no organic material can be introduced in the coil before the treatment and the conventional insulation systems such as polyimide cannot be used.

After the heat treatment, the material is very brittle and strain sensitive. As a consequence, in practice, most of the coils are produced with the "Wind and React" technique.

Manuscript received September 19, 2005.

A. Puigsegur, L. Quettier, JM. Rey and F. Rondeaux are with the CEA/Saclay, DSM/DAPNIA/SACM, Gif-sur-Yvette, 91191, France. (e-mail: françoise.rondeaux@cea.fr)

E. Prouzet is with the Institut Européen des Membranes, (CNRS UMR 5635), 1919 Route de Mende, Montpellier, F-34293, France.

Typically, the cable is wrapped with a mineral tape, and then wound to form the coil. 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 a risky operation. To avoid these, we have developed a one-step innovating ceramic insulation deposited directly on the un-reacted cable, which achieves, after the heat treatment, a coil having a mechanical cohesion, while maintaining a proper conductor positioning and a suitable electrical insulation. The process is described in [1, 2].

We present the electrical characterisation of this new insulation, which has been done in two steps. Due to the duration and elevated temperature of the reaction cycle used to form the Nb_3Sn superconducting phase, the diffusion of species coming from the ceramic precursor can not be neglected. As the detrimental effects could influence the copper as well as the superconducting properties, we have verified that the intrinsic properties of the wire are not affected using RRR and critical current measurements. Then, we have built a small solenoid using this insulation and we have tested it with success in high external magnetic fields.

II. RRR MEASUREMENTS

An important point was to verify there is no modification in the electrical properties of the conductor due to the ceramic insulation. First, we checked the copper resistance. As it was not possible to wrap wires directly with the tape we have developed, RRR measurements were performed on wires covered directly with the ceramic solution and reacted. A comparison was made with uncovered wires.

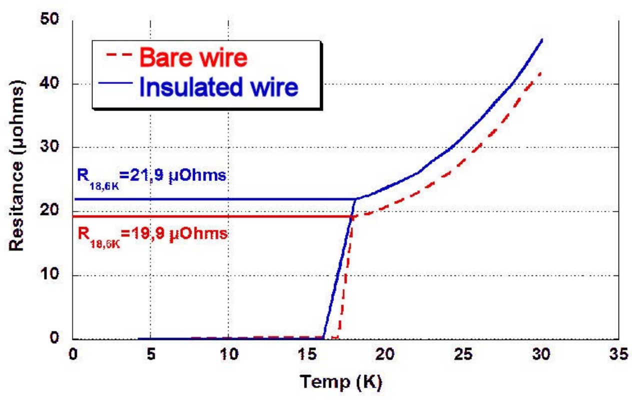

Fig. 1. Comparison of resistance between bare and insulated wires

The measurements have shown that the insulation method does not essentially affect the copper resistance. The two curves show the same behavior and we have observed only a slight decrease in resistance, which corresponds to a decrease in RRR value from 329 to 290. The RRR value is defined as the ratio between receptivity at 298K and the resistance at transition temperature. Typical RRR specifications require values greater than 100. We have also to take into account that the conditions for the preparation of the insulated wires are more « aggressive » than the conditions of reaction for the wrapped cables: the wires were directly in contact on the entire surface with the solution, whereas the cables have only partial contact with a dry impregnated tape.

III. Critical Current Measurements

Measurements have been made using the VAMAS configuration in the CETACEs test facility [3]. Two different samples have been prepared in order to study the influence of insulation on critical current performances in a perpendicular field at 4.2 K. The background field is provided by a hybrid NbTi/Nb3Sn solenoid capable of 15 T at 4.2 K. The magnet and the sample holder have a common cryostat, but two separate helium baths. The Nb_3Sn sample, about 1m in length, is wound on the helical groove of a Ti-Al cylinder, with a 32.5 mm diameter, according to VAMAS specification. After mounting and before the heat treatment, three samples have been coated with the ceramic insulation. The current is fed to the sample to produce inward Lorentz forces (self field parallel to the applied field). Two voltage tap pairs, spaced by 45 and 90 mm, are soldered to the sample in the middle of the test section. Measurements were carried out on three different samples per type of wire for magnetic flux density in the range of 5-14 T. The critical current has been estimated from the voltage current curve using an electric field criterion of 0.1 μV/cm. Fig. 2 presents a plot of the average critical current density, Jc, over the non-copper cross sectional area of the wire, versus applied magnetic flux density, B.

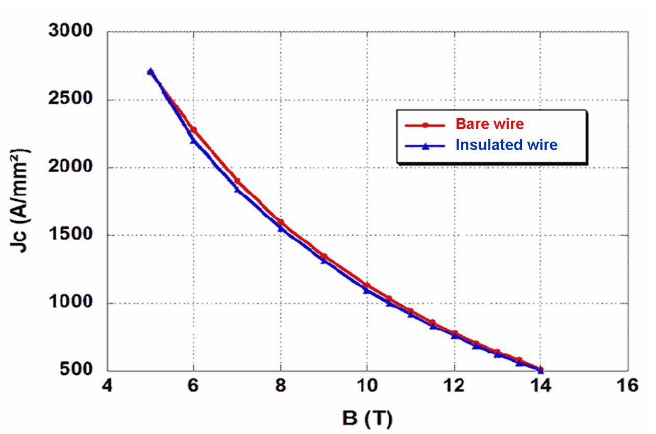

Fig. 2. Critical current density vs. applied magnetic flux density as measured on bare and insulated wires.

This shows that the ceramic insulation does not change the critical current density performance of the wire.

IV. Demonstrator

Once proved that the ceramic precursor had no detrimental effects on electrical properties, we developed a small coil to check the mechanical integrity of the ceramic insulation under operating conditions. An insulated coil was built to confirm the previous properties of ceramic material in the real magnetic configuration. The coil was designed to be tested in the CETACEs test facility. The dimensions of the coil have been chosen to be compatible with the sample rod generally used for the critical current measurements on VAMAS coils. The coil is a small solenoid with an external diameter of 40 mm and a length of 50 mm. It has 180 turns in 9 layers wounded on an internal diameter of 22 mm. The different steps of the coil manufacturing are shown in figures 3a to 3e.

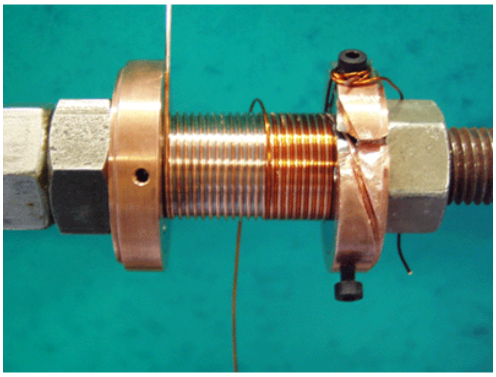

Fig 3a. First layer

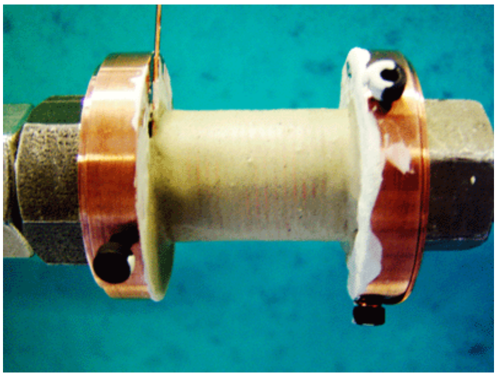

Fig. 3b. First layer + ceramic solution

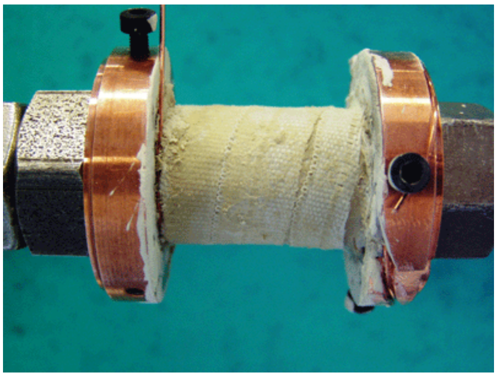

Fig. 3c. First layer + impregnated tape

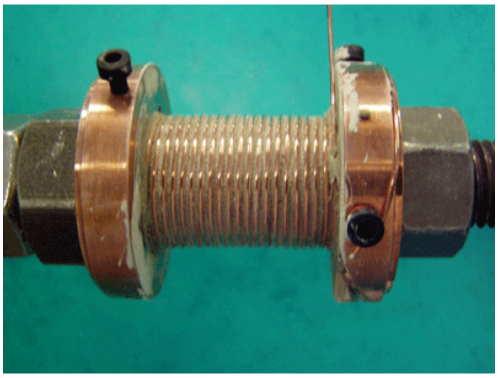

Fig. 3d. Second layer

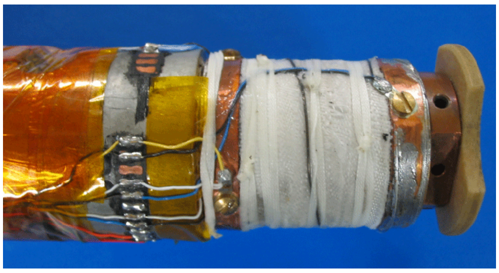

Fig 3e. Final coil on the sample rod

(a) The first layer is wound on the titanium mandrel using a guide wire to maintain a pre-defined space between two turns.
(b) After the completion of the layer, the ceramic solution is applied on the entire surface. The gelification process of the solution allows a stable behaviour for the following steps.
(c) A layer of impregnated glass tape [1] is wrapped between two layers and acts as an interlayer insulation. The estimated value for the insulation thickness is 260 µm.
(d) The second layer is wound in the same way as the first layer and the process continues until the completion of the nine layers. A layer of desized glass tape is then added to finish the coil.
(e) The coil is fixed on the sample rod of the CETACEs test facility and equipped with voltage taps fixed at each extremity of the mandrel on the copper rings.

V. Numerical Modelling

For a given background field, a numerical modelling of the demonstrator has been made using the software Roxie [4] in order to evaluate the quench margin and the mechanical stresses. The model simulated each of the 9 layers as one rectangular conductor and applying a current twenty times higher as in a single wire. The model takes the interlayer insulation into account but neglects the influence of the inter strand insulation.

A campaign of tests has been launched, based on the previous results of critical current measurements to always ensure a minimum quench margin of 15%. This value was chosen to incriminate the insulation in case of a premature quench and to be sure that this does not come from a too high current value.

Two different magnetic configurations have been investigated. In the first case (labelled case A), the current in the demonstrator produces a magnetic field opposed to the external field which produced an inward Lorentz forces). The maximum field value is located outside the demonstrator and maximum stresses are consequently located on the inner side of the winding. These forces maintain the wire on the mandrel, thus preventing any motion of the conductor. Coil compression is limited by the ceramic insulation and the titanium mandrel.

In the other case (labelled case B), both magnetic fields are in the same direction. Here, local Lorentz forces can have various directions, even inside the demonstrator, and the maximum stresses are not necessary located on the inner side of the winding.

In the particular case where there is no external field, the Lorentz forces are of course always outward forces, and the coil winding remains in tension.

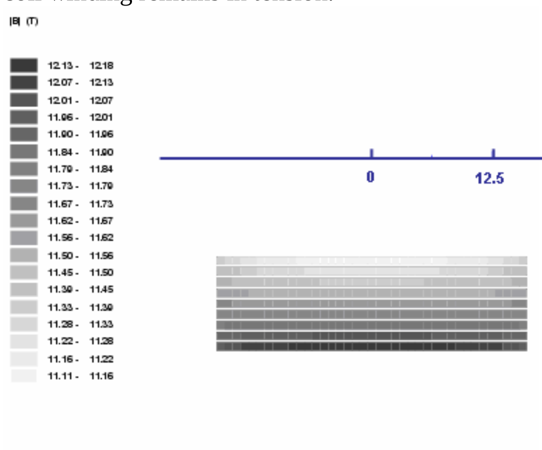

Fig. 4a. Field map in the demonstrator, in the case A, for I_{quench}=175A.

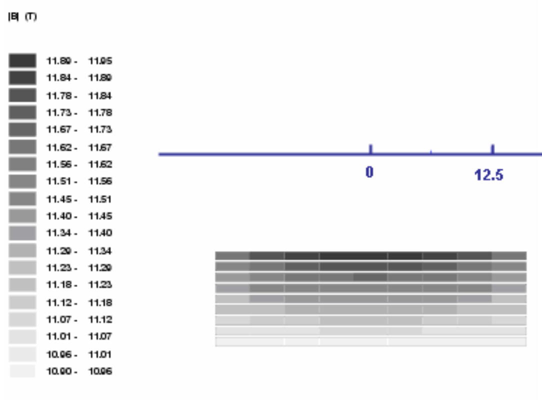

Fig. 4b. Field map in the demonstrator, in the case B, for I_{quench}=179A.

VI. Results

In each case, various configurations were tested to estimate the quench current at given value of the external field. These values are reported in the tables I and II with the corresponding critical current density in the wire, the magnetic field contribution of the demonstrator, the magnetic value from the CETACEs, the peak field value, and the maximum stress inside the winding.

The peak field corresponds to the maximum induction value inside the demonstrator. The hoop stress is calculated using *B.R.J* where *J* is the average value of the critical current density over the winding, *B* is the peak field, and *R* is the radius where the induction is maximum.

As *J* is the average value of the current density over the whole winding that includes 70% of insulation, we can consider the mean hoop stress was a very conservative value. Especially in the case A, where the maximum stress is in tension located on the outer layer of the demonstrator coil, the stress pattern is very unusual and critical for the structural insulation, the interlayer insulation being also in tension.

Further 3D calculations will be needed to estimate a more precise value of stress and the Van Mises stress in the ceramic insulation.

TABLE I
CASE A

I_{quench} (A)	J_{quench} (A/mm²)	$B_{demostrator}$ (T)	$B_{CETACEs}$ (T)	Peak field (T)	Max stress (Mpa)
740	1384	3.86	0	3.91	33.64
680	1272	3.5	-4	-4.51	-36.21
559	1046	2.9	-5	-5.42	-35.82
375	702	1.9	-7.5	-7.8	-34.55
175	327	0.9	-12	-12.18	-25.20

TABLE II
CASE B

I_{quench} (A)	J_{quench} (A/mm²)	$B_{demostrator}$ (T)	$B_{CETACEs}$ (T)	Peak field (T)	Max stress (MPa)
559	1046	-2.97	-2.5	-5.51	18.1
382	715	-1.96	-6	-8	18.9
179	335	-0.92	-11	-11.95	13.2

These values have been compared with the critical current value obtained on VAMAS type sample and the quench current values obtained on the demonstrator (Fig.5.).

A good correlation is observed both with the measurements performed on short lengths of wire using the VAMAS standard and with the quench current obtained on the demonstration coil.

This shows clearly that in all cases, we have been able to reach the limiting performances of the superconducting wire without generating degradation inside the insulation.

Finally, a last test has been carried out with the demonstrator without external field. A quench has been observed for a current of 740 A, which corresponds to a field of 3.86 T created at the centre of the demonstrator.

The demonstrator was quenched approximately 10 times thus showing no ceramic insulation was damaged.

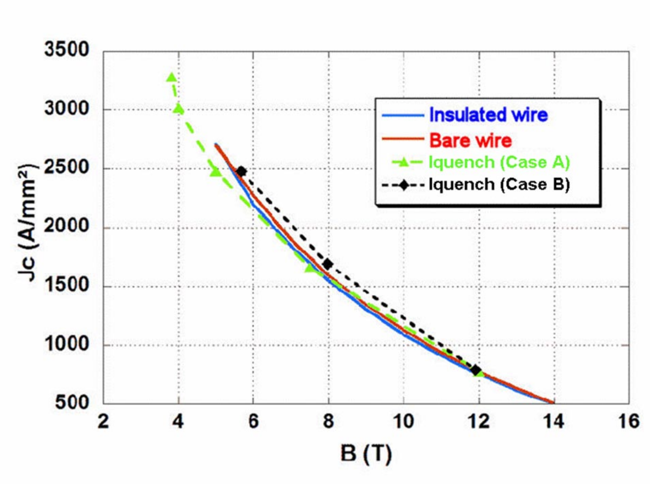

Fig. 5. Comparison of the critical current values obtained on VAMAS sample type and the quench current values obtained on the demonstrator

VII. Conclusion

At maximum stress level of about 30 MPa inside the coil, the performances of the ceramic insulation on a real magnetic system was demonstrated by confirming the results on critical current and RRR measurements obtained on a bare wire. Nevertheless, other magnetic configurations should be tested in order to study the effect of mechanics on the behaviour of the ceramic insulation in more detail.

The performances in terms of critical current value are the same even after several quenches of the coil.

This step is a very first validation of using ceramic insulation as a solution for building of superconducting magnets based on niobium-tin technology.

Acknowledgment

The authors wish to thank C. Genin for his help in the preparation of the demonstrator, E. Jacques for RRR measurements, and JM. Gheller, D. Mouyon and L. Kulbicki for their technical support with the CETACEs facility.

References

[1] A.Puigségur, F.Rondeaux, E.Prouzet, K. Samoogabalan, “Development of an innovative insulation for Nb3Sn Wind & React coils”, Adv.Cryo. Eng. (Materials), Vol.50A, pp.266-272.

[2] A.Puigségur, “Isolation céramique pour câbles supraconducteurs en Nb3Sn », Ph.D. work presented in Jan.2005.

[3] Ph.Chesny, F. Fazilleau, J.M.Gheller, An original sample rod for critical current measurements, presented at CEC-ICMC, July 2005.

[4] S. Russenschuck, “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, 16-18 March 1998, CERN, Switzerland