First Quench Measurements with Ceramic-insulated Nb_3Sn Conductors

E. Rochepault, W. M. de Rapper, F. Rondeaux, P. Vedrine

***Abstract*—An innovative ceramic insulation has been developed by CEA Saclay for Nb_3Sn cables. As the ceramic cures during the heat treatment of the Nb_3Sn, there is no need for an impregnation afterwards. This process eliminates the epoxy-impregnation steps which present the risk to damage the conductor. The porosity of this insulation is expected to enable the high heat evacuation needed by the next magnets generation. However, in high field magnets, the transverse compressive stress on the cables, due to Lorentz forces, can be higher than 150 MPa. It is well known that Nb_3Sn is very sensitive to the strain. The degradation of the Nb_3Sn critical current under pressure has been investigated at CEA Saclay in collaboration with CERN using two experiments. This paper reports the first quench data measured on ceramic-insulated cables. The measurements are carried out under stress with an external field up to 11 T. The samples are compared to a witness sample in order to compute the degradation. It finally appears that the ceramic insulation gives a weaker mechanic support than epoxy-impregnation, leading to a worse critical current decrease at high fields. However, the heat evacuation is better, allowing to reach higher currents at low fields.**

***Index Terms*—Nb_3Sn, critical current, cable, transverse compressive stress, ceramic insulation.**

I. INTRODUCTION

The beam luminosity and energy in particle accelerators keep increasing, leading to higher beam losses. For instance, the heat load in the LHC magnets is currently 0.42 W/m and is expected to be around 2 W/m for the LHC upgrade [1]. Thus the electrical insulations for the next generation of accelerator magnets will have to extract better this heat load. In this context, CEA has designed an innovative insulation, for Nb_3Sn wind & react coils, which satisfies this criterion [2], [3]. Compared to a "classical" insulation process, the resin is replaced with a ceramic solution which cures during the heat treatment of the Nb_3Sn. The overall process is simplified since the insulation is applied before the heat treatment. This ceramic insulation proved its good thermal properties [4].

On the other hand, increasing the beam energy means increasing the magnets field. This leads to higher Lorentz forces and higher transverse pressure on the conductors. Several papers deals with the sensitivity of Nb_3Sn critical current under transverse stress. The first measurements were reported with a single strand [5]. Then experiments were carried out on cables and it was understood that stress on a strand could be locally very high in the cable, depending on various parameters: strand crossings, thin edge bendings and cable impregnation in the insulation. Thus it was shown that : (i) a strand with a pin is more damaged than a straight one [6]; (ii) an epoxy-impregnated cable is less sensitive than a bare one [7]; (iii) a cable totally filled with resin withstands the stress better than a cable only covered [8]. Cables submitted to cyclic loadings appeared to have a high irreversible degradation [9], [10], [11].

The behavior of ceramic-insulated conductors under stress needs to be investigated. This paper first describes two experiments allowing to measure critical current of conductors under compressive stress. Then it compares the first results of both experiments.

II. EXPERIMENTAL SETUPS

A. CEA experiment

1) Sample holder modeling: The apparatus is designed to apply a 200 MPa transverse pressure on 60 mm of cable length (corresponding to a twist pitch). The sample has a hairpin shape. The assembled sample holder fits in the 90 mm bore of a 11T solenoid. A 3D FEM model has been developed (CAST3M). To apply a homogeneous pressure on the cable and gain with thermal contraction, several combinations of materials has been tested among stainless steel 316L, aluminum and titanium. The best compromise is found with all the parts in 316L. The shape has also been optimized to get a stress homogeneity lower than 1 %.

The thermal contraction is integrated between 300 K and 4.2 K, assuming a linear contraction coefficient. The cool down brings 8.5 MPa on the cable. Only the foot of the hairpin see a Lorentz force. This force is mainly directed perpendicular to the transverse pressure, so it is not added to the total pressure.

2) Sample holder assembly: The tested cable is a SMC039 Rutherford cable containing 14 PIT strands. The strand has a 1.25 mm diameter and contains 288 sub-elements with a diameter of 50 μm. The copper to non-copper ratio is 1.25. The expected performances are a $J_c(12T) = 2335$ A/mm^2 and a RRR of 360. The cable is insulated with ceramic. A S2 fiberglass tape is first soaked in a ceramic solution bath. Then the cable is wrapped with the impregnated tape with two layers without overlap, shifted by a half-width. A piece of about 600 mm is cut and the insulation is removed in order to let only a twist pitch insulated (60 mm). To transfer

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the stress like in the coils, this active cable is sandwiched between two pieces of insulated cable (inactive cables). Since the current leads can carry a maximum of 1800 A, only one strand can be powered. Thereby, all the strands are cut except two. Afterwards the cable is bent into two holding parts to form a U shape. Then the cable is reacted in its sample holder at 650 ° C during 100 h. After the heat treatment, one strand is soldered in the current leads and the other one is insulated. The second can serve as an ”emergency strand” in case the first one breaks. Strain gages are glued on the bolts and the strain measurements are compared to the computed data. The cable is finally compressed with the bolts to a small pressure (12 MPa). The tightening is controlled with a torque wrench and checked with the strain gages. The assembly is shown Fig. 1.

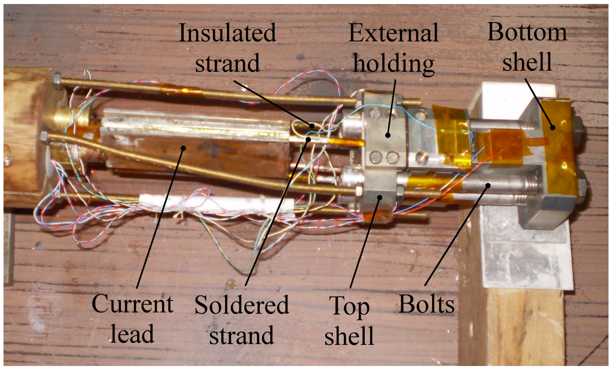

Fig. 1. Fully instrumented assembly.

3) Test facility: The sample holder is inserted in the 90 mm bore of a solenoid in the CETACEs facility at CEA Saclay. The current is raised with different ramps (between 3 and 30 A/s) in one strand of the cable until it reaches the 1 μV/cm criterion. The measurements are carried out in a background field up to 11 T at a temperature of 4.2 K. Once this measurements are done, the sample holder is removed from the cryostat, warmed up, and the sample is compressed to a higher pressure (50 MPa). Then a second run is performed to see the degradation of the cable.

B. CERN experiment

1) Sample holder modeling: The sample holder has been designed to test long lengths of cables [12] in the CERN FRESCA facility [13]. The sample holder length being around 2m, a 2D FEM model is expected to be representative of the system (see Fig. 2). A similar model has been developed for a previous sample holder [14]. The external shell is in 316L. The cable stack consists of two cables, one with a positive current, the other with a negative current. The stack is compressed between two G11 spacers and the force is transmitted via two 316L plates. The pre-stress is imposed using an interference between the shell and the top plate. The thermal load is computed like the model of the CEA experiment. The magnetic load is calculated using an analytical formula. The two extreme cases are presented : 9 T background field parallel to the self field (c direction), and 9 T background field anti parallel (d direction). In both cases, the current in the cable is 32 kA. These parameters correspond to the maximum capacities of the facility. The results are summarized in Fig. 3. At room temperature, the average transverse stress on the cable is about 47 MPa. At cold, the thermal differential contractions bring the average stress to 43 MPa. Note that the G11 plates dissymmetry leads to a deforming torque on the cable (see Fig. 2) which results in a stress inhomogeneity in the cable observable in Fig. 3. In the c direction, the background field adds to the self field and the cables are pushed away from each other, so the pressure decreases to an average of 36 MPa. In the d direction, the self field substracts to the background field and the cables are pressed against each other, so the pressure increases to an average of 49 MPa, with maxima higher than 70 MPa. Various cases have been tested, by varying interference, current and background field. Then an empirical law can be found (Eq. 1), giving the average transverse stress $P_{Y,av}$ in MPa on the cable, as a function of the interference $inter$ in mm, the current I in A and the applied field B_{app} in T.

$$P_{Y,av} = -2,220.10^{-4} I B_{app} - 942,2 inter - 4,275 \quad (1)$$

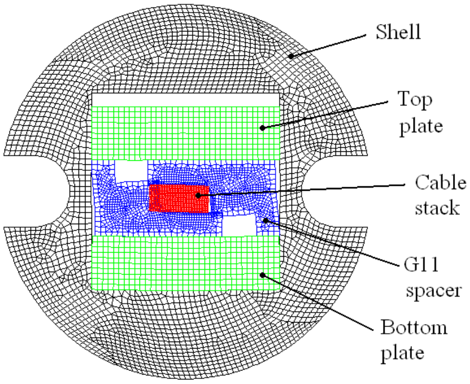

Fig. 2. 2D FEM Model of the CERN experiment : 0.05 mm interference, distortion by a factor 50.

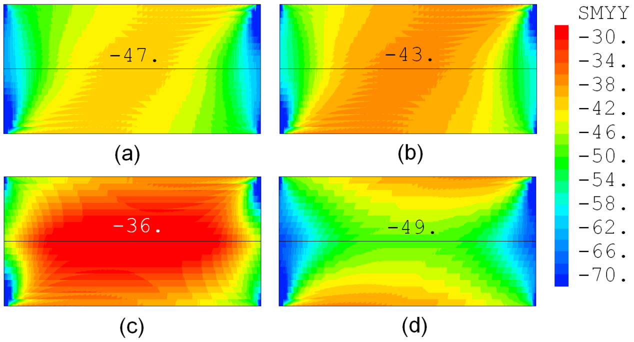

Fig. 3. Stress in Y (transverse to the cable stack) in MPa. The averaged pressures are indicated. (a) mechanical load. (b) mechanical and thermal loads. Mechanical, thermal and magnetic loads with : (c) a 9T parallel background field and : (d) a 9T anti parallel background field.

2) Sample holder assembly: Two types of samples have been prepared for comparison with the SMC039 cable. Two cable pieces were insulated with ceramic before the heat treatment. Then they were reacted with two bare cable pieces, according to the same thermal cycle described above. Two samples (two pieces per sample) were mounted at CERN in a FRESCA sample holder, as described in [15] (for the ceramic sample, the process was adapted). The bare cables were insulated with a CTD 101 epoxy impregnation. The ceramic sample was compressed to 12 MPa for the first run and 40 MPa for the second run. The tightening is controlled with a torque wrench.

3) Test facility: The two samples were tested in the FRESCA facility. Its dipole magnet can produce a background field up to 9 T and the power supply can deliver up to 32 kA. The samples were tested at 1.9 K then at 4.2 K. All the cable is powered and the transition criterion is 1 μV/cm. Different current ramps were tested between 100 and 1000 A/s.

III. RESULTS

A. Discussion

The results of the two experiments are presented on Fig. 4. Data are compared to an uncabled virgin strand (black line). The current of the cables is normalized to one strand for comparison. Values are plotted versus the computed peak field in the sample. Results are given in d direction. The data are averaged measurements. Unfortunately a power supply failure damaged the sample, preventing the measurement of the cable with a ceramic insulation and a 40 MPa pressure at 4.2 K. In order to have a qualitative comparison between 12 and 40 MPa for the ceramic, and between ceramic and epoxy at 40 MPa, measurements at 1.9 K have been ploted (open diamonds and open triangles). The 4.2 K data are plotted with closed symbols.

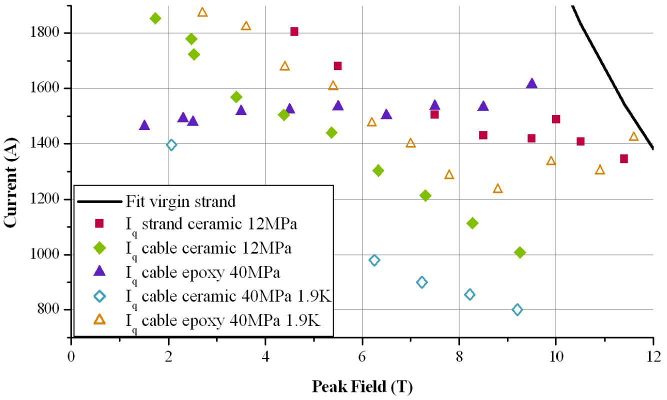

Fig. 4. Strand quench current versus peak field. The ceramic insulation is compared to a classical epoxy one. ”Strand ceramic” was measured at CEA. ”Cable ceramic” and ”Cable epoxy” were measured at CERN. 12 MPa and 40 MPa indicate the transverse stress on the cable. Closed symbols are at 4.2 K and open symbols are at 1.9 K.

All the measurements, except a few for the epoxy sample, were premature quenches (no voltage build-up). They are characterized at high fields (>10T) by quenches or transitions close to the $I_c(B)$ fit, and below 10 T, by quenches located on a lower “$I_q(B)$ curve”. This behavior denotes the instability of the Nb_3Sn cable. It is consistent with a model proposed [16] for strands with a high RRR (here 360) and high perturbations. For the CEA experiment, the measured strand showed fairly good performances at 12 MPa (closed squares), with quenches at 90 % of the virgin sample. At 50 MPa, the cable was severely damaged. The V(I) curves presented a resisitive foot for both strand and ”emergency strand” that prevented the transition measurements. For the CERN experiment, the ceramic insulation has been damaged during transport and preparation : the performances of a cable insulated with ceramic at 12 MPa (closed diamonds) are far below the same cable with a classical insulation at 40 MPa (closed triangles). After the pressure was increased to 40 MPa, the ceramic cable (open diamonds) was strongly damaged compared to 12 MPa and to the epoxy cable (open triangles). The degradation of the ceramic insulated cable under a transversal pressure is probably due to the weak mechanical support given by the ceramic insulation. The cable is not sufficiently impregnated and the surrounding materials are too fragile. Thus the pressure is not uniformly spread on the cable, leading locally to very high stresses (*cf papier Fuji*). However, ceramic samples can reach higher quench currents for low fields at 4.2 K (closed squares and diamonds) than the epoxy sample. This can be explained by the fact that the ceramic insulation offers a better heat extraction.

B. Outlooks

The present FRESCA sample holder is limited to a transverse pressure of 60 MPa. A new sample holder is currently in preparation [17] and will be able to apply a pressure up to 200 MPa on cables.

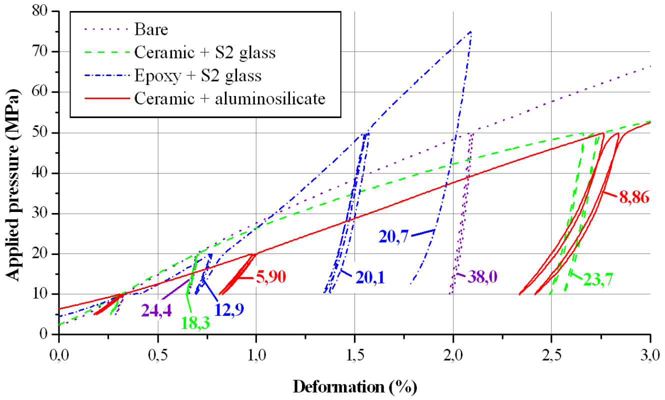

Fig. 5. Stress versus strain for small racetracks under load-unload cycles. Comparison between different kinds of insulation. Averaged Young moduli indicated in GPa.

The ceramic insulation is currently satisfactory for the process of coil manufacturing and the heat extraction. Its weak point remains the mechanical strength, but it still can be improved on several points. Small stacks [18] and small racetracks [19] with dummy cables have been tested under stress to compare the performances. Fig. 5 and 6 show the typical behavior of the cable : a plastic deformation under an increasing pressure (monotone cycle) and elastic deformations under cyclic loadings. The plastic domain is principally driven by the copper cable. The Young moduli are calculated on the slopes in the elastic regime. The low moduli of the materials are due to the void fraction of the cable. Different ceramic compositions have been explored to increase the strength but there is no significant improvement for the moment. An aluminosilicate ceramic-fiber tape has been tested instead of the S2 fiberglass tape. The holding of the ceramic solution is better on the aluminosilicate tape. On the other side, the overall deformation is similar. The process has also been modified. To improve the cable impregnation, a cable stack has been brushed with ceramic solution, in addition to the tape soaking. The mechanical strength is higher (lower deformation for the same applied pressure, see Fig. 6).

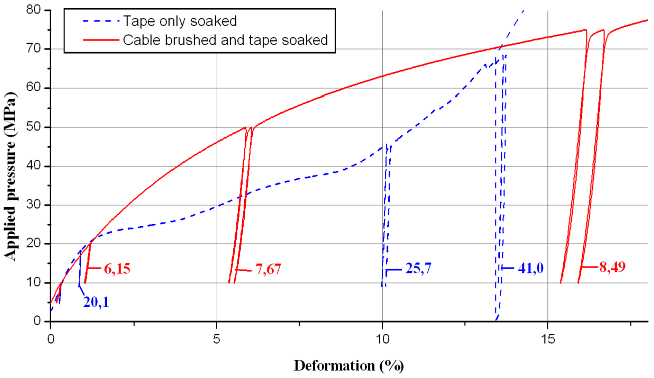

Fig. 6. Stress versus strain for dummy cable stacks under load-unload cycles. Comparison between two impregnation processes. Averaged Young moduli indicated in GPa.

IV. CONCLUSION

A new experiment has been designed, modeled and built at CEA. Its aim is to measure the critical current of strands in their cable with a magnetic field up to 11 T and under transverse pressures up to 200 MPa. Another existing experiment at CERN has been used for comparison. It allows to measure critical currents of entire cables in a magnetic field up to 9 T, but the stress is limited to 60 MPa. The new sample holder has also been modeled. Thanks to this two experiments, quench currents have been measured for the first time in ceramic-insulated cables. Only small compressions have been applied at the moment (up to 40 MPa) but higher compressions are planned to be explored. The ceramic insulation is promising for the heat extraction and a simplified coil manufacturing. On the other hand, the current formulation of this insulation appears to be mechanically weak, leading to high instabilities and damages in the samples. New ceramic insulation processes are under investigation to improve the Nb_3Sn cables mechanical and should allow to reach higher transverse pressures.

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