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A high performance insulated REBCO pancake with conductive cooling capability

Julien Vialle, Arnaud Badel, Kohki Takahashi, Satoshi Awaji, Pascal Tixador

Abstract—REBCO Coated Conductors have high tensile strength along their length. They are however sensitive to delamination when traction force is applied on the tape surface, which in a pancake winding corresponds to radial tensile stress. For this reason, most REBCO magnets are dry-wound (not impregnated). One of the drawbacks of dry winding is that conduction cooling to low temperature (below 20 K) would be inefficient. Edge impregnation structures were developed to mitigate this problem but retaining a soft non-stick insulating layer in between the turn. In this paper, we propose an improved pancake structure with the benefits of edge-impregnation but using Hastelloy tape with thin insulation coating to reinforce the winding. The mechanical behavior of such structure is first estimated then validated with high current tests under large background magnetic field. The insulation performance is then tested by rapid ramping and fast discharge.

Index Terms— Superconducting magnet, Insulated REBCO magnet, High Magnetic field, Impregnation, Co-winding, Conduction cool capability.

I. INTRODUCTION

The effort to reach very high fields (30 T and above), requires to operate REBCO inserts with large current densities and high mechanical stresses. In other magnet applications such as energy storage, the trend is the same, to gain performance and/or to reduce the conductor cost.

The recent REBCO tape performances makes it possible to consider operation up to intermediate temperatures (in the 10 to 30 K range) even for high field and high current density applications [1]. Combined with the growing price of liquid helium, this makes conduction-cooled magnet (cryogen-free) more and more attractive.

To stably operate a REBCO coil in a cryogen-free system and enable efficient cooling of the winding, it is beneficial to impregnate the coil. However, the variations of thermal contractions between the conductor, the insulator and the bonding (epoxy) can lead to dangerous radial tensile stress and winding degradation due to the delamination during cooling down. This is especially true for the windings with large thickness-over-diameter ratios, necessary for high field inserts among others. During operation, Lorentz forces distribution in such thick windings will also lead to large radial tensile stress. The solution proposed in [2] is to use non-stick material to separate the turns in several blocks in radial direction, or even separate all turns from each other. It was used successfully in recent magnets wound by Toshiba for HLFSM (High Field Laboratory for Superconducting Materials), where the insulation between turns is a co-wound thin polyimide tape with fluorine non-stick coating [3, 4, 5]. Using this technique leads

to an edge-only impregnation, where the REBCO tape edges are glued to the thin FRP flanges on each side but not to each other. The resulting structure has an intermediate mechanical behavior between solid-block impregnated winding and dry winding, while maintaining a good thermal conductivity required for conduction-cooling [4, 5]. However, the mechanical performances of these winding can still be improved, as part of the winding cross section is occupied by a mechanically weak material (the polyimide co-wound insulation).

Here we present an improved edge-impregnated insulated REBCO pancake concept suitable in particular to magnetic field inserts, with enhanced mechanical performance while retaining conductive-cooling capability. The design, fabrication and tests of a prototype are presented in the next sections, focusing on the mechanical and dielectric performances. Thermal conduction tests have been successfully performed but are not the topic of this paper, for which the tests were conducted in LHe bath to reach high currents.

II. PANCAKE STRUCTURE AND CHARACTERISTICS

A. Pancake concept

The novelty of this pancake concept is to use edge-impregnation as in [4, 5], but replacing the usual Polyimide insulation co-winding by high strength material. The idea of using high strength reinforcement material with thin insulation coating as insulation co-winding was already proposed in [6] and notably used for the REBCO insert of the 32 T magnet at NHMFL. In our case, we use a Hastelloy tape on which a layer of MgO is deposited to ensure the electrical insulation.

One key difference with the previously made edge-impregnated pancakes is that there is no non-stick material on the insulation co-winding. In order to guarantee that the turns are not glued together, the thin FRP flanges are glued to the surfaces of the pancake after the winding process.

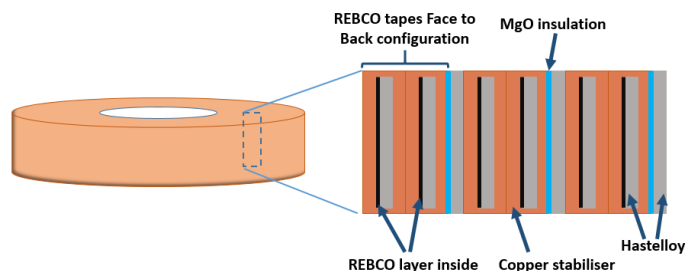


Fig. 1. The stacking arrangement of the tapes in the winding.

As in [3], a two-tape bundle conductor in face-to-back configuration is used. This ensures current redistribution between the tapes in case of local degradation of the critical current of one tape and reduces the risk of thermal runaway, as was shown in [6]. Fig. 1 shows the configuration of the tapes in the winding. The pancake was wound with REBCO Fujikura FESC tapes with artificial pinning center [1, 7]. The insulated Hastelloy reinforcement co-wind is actually a THEVA substrate. Dimensions of the conductor and pancake can be found in Table 1.

TABLE 1
PANCAKE AND TAPE DIMENSIONS

No. of turns	155
Inductance	6.58 mH
Tape dimension	4 mm wide / 150 μ m thick
Substrate thickness	50 μ m
Cu stabilizer thickness	2x40 μ m
No. of bundled tapes	2 (face-to-back)
Tape reinforcement	50 μ m (hastelloy)
MgO insulation thickness (on reinforcement tape)	5 μ m
Inner diameter	148 mm
Outer diameter	257.3 mm
Outer/inner ratio	1.74
FRP flange thickness	0.2 mm

B. Realization

Initially the coil is dry-wound (Fig. 2). The two conductors are soldered to the copper connections at the inner and outer diameters of the pancake.

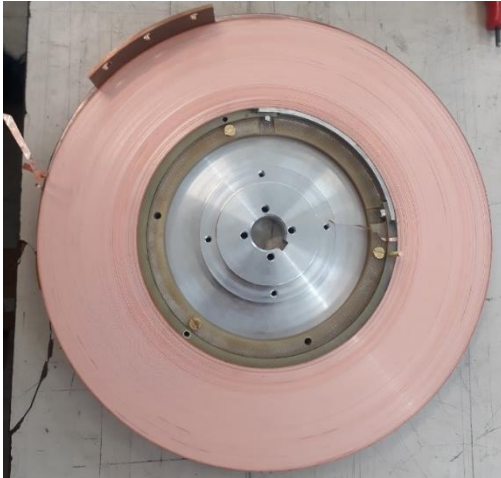


Fig. 2. Pancake before impregnation.

Once this is completed, two 0.2 mm thick FRP flanges are glued by means of araldite epoxy resin mixed with quartz powder (Araldite DBF + Aradur HY 951 + Quarzgutmehl SILBOND® FW 12 EST (mixing ratio Araldite + Quartz = 1:1)) [8] on each side of the pancake to make the thermal link between the turns, improve the rigidity of the coil and reduce the radial stress on the tapes. In this way, the coil turns are only glued to the flanges and not between them.

One goal for this test pancake was also to reproduce as best as possible the space constraints in the high magnetic field

inserts. The inner and outer copper contact are thus made very thin: 2 mm at inner and outer radius. Connections with the current leads terminals, representing the connections between pancakes, are made afterward with a lower temperature solder compound (InSn 118 °C).

III. PANCAKE MECHANICAL BEHAVIOR : MODELING AND EXPERIMENTAL TESTS

A. Stress evaluation

The hoop stress in insert coils is commonly estimated with the following assumptions: for dry winding, with tapes fully separated, the stress follow the BJR equation. For impregnated winding, the stress distribution follows the Wilson formula. Both formulas are only valid for roughly isotropic structures.

The composite structure of an edge-impregnated pancake requires more complex modeling, accounting for the different contact interfaces turn-to-turns and turn-to-flanges. We developed a simple FEM model to represent this structure, in which the contacts are all considered as thin elastic interfaces: A layer with very low Young's Modulus (1 MPa) represent the turn to turn interface, which is not glued, while the epoxy between the conductor and the FRP flanges is represented realistically as a thin layer with a Young Modulus of 10 GPa. These interfaces can be seen in Fig. 3 in white and blue (white between turns and blue for the epoxy). Each turn is represented independently in this modeling. The equivalent Young's modulus of the conductor itself is evaluated at 143 GPa taking into account both REBCO tapes and the co-wound Hastelloy reinforcement tape with its 5 μ m of MgO insulation (135 GPa for Fujikura tapes and 163 GPa for Theva Hastelloy/MgO reinforcement tape if hastelloy young modulus is 180 GPa). The equivalent radial Young's Modulus of the 0.2 mm FRP flange is 50 GPa.

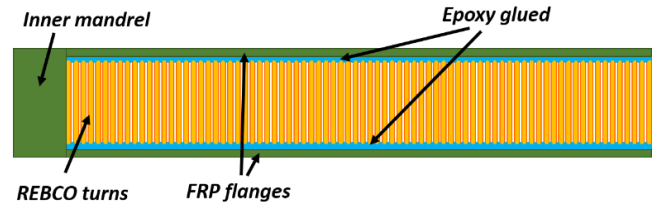


Fig. 3. 2D axisymmetric schematic of the edge-impregnated pancake.

B. Experimental test and performance limits

A first test up to 80 A in liquid nitrogen is conducted to check for degradation due to winding and/or cooling-down delamination. The winding is then equipped with 7 strain gauges. 4 on the outer diameter of the pancake to measure the strain caused by the hoop stress, two of which were functional during the tests (SG_HS1, SG_HS2). 3 on the FRP flange to measure the strain caused by radial stress. One was functional during the tests (SG_RS1).

To evaluate the mechanical performance of the pancake, the tests are performed under a background magnetic field of 8 T. The goal is to ramp the coil until its mechanical limits without concerns for current margin, reason why the tests are conducted

in LHe. A current of 800 A is reached before degradation, which occurred at the inner contact. A second ramp was carried out with the aim to go higher in current, but the inner contact degraded just above 800 A, to reach $1.1 \mu\Omega$. Therefore, we stopped the ramp at this level. A third ramp up to 750 A was carried out in 8 T background field and a fourth in self-field up to 800 A without any further deterioration of the inner contact.

Fig. 4 presents the mechanical modelling results for the highest current reached experimentally. It illustrates the benefit of using insulated reinforcement tape instead of Polyimide, with a 20 % reduction of stress on the REBCO tape (Red vs Blue, and Yellow vs. Purple).

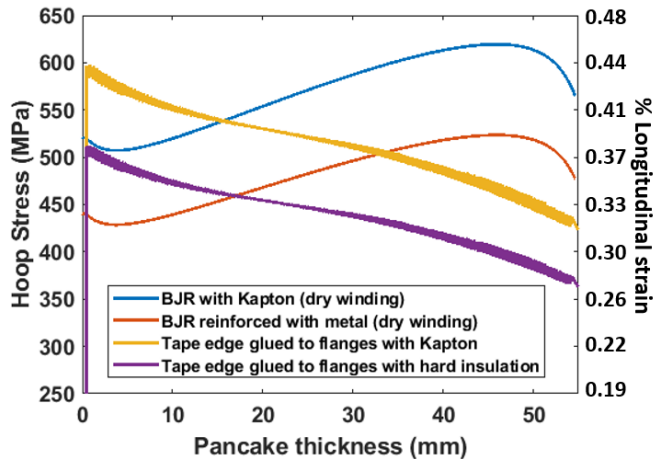


Fig. 4. Hoop stress and longitudinal strain expected in the pancake thickness for 800 A under 8 T background field.

For this test pancake, the comparison between edge-impregnation behavior and BJR is not very favorable. The peak hoop stress is transferred to the inner diameter of the winding compared to a dry winding. It is slightly lower, but not by much. This is because of the pancake dimensions. The reduction of peak stress using edge-impregnation is much larger in a real configuration (a full size REBCO insert made of several pancakes, as modelled in [3]).

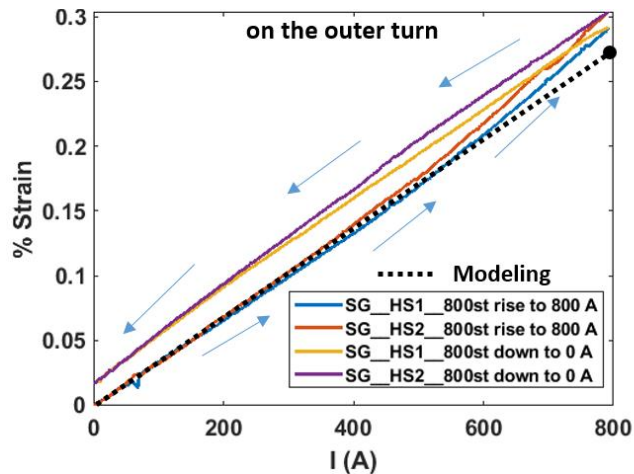


Fig. 5. Strain gauge measurements in circumferential direction under 8T. In dotted black, expected value from modelling.

According to the modelling results, the maximum hoop stress safely reached was about 505 MPa (purple curve, inner radius)

corresponding to 0.38 % elongation. To produce the same field, a dry wound coil with a standard insulation material would have needed to reach more than 620 MPa tensile stress on the tape, resulting in more than 0.45 % elongation, value for which the risks of damage become overwhelming.

C. Measured Strain and discussion

Fig. 5 presents the strain measurement on the outer diameter for the first ramp to 800 A under 8T. The measured longitudinal strain went up to 0.29 and 0.31% on the outer diameter for SG_HS1 and SG_HS2 respectively, while the radial strain reached 0.25% for SG_RS1 (Fig. 6).

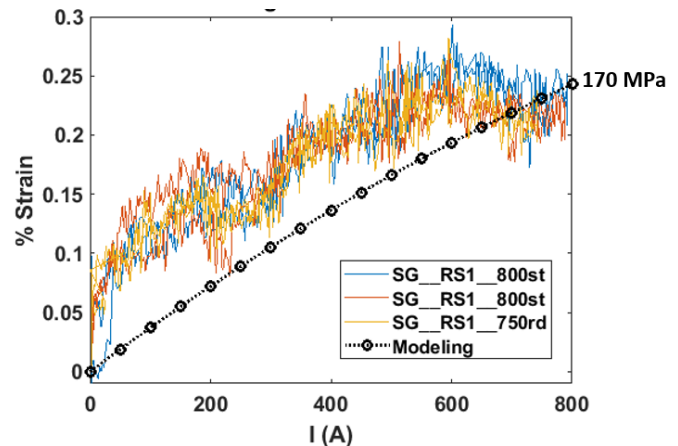


Fig. 6 Strain gauge measurement in radial direction on FRP plate under 8T. In dotted black, expected value from modelling.

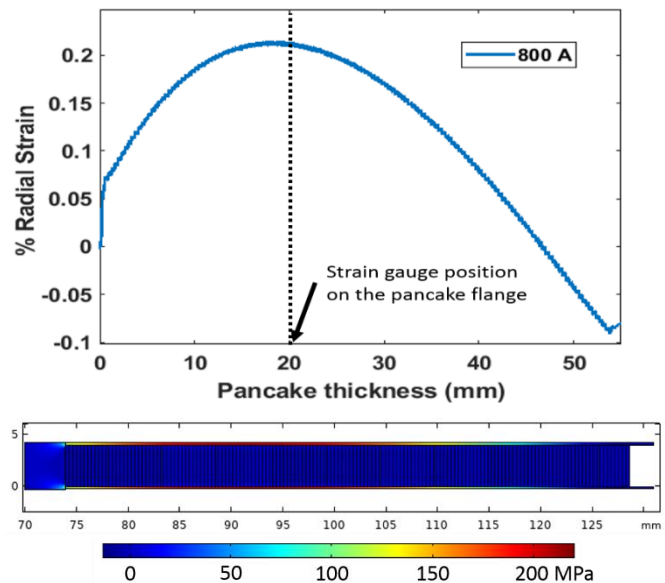


Fig. 7. Modeling of the stress in FRP plates.

Fig. 5 and 6 show good agreement between experiments and expected values from modelling results, although modelling was slightly optimistic (0.27 % strain on the outer radius of the coil compared to 0.29 and 0.31 % in the experiment). A slight residual strain can be observed after a first cycle of charge and

discharge remains in the coil strain Fig. 5, which is cannot be represented using our simplified linear mechanical model.

Still, the model agreement with experiment at the outer turn validates the estimation of stress and strain at the inner radius of the winding presented in previous § at about 0.38 % for 505 MPa. Moreover, it is to our knowledge the first time that radial strain in such composite structure is measured, at about 0.25% , corresponding to a large 170 MPa radial stress in the flanges (Fig. 7). This high radial stress and strain value illustrate the fact that the turns are not glued together, as such stress would surely cause delamination [11], and that radial stress is solely applied to the flanges.

IV. ELECTRIC TESTS AND DIELECTRIC STRENGTH

A. Measurement setup

For the experimental tests, 4 voltage taps were placed on the coil. 2 on each side of the inner and outer contacts in order to measure their resistance and check the superconducting state of the coil during the tests. The first tests in liquid helium were carried in self-field configuration up to 850 A (600 A/mm²) with no dissipation. The contact resistances at the current terminals are 120 nΩ (60 nΩ.cm) and 200 nΩ (100 nΩ.cm) for the inner and outer contact respectively. To protect the pancake from a possible hot spot, we use a pick-up coil to compensate for most of the inductive signal of the coil when it is charged as in [9]. In this way, we can more accurately observe the onset of a thermal runaway. The compensated voltage during the first test up to 800 A under 8T is shown Fig. 8. As expected, a drift upwards can be observed on both as the current in the coil increases. This is due to redistribution of the current density within the conductor as discussed in [10]. Many spikes due to wire movement are visible during this first test, they were much fewer in the following tests.

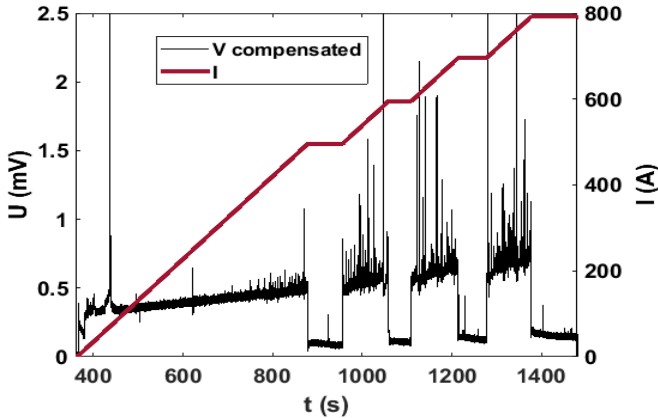


Fig. 8. Top: Current cycle and Compensated voltage of the coil.

B. Validation of insulation characteristics

In order to test the electrical insulation of the winding thanks to the Hastelloy reinforcement on which a 5 μm layer of MgO was deposited, several tests of charge and discharge of the coil at different speeds were carried out to see the inductive behavior of the magnet and its energy efficiency. Using the power

supply, we achieved current ramps from 5 to 100 A/s. To go to higher discharge speeds (up to about 300 A/s) we used a dump resistance.

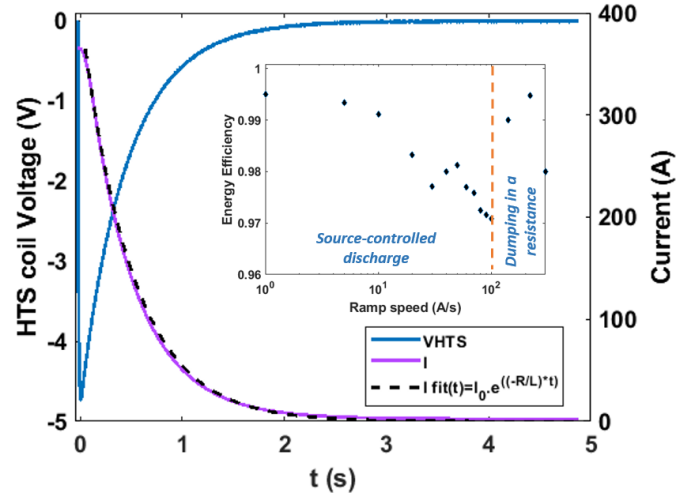


Fig. 9. Energy efficiency of the coil for different current ramp speeds.

In Fig. 9 we visualize the fastest discharge that we have realized (about 300 A/s). If we make a fit of the discharge current, we find a perfect exponential curve (dotted curve) which overlaps perfectly with the experimental curve. This highlights the good insulation of the coil. The peak voltage during this discharge is 4.7 V which corresponds to 30 mV of voltage between turns. At last, in order to check more precisely the good insulation of the pancake we also look at the energy efficiency of the coil for each cycle and charge/discharge speed. As can be seen in Fig. 10 the energy efficiency of the coil is very good. Between 97 and 99 % even with very fast discharges. With such a good energy efficiency, we can consider that the MgO insulation fulfils its function perfectly up to this voltage and makes it possible to charge or discharge a REBCO magnet very quickly.

V. CONCLUSION

This work represents the first experimental validation of edge-impregnated REBCO pancake without soft non-stick material in between turns. The insulation-coated Hastelloy co-wound improved the winding stiffness while retaining the benefits of edge-impregnation (hoop stress redistribution, conduction cooling capability...). The test pancake reached an estimated hoop stress of above 500 MPa at 800 A under 8T background before degradation, operation conditions for which the strain would have exceeded 0.45 % if conventional Polyimide insulation and winding had been used. For the first time, radial strain in such structure was measured and was in good agreement with the expected model values.

Finally, rapid charge and discharge tests of the pancake from 5 to 300 A/s show that the thin MgO coating is an effective electric insulation for turn-to-turn voltages up to at least 30 mV. The energy efficiency of the pancake shows that this innovative winding design can be used to rapidly charge or discharge a high field REBCO magnet.

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