Construction and test of a non-insulated insert coil using coated conductor tape

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Abstract. A small coated conductor coil (central field 1 T at 200 A) was constructed and tested in order to evaluate the benefit and the possible disadvantages of non insulated, double pancake construction, in particular regarding quench protection. The insert coil consists of three double pancakes without turn to turn insulation, and it was impregnated with beeswax. The coil was equipped with voltage taps on each pancake, thermocouples and a quench heater. Quench tests were carried out because quench protection is one of the main issues in developing coil technology for coated conductors. Quenches were induced either by a heater or by exceeding the coil critical current; in all cases the quench protection system was able to detect the quench.

1. Introduction
In the last few years remarkable results have been achieved in the construction of high field insert coils using coated conductors [1]. In the Superconductivity Group at CRPP a project aiming at the construction of 4 T insert coil is running [2]: it was planned to build a coil composed of double pancakes using a coated conductor tape without electrical insulation. There are just a couple of examples of non insulated magnets [3] and one of them is the CMD-2 solenoid [4]: it was constructed by winding the NbTi cable without any insulation on the steel former, which act as current shunt during a quench. This concept has been recently applied to coated conductors coils [5], the main advantage being the remarkable tolerance to over current compared with coils wound with insulated tapes.

If the coil under development at CRPP [2] was constructed with insulated tape, it could be easily protected with the same technique used for standard LTS magnet. Nevertheless, the use of a non insulated tape adds a generous margin to the quench protection, without any major drawback. The only disadvantage is the time constant that appears during transient (charging and discharging), but in this case it is limited to less than a second, and it does not perturb the normal operation.

In this work a test coil, composed of three double pancakes, is constructed and tested at 4.2 K in background field. Quench detection and protection have been also implemented and tested.

2. Coil construction
The coil consists of three double pancakes each wound on a common long former made of fibreglass. Each double pancake was wound with about 6.5 m of non insulated tape (Superpower SCS4050); inner diameter is 43 mm and outer diameter is 52 mm. Each pancake is insulated from the other with a cardboard ring, which has been previously impregnated with bee wax. In coils made of double pancakes wound on separate formers, an axial pressure can be applied to reduce the gaps in between
the pancakes during the assembling of the double pancake modules. If the double pancakes are wound one after the other on the same common former it is inevitable that a gap is present in between each pancake. During operation the winding pack can move and hence the strain could locally exceed the irreversible limit. Therefore the coil should be impregnated, in order to fill up the voids in between the pancakes. In order to achieve this objective, the presence of a cardboard disk impregnated with wax will help the wax to diffuse, even if the impregnation is not carried out in vacuum. The bee wax was mixed with quartz powder (Quarzmehl K8 from ASTORIT) at about 20% in weight; the reason is to reduce the thermal contraction and improve the strength during thermal cycling.

The two joints were prepared using three short pieces of tape, cut diagonally and placed one besides the other (see figure 1) with the superconducting layer side facing upward (outward). The tapes from the two double pancakes to be jointed were overlapped upon the three tapes in diagonal, so that the sides with the superconducting layer are in contact. On the outer side of the joint a brass foil (8 mm wide, 40 mm long, 0.2 mm thick), acting as mechanical reinforcement, was soldered.

Voltage taps were attached to each double pancake, so that they could also be used to measure the voltage drop across the two joints. A heater (strain gauge) was placed between the uppermost pancake and the flange. One thermocouple was placed besides the heater, and two more were located close to the lowermost joint and between the lowermost pancake and the flange.

Finally the coil was wrapped with glass band and impregnated with wax. The function of the wax/glass over-banding is to insulate thermally the coil from the bath, so that the heater can efficiently heat the coil, without dispersing too much heat into the bath.

![Figure 1. Joint preparation. Left: overlapping the tape to the diagonally cut tapes. Center: Overlapping completed; then it will be soldered. Right: A thin brass foil is soldered over the joint as mechanical reinforcement.](image)

3. **Coil test at 77 K**

The coil was first tested in liquid nitrogen. The critical current was about 35 A at a total voltage drop of 0.1 mV; the exponential $n$ value was about 18; these values are in line with the expectations. Few quench experiments were carried out, either using the heater to initiate the quench, or by running the coil above the critical current, till the thermal runaway. During these tests no quench detection/protection was used, and for several seconds the power supply delivered currents of over 30 A with total voltage drop on the coil higher than 10 V; therefore a power between 400 W and 550 W was dissipated into the coil, with a large boil-off of liquid nitrogen. Such operation is possible only with non insulated coils, where the current can be shunted through the copper and the dissipation distributed eventually over the whole coil, instead of being localized into a small hot spot region, which would quickly burn out.

It was observed that the time constant was gradually reduced during the quench tests (see figure 2). The temperature measured in these tests was of the order of 250 K, but it can not excluded that the actual temperature in the winding pack was higher thus exceeding the melting temperature of beewax (about 350 K). In addition, the increase of temperature may have led to a reduction of tension in the winding because of the thermal expansion of the winding pack, while the former being in contact with liquid nitrogen was still cold; it can be speculated that the liquid wax may have infiltrated the turns, increasing the turn to turn resistance and thus reducing the time constant; the corresponding resistance was estimated to be increased from 5.4 to 13.5 mΩ. Such situation should not occur in a real operation...
of a wax impregnated coil, because the quench detection and protection is designed so that the temperature never exceeds 150 K.

Figure 2. Time evolution of the voltage drop during the current ramp. The time constant is clearly reduced from the first test (left) and after quenches (center and right).

4. Coil test at 4 K

Despite the change in time constant, the coil was tested also in liquid He. The V-I characteristics are shown in figure 3. Measurements were carried out in self field and in background fields of 5 T and 9 T, generated by an Oxford 15 T magnet. As expected, the central double pancake (B) is the last to start the transition, because the radial component of the magnetic field is the lowest and thus the critical current is the highest. The critical currents have been determined using the resistivity criterion at $10^{-14}$ Ωm: the values are 400 A in self field, 378 A in background field of 5 T and 353 A in background field of 9 T. The little variation with the background field is due to the fact that the field is almost only parallel to the wide face of the tape, and the critical current is weakly affected by parallel fields.

The V-I characteristics of the joints are plotted in figure 3. The total resistance is acceptable for an insert coil, because the power dissipated at each joint would be less than 5 mW at 250 A.

Figure 3. Left: voltage drop versus current in self field, 5 T background field and 9 T background field. The linear slope is due to the resistance of the joints. Right: V-I characteristics of the two joints.

For the tests at 4.2 K a simple quench detection system was installed: when the total voltage drop across the coil is larger than 15 mV a 5 V signal is sent to the power supply, which then switches off. One example of the system operation is shown in figure 4 (left): at 388 A the heater is first turned on
at $t=480$ s, but the power is not sufficient to induce the quench; only a stable increase of voltage is observed. The current is increased to 402 A, and the heater is switched on at $t=530$ s; this time the self heating effect is sufficient to put the pancake in thermal run away. As soon as the voltage exceeds 15 mV the current drops to zero.

In figure 4 (right) the coil current is increased till the thermal run away appears. Again the quench protection switches the power supply off as soon as the voltage exceeds 15 mV.

![Figure 4](image)

**Figure 4.** Example of quench detection. Left: after the second heat pulse the coil is driven in thermal runaway; when the total voltage drop (main contribution is from double pancake A) exceed 15 mV the current is set to zero. Right: the current is increase (470 A) till runaway.

5. **Summary**

A non insulated coil composed of three double pancakes has been prepared. The pancakes were wound on the same common former and insulated one from the other with cardboard disks; the coil was impregnated with wax at ambient pressure. During the over-current operation at 77 K the temperature exceeded 250 K. The coil was not damaged, but an increase in the turn to turn resistance was observed, probably because melted wax infiltrated in between the turns during the quenches.

The test at 4.2 K was carried out up to 9 T background field. Critical current in self field was 400 A and in 9 T background field about 353 A. During the tests at 4.2 K a quench detection circuit was used, which switches the power supply off when the total voltage drop exceeded 15 mV.

**References**

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