24. PRE-INDUSTRIALISATION OF THE WINDING AND POLYMERISATI ON TECHNIQUES

24.1 INTRODUCTION

This chapter discusses the tests which are foreseen to ascertain both the winding and the curing techniques.

These tests will be performed in collaboration with competent industrial firms who are familiar with the retained winding process. This should allow us to profit of an industrial assessment, allowing to adjust at an early stage, the final definition of the winding process.

The program is divided into different activities each one aiming to verify a particular aspect of the winding operation, such as; bending, insulation behaviour, curing, etc.

An important aspect of these winding tests is that they need to be carried out using significant lengths of the final conductor. These lengths will be manufactured following the conductor pre-industrialisation program as described in Chapt. 23 [23-22]. However, in order to allow an early start to the winding tests, “dummy conductors” made on a case by case basis will be used at first.

24.2 MAIN ACTIVITIES

The whole program is organised around five lines of development.

- Bending and stacking tests on bare conductor;
  to test the different winding techniques, determine the cross section deformation of the conductor and the forces to be applied during the winding process.
- Bending and stacking tests on insulated conductor;
  to understand the problems related to the insulation, (i.e. maximum pressure to be applied without damaging the insulation), the flow of the impregnation under pressure before curing, and to produce test stacks to measure moduli.
- Characterisation of the insulation;
  to characterise the properties of the insulation using the test stacks obtained from the previous activities, and to perform mechanical, electrical and thermal tests.
- Quench back cylinder, winding and welding tests;
  to qualify the assembly process of the quench back cylinder and check that the maximum welding temperature behind this cylinder corresponds to the computed estimations.
- Winding a short length model of the solenoid;
  to validate the winding and curing process in order to finalise the specification of the winding machine.

Table 24.1 resumes the main activities of the pre-industrialisation program [24-1].

24.3 BENDING

These tests will be done to evaluate and to compare three different bending methods. By measuring the required forces and the cross section deformation the most simple and reliable bending process can be chosen.

The three techniques to be explored are the following:

1) bending by directly pulling the conductor while winding it over a mandrel,
2) bending using the same method as above, but in addition applying a radial force,
3) pre-bending the conductor by passing it through a roller box and then winding it over a mandrel under slight traction.

The preliminary tests will use a simple dummy conductor composed of a pure aluminium insert surrounded by two aluminium alloy sections.

All these tests will be carried out by bending short lengths of the dummy conductor to a radius of 3000 mm and a sector of between 30° and 45°.

The main implication coming from these three choices is the sequencing of the conductor insulation. In the first two cases the insulating tape must be wrapped over the conductor before bending, consequently it has to withstand the forces generated by the bending process. In the third case the conductor is bent before being insulated therefore allowing the cross section to be corrected to the final shape before applying the insulation.

The third method is preferred because it imposes less stringent requirements on the insulation, however it is important to determine if sufficient space can be made available for the installation of the insulation unit which must sit between the bending device and the mandrel.

Stacking of the bare conductors

The first study to be performed, will be to check that the spooling, de-spooling and straightening operations have no adverse effects on the cross section of the conductor. Then short lengths of conductor will be prepared and machined.

The lengths will be cut into short segments and stacked to measure the overall Young's modulus at several points. These measurement will be used to estimate what axial pressure has to be maintained on the conductor during the winding process in order to ensure the correct parallelism of the turns, and therefore the proper filling factor for the final coil. They will also provide a reference for the next series of tests destined to estimate the final thickness of the insulation after curing.

Bending and stacking tests of the insulated conductor

The object here is to test the inter turn and inter layer insulation behaviour during the winding operation. The principle of the test is shown on Fig. 24.1.

These tests will be performed on a stack of bent segments of insulated conductor to determine the volume contraction of the insulation under pressure, both before and during curing. The bending will be done using the third method mentioned above, as it is the simplest method to bend the required length of conductor without a mandrel.

Two models will be built using different insulating materials. They will consist of a stack of ten conductor segments, one meter long, obtained from the bending tests mentioned above. As the final insulation will not be available at this time, the insulation material will be simulated by a B-stage material and semi-wet insulation using glass cloth obtained from DELPHI [24-2], or by using glass cloth over Upilex® or Kapton® material as is currently used at KEK [24-3].

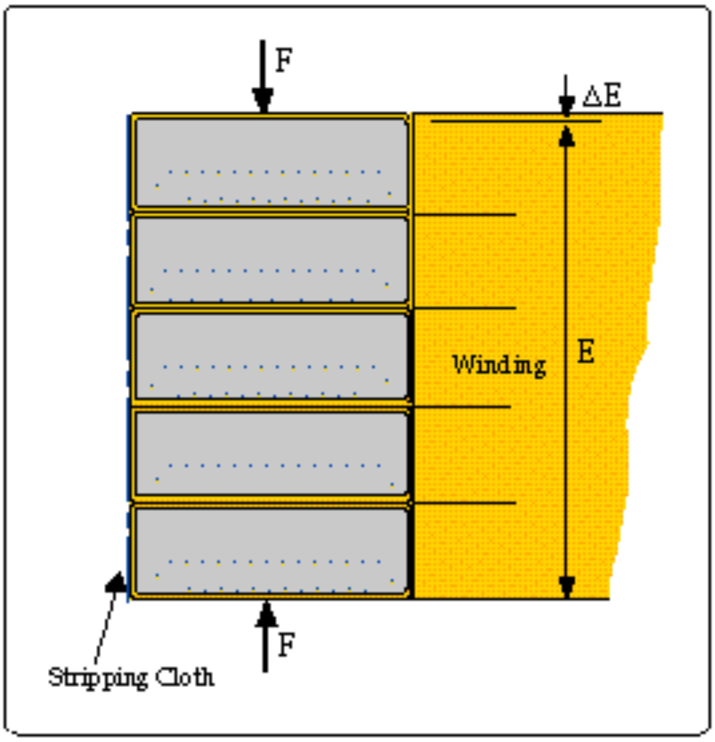

Fig. 24.1: Stacking measurement on insulated conductor.

After completing the test stacks, an axial pressure will be applied during the curing process with the aim of getting a uniform inter-turn insulation thickness.

Measurements will be done on each model, before and after curing to estimate:

- the release of resin from the semi wet prepreg insulation,
- the flow curves of the insulation under constant pressure,
- the filling factor.

Understanding how the resin is released from the insulation is very important for the winding process, as this will determine how the last turns will creep and settle. The insulation thickness can then be measured to determine its accuracy.

During all the tests extensive measurements will also be performed to understand :

- the residual conductor twist deformation,
- the conductor cross section deformation,
- the straightness and influence of spooling and de-spooling,
- the forces required to straighten the conductor,
- the spring back effect, if any.

24.4 CHARACTERISATION OF THE INSULATION

The filling factor of the winding will be estimated after the curing of these layers. The axial elastic modulus will then be measured.

The outer surface of the cured layer will be verified in terms of adherence to the next layer.

The inter-layer insulation will be placed on the outside of the stack. Then, in order to obtain a good contact with the turns, the pulling force or pressure to be applied to the insulation will be measured. The release of resin from the inter-layer insulation will be checked to verify if any extra resin must be added during this process. The stripping cloth material will then be placed on the outside of the inter-layer insulation.

To obtain a complete knowledge of the insulation behaviour, different curing techniques will be tested on several samples. The curing operation will always be carried out with the axial pressure applied and the dimensional changes will be recorded during the whole process.

The insulation will be fully analysed by cutting the stacks after curing. The mechanical, electrical and thermal characteristics will be measured at room and cryogenic temperatures.

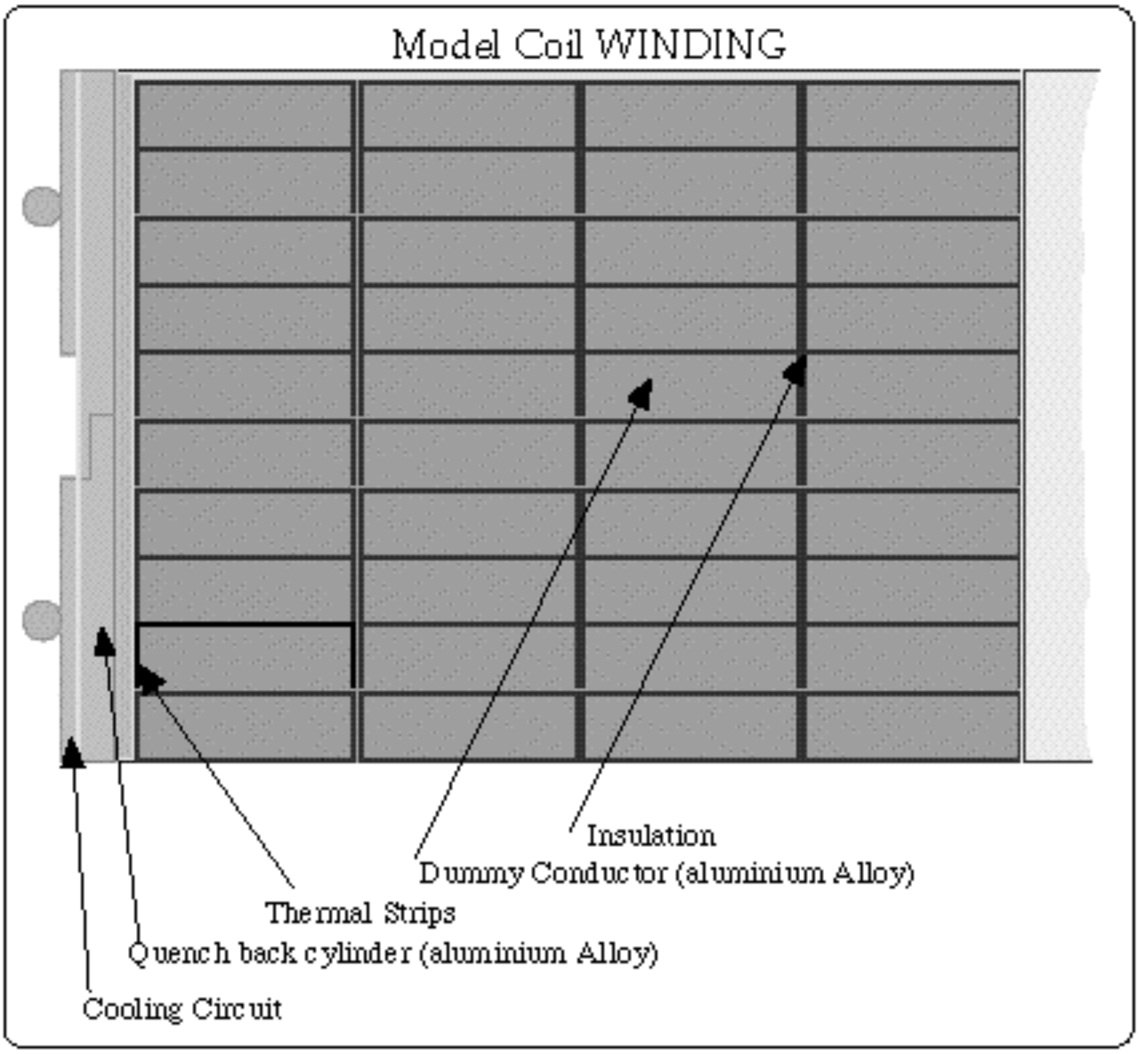

Fig. 24.2: Full diameter short model coil

24.5 QUENCH BACK CYLINDER WINDING AND WELDING TESTS

To qualify the techniques selected for constructing the quench back cylinder, a half scale model will be made on a 2 m long wooden support. This model will contain instruments to verify the maximum temperature reached during the assembly process. Mechanical tests will then be performed to measure the effectiveness of the welding process.

24.6 FULL DIAMETER SHORT WINDING MODEL

When the conclusions of the previous tests have been made and the winding technique finalised, a short length solenoid (10 turns and 4 layers) will be wound. No joints or inter-layer connections will be simulated but the final insulation material and the selected curing process will be used. All the components of the solenoid will be assembled: the four layers, the inter layer insulation, the thermal strips, the quench back cylinder, and the cooling circuits. Each layer will be cured upon completion, and the final curing will be performed after the installation of the heat exchangers, as shown in Fig. 24.2.

The following tests will be undertaken on sections cut from the short model:

- electrical, mechanical and thermal tests,
- estimation of the filling factor,
- bonding tests before and after cooling down,
- destructive testing.

24.7 SOLENOID WINDING PROTOTYPE

At the end of the pre-industrialisation program, the technical specification of the winding machine will be finalised and the call for tender launched. This machine will then be used to build a short length (1.5 m) winding prototype of the solenoid, complete with electrical connections between the layers and conductor joints inside the layer.

This prototype will be used to control the manufacturing process step by step in order to qualify the complete construction process of the coil, and to commission the winding machine and the solenoid components. The prototype will then be examined and tested but not energised. Destructive tests will be performed to measure the bonding quality and the mechanical properties of the structural material. Only after all these tests, have been successfully performed, will the winding of the CMS solenoid proceed.

Table 24.1
Synthetic table of the pre-industrialisation activities foreseen for the winding and polymerisation technique.

	Test	Goals	Implication	Schedule
1	**Winding technique assessment** 1. Winding by pulling the conductor around the mandrel 2. Same as above + radial force 3. Pre-bending and winding	Define winding tension Assess: • twisting • spring back effect • deformation of the cross section • superconducting performance degradation • elastic energy stored in the winding and, if, how to minimise it.	Define winding procedure and implement spec. for winding machine For technique 3: • define pre-bending radius • assess shear forces between layers due to layer shrinking after removal of the mandrel.	Sept. '97
2	**Stacking test** • using short (2.5 m) length of straight, bare, dummy conductor • using short (2.5 m) length of insulated dummy or real conductor.	Understand the behaviour of the conductor in the stacking operation. Begin to evaluate part of the axial mechanical characteristics of the winding.	Have stacking references Define first winding instructions and specs for axial pressure jigs	Oct. '97
3	**Straightening test** of separate components and assembled conductor with dummy profile or short (2.5 m) samples.	Quantify cold work in the different operations Check bonding behaviour at interfaces	Definition of the straightening jigs	Nov. '97 Depending on the tooling available from industry
4	**Machining of conductor** - before bending - after bending - both with dummy and real conductor.	Define appropriate cross section Optimise the way of machining the profile	Define the tooling to rectify the cross section	End '97
5	**Insulation/Curing** on short samples	Understand the behaviour of the insulation and how the resin flows out.	Qualification of the process	End '97

6	**Cool down** using the insulated short samples of 2.5 m	Assess possible problems during cooling down and steady state at 4.2K		March '98
7	**Welding technique of the quench back cylinder** Short samples welded with TIG, EB, Laser	• To find the technique which needs the lowest heat input • Measure the maximum temperature reached behind the aluminium profile	Qualify the quench back welding process	End '98
8	**Short model at full diameter** 4 layers, 10 turns • with 100/200 m of insulated final conductor • with the selected bending technique • with the qualified insulating process • with the qualified curing process	Assessment of: • friction wear behaviour of glass before curing • measure filling factor before and after curing	Finalise and qualify the whole winding technique	June' 98
Writing of winding and winding machine specification and launch the call for tender: End '98				
9	**Winding prototype** 1 m long, full diameter winding	Global winding assessment	Commissioning of the winding machine	First half 2000