Pre-industrialization Activities Related to CMS Coil Winding

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***Abstract*— The CMS coil is a large 4 layer superconducting solenoid involving the use of a new design reinforced conductor. In order to understand the feasibility of the coil manufacture using the inner winding technique for this particular conductor, the CMS Collaboration has developed a pre-industrialization activity. The main objectives were: 1) Study of the methods for winding a coil using a stiff conductor, 2) Design, construction and testing of a prototype winding line, 3) Construction of a Model for the fine tuning of the required operation and procedures. The activities, carried out in cooperation with industry, were successfully completed, giving basic information for the necessary tool and methods to be used for the coil winding.**

***Index Terms*— Al stabilized conductors, Detector Magnets, LHC project, Winding.**

I. Introduction

The Compact Muon Solenoid (CMS) is one of the experiments under construction in the framework of the Large Hadron Collider (LHC) project at CERN. The design field of the CMS magnet is 4 T, the magnetic length is 12.48 m and the aperture is 6.36 m [1], [2]. The CMS solenoid presents two new features with respect the previous detector magnets [3]:

- Due the high ampere/turns required (46.5 MA), the winding is composed of 4 layers, instead of the usual one (as in the Aleph or Delphi coils) or max 2 layers (as in ZEUS coil).
- The standard conductor, made from a Rutherford cable co-extruded with pure aluminium, is mechanically reinforced with aluminium alloy [4].

The basic new idea in the design of the CMS magnet is to use a self-supporting conductor. The magnetic stresses are shared between layers (70%) and support cylindrical mandrel (30%) rather than taken by the outer mandrel only, as was the case in the previous generation of thin detector solenoids.

The coil is made of 5 modules, mechanically coupled and electrically connected in series.

The main components of the superconducting coil are now in construction phase under the control of the CMS Coil Collaboration [1]. In particular the winding of the 5 modules in industry and their assembly in the vertical position on CERN site is under the responsibility of INFN-Genova, which carried out an international tender for the winding operation. The order was awarded to Ansaldo Energia at the beginning of 2000. This was the last step of a long process which started in 1997, when it appeared clearly that the use of a new kind of reinforced conductor would require a development at an industrial level of the methods and the tooling for the winding. This winding pre-industrialization activity was carried out by INFN and by the Coil Collaboration with an important participation of Ansaldo Energia, which won an INFN tender specific to the industrial development of a winding line capable of handling the reinforced conductor

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II. Objectives

The goal of the winding pre-industrialisation was to develop a credible and reliable technology for the winding of the CMS solenoid. In this perspective several activities were carried out (mostly by industry):

Bending tests – These tests were carried out by bending the conductor in a single and multiple steps in its higher inertia using a 3-roller bending machine. The aim was to understand the effects of bending parameters and tooling layout on the conductor deformations.

Stacking tests – Three stacks of 10 bent conductors (1.5 to 2.5 m in length) were made after wrapping the conductors with fiber-glass tapes. These tests served both to evaluate the relation between axial pressure and degree of turn compaction and to determine the proper kind of glass tape to be used in the winding.

Welding tests for external cylinder - Different tests have been carried out (both at CERN and in industry) on the Al alloys which have been considered possible candidates for the external mandrels (5083–H321, 5083-H111, 6082-T6). Another objective of this development line was to qualify a MIG welding procedure for potential application to the mandrel construction.

Insulation tests - The bonding between the insulation and the conductor or the external mandrel is related to the wetting properties of the resin and the preparation of the metallic surface. Methods for obtaining a bond stronger than the insulation composite itself have been developed at CEA [5]. The influence of a surface treatment of Al alloy on the bonding between the insulation and the alloy has been studied. Different surface treatments were compared: sand blasting, solvent cleaning and anodic oxidation

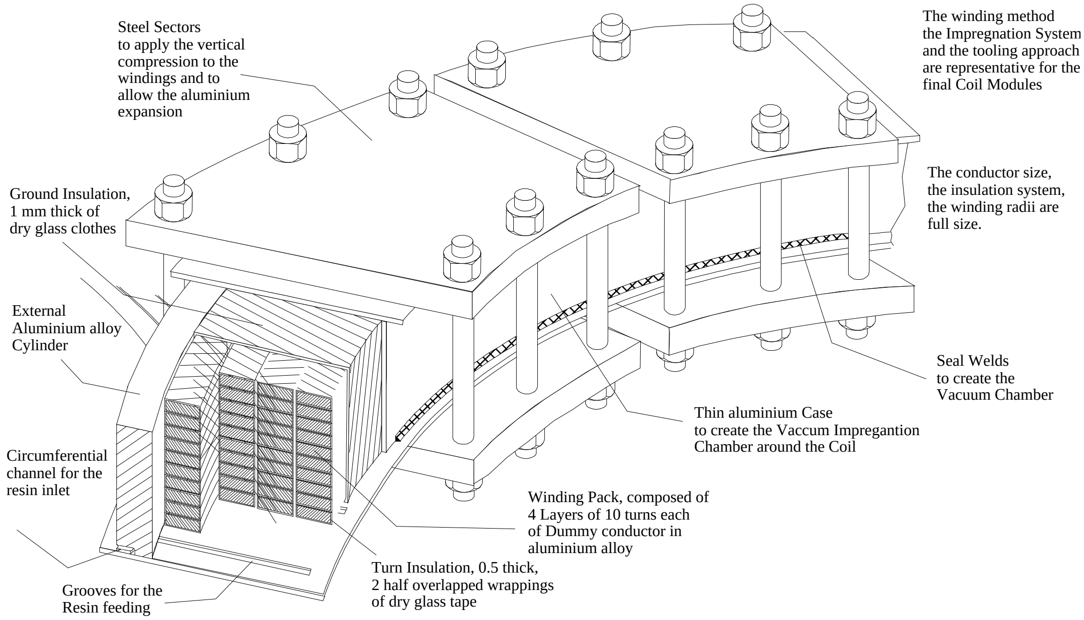

Fig. 1. Artistic view of the model coil as designed at ANSALDO. Four layers (10 turns per layer) of Al-alloy 6082 are internally wound on a 6900 mm ID mandrel of the Al-alloy 5083.

Winding test - The CMS conductor is so stiff that the usual inner winding technique (used for several existing detector coils) had to be verified and possibly modified. The critical operation is the insertion of the pre-bent conductor inside the winding pack. The classical pure Al-stabilized conductors are so soft that only a small force is required for this operation. For a stiff conductor a higher force is required with, as consequence, the risk of damaging the insulation. We have tested one possible technique based on a *winding* plus *transferring* method. Each layer composing one module is freely wound on air (without internal mandrel) using a bending machine. The layer is then transferred inside the external mandrel, or an existing layer, using a dedicated tooling working on the elasticity of the conductor.

Construction of a model coil - A central role was played by the model coil, shown in Fig.1. In order to be fully representative of the CMS coil, the model is composed of 4 layers supported by an outer Al-alloy mandrel. The number of turns per layer was limited to 10. Since long lengths of conductor were not yet available, the model was wound with an aluminium alloy dummy conductor.

The main results of the pre-industrialization are summarized in the following sections.

III Bending and Stacking Tests

Generally speaking, when dealing with stiff conductors, the winding quality depends on two parameters related to the pre-bending operation: constancy of radius and cross section deformation. For the CMS reinforced conductor, bent in its larger inertia direction, both parameters are critical.

The constancy of radius depends on the homogeneity of the mechanical properties along the conductor length, and this is not easily obtained due to the complex process leading to the conductor production (from strands to cable, to co-extruded insert with addition of Al-alloy side reinforcement by EB-welding). After long series of tests carried out on 6 m long prototype conductors, the main results obtained on the bending operation were that the constancy of the radius is better controlled if the bending is performed through a multi-step process. As an example Fig.2 shows that the bending radius of several samples processed with a 2-step bending operation is more constant than the radius of samples bent with a single operation.

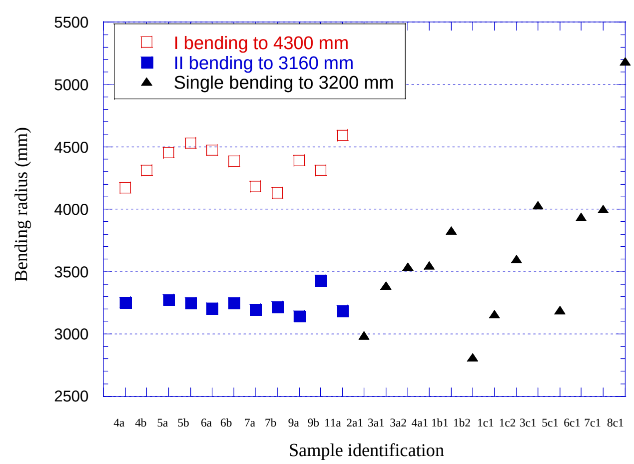

Fig. 2. Results of bending tests with 2-step and single step processes.

The deformation of the cross section is dominated not only by the conductor layout but also by the degree of hardening of the pure aluminium insert and by the quality of the EB-welded interface. According to our measurements, for an Al-alloy profile having the same dimensions as the CMS conductor, the cross section deformation results in a key-stoning presenting a 0.320 mm difference between the side at inner radius (the thicker) and the one at the outer radius (the thinner). The deformation of the prototype conductor (with the pure Al insert) is not a real keystoning but rather a bump in the pure aluminium insert of +0.315 mm with respect to the nominal conductor thickness. The Al alloy reinforcement is deformed by +0.145 mm at the inner radius and -0.032 mm at the outer radius. The bumping of the pure aluminium can be reduced to 0.2 mm by applying later an axial pressing.

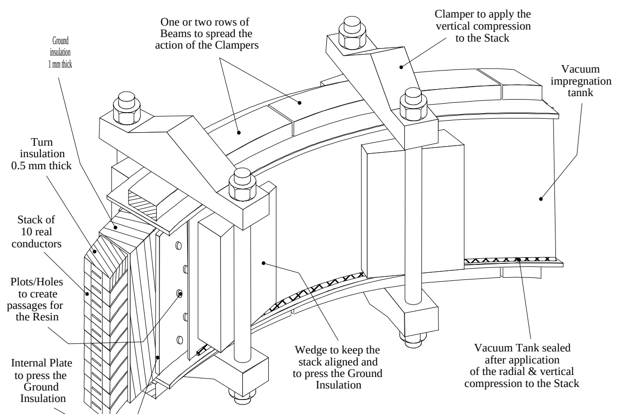

Fig. 3. Artistic view of a stack sample (from ANSALDO).

Fig. 4. One of the stacks during construction: (a) assembling phase, (b) after impregnation, (c) sectioned.

In order to verify the packing of bent real conductors, the construction of three different stacks was planned. The stacks, made up of 10 conductors bent at a radius of 3160 mm, are 1.5-2.5 m long. A schematic view is shown in Fig.3, while Fig. 4. shows a stack during construction and after sectioning. The first stack was made using a fiberglass tape 0.15 mm thick two times half overlapped to get 0.59 mm of insulation thickness. When pressing the stack with 3 MPa, the nominal average thickness of 0.5 mm was achieved. The analysis of the impregnated stacks (Fig.4.c) revealed no glass free regions. Furthermore the stacks height is constant within 2 mm on 10 conductors. This means that the insulation was able to compensate part of the conductor deformation.

IV MODEL COIL CONSTRUCTION

Figs. 5 and 6 show the constructed tool for pre-bending a layer and for transferring it inside the cylinder or an existing layer. The construction of the model coil has given significant information for the module manufacturing. Contrary to previsions it was understood that the crucial process is not the transferring but rather the bending operation. In order to obtain an acceptable winding quality it is necessary to pre-form the conductor to a radius slightly larger (20 mm) than the nominal, with limited variations with respect nominal radius(± 20 mm).

Fig. 5. Pre-bending operation. After spooling the conductor is straightened and bent. After bending the turns are stored on the large wheel.

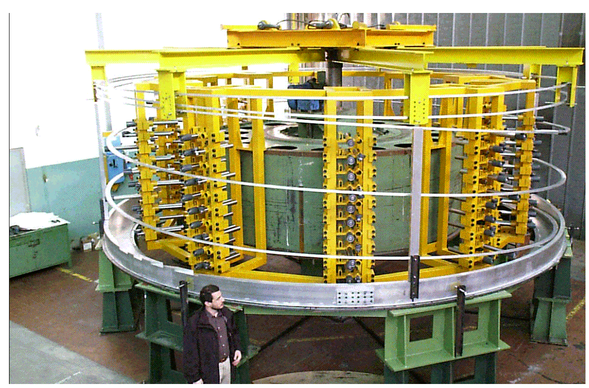

Fig. 6. Transferring unit during tests with non-insulated conductor.

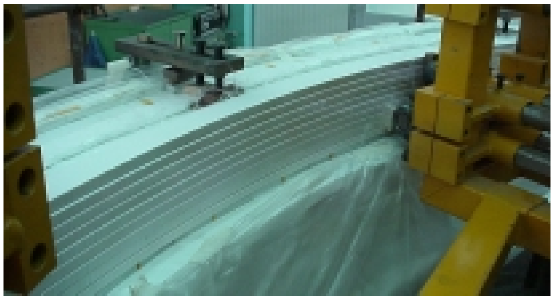

Fig. 7. Model coil after winding of the inner layer.

The pre-bending of all the turns of a layer and the following transfer into the winding pack is a difficult operation, due to the critical handling of the free layer. It is better to wind a few turns and transfer them immediately using a combined process.

Once the conductor has been bent, its shape cannot be easily modified (small waves of the order of 50 cm are not recoverable). In order to optimize the radial stacking of a turn inside the mandrel or a previous layer, it is helpful to apply a force tangential to conductor just when it is approaching the winding. Fig. 7 shows a detail of the model coil after the winding of the 4^{th} (and inner) layer. Great care must be taken not to damage the insulation. Due to its dimension, it was not possible to put the model coil inside an autoclave for epoxy impregnation under vacuum. A vacuum jacket was then constructed around the coil (Fig.8.a). The heating for impregnation and cure was performed through electrical feeding of the coil itself. Fig.8.b shows the detail of the vacuum jacket surrounding the coil at the electrical exits.

a

b

Fig. 8. Model coil during impregnation (a), detail of electrical exits and impregnation mold(b).

Fig. 9. The model coil extracted from impregnation mold.

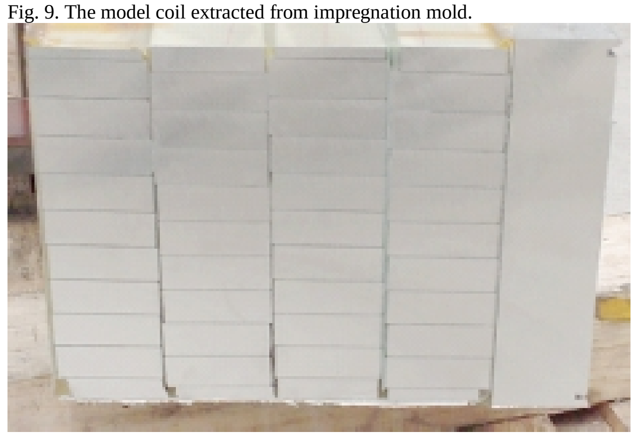

Fig. 10. Cross section of model coil.

After impregnation (Fig.9) the model coil was subjected to dimensional and electrical tests. The measured difference between maximum and minimum inner diameter was 10 mm (over 6500 mm). The coil was sectioned in order to inspect the quality of the impregnation. Fig.10 shows a cross section. The resin filled all voids created by imperfections of the winding. The winding quality was good though not yet acceptable in terms of tolerances as imposed by the design requirements.

These results have given us confidence that it will be possible to obtain an excellent winding quality when using the proper and dedicated winding tools in the manufacturing stage and the final conductor that will be much more homogeneous than the dummy conductor.

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