A Non-Linear Finite Element Model for the LHC Main Dipole Coil Cross-Section

Mirko Pojer, Arnaud Devred, and Walter Scandale

Abstract—**The production of the dipole magnets for the Large Hadron Collider is at its final stage. Nevertheless, some mechanical instabilities are still observed for which no clear explanation has been found yet. A FE modelization of the dipole cold mass cross-section had already been developed at CERN, mainly for magnetic analysis, taking into account conductor blocks and a frictionless behavior. This paper describes a new ANSYS® model of the dipole coil cross-section, featuring individual turns inside conductor blocks, and implementing friction and the mechanical non-linear behavior of insulated cables. Preliminary results, comparison with measurements performed in industry and ongoing developments are discussed.**

Index Terms—**Finite Element model, LHC, superconducting dipole magnet.**

I. Introduction

MORE than eight hundred dipole magnets, over the 1232 needed for the construction of the Large Hadron Collider (LHC) [1], have already been delivered at CERN. Most of them have been cold tested, proving that the operation field of 8.33 T at 1.9 K is obtainable with a limited training.

The geometry of the LHC dipole magnets [2] has been iteratively refined, and the final design has taken advantage of an accurate positioning of the cables and a well calibrated applied pre-stress [3], [4]. Although this allowed a reduction of quenches in the straight part of the series magnets with respect to the prototypes, a few magnets still exhibit a lower than expected performance, whose origin is not fully understood yet. Furthermore, the problem has only been partially solved for the ends, where the majority of quenches originate (see Table I), with a prevalence in the non-connection side end with respect to the connection side end, despite the greater complexity of the latter [1].

In superconducting accelerator magnets, accurate geometrical positioning of the cables plays a very important role, firstly for magnetic field quality issues, but also for stability against quenches. It is the main reason why the cables need to be blocked in their position with a pre-stress of 60 to 90 MPa. This permits to compact the coil and reduces the effect of the Lorentz forces, which tend to further squeeze the coil towards the dipole mid-plane.

A modelization of the LHC dipole cross-section, which takes into account the fine structure of the coil, has not yet been attempted, due to the great complexity of the problem. In this paper a recently developed model is presented, which can be used as a starting point for further analyses and applications.

TABLE I
Quench Distribution over 750 LHC Dipole Magnets

	All Firms
Average quench number (to reach 8.33 T) per magnet	0.95
Quenches in straight part	9 %
Quenches in Non Connection Side End	56 %
Quenches in Connection Side End*	35 %

*CSE also includes splice region.

II. Why Enhance Model Complexity?

It is not obvious that a finer modeling of the complex mechanical structure of the dipole coil cross-section better reflects its behavior when energized, and can be used to explain the lower quench performance that is sometimes observed.

Nevertheless, there are evidences that even the movement of a single cable can trigger a quench, as the consequence of the solid friction originating between rough surfaces: the stick-slip motion (with the combined effect of local temperature increase and fluxoid motion [5]) is at the basis of the magnet quench. In particular for the LHC, with operating fields around 8 T, the superconductor works at more than 80% of its critical current on the load line. The temperature margin for operation at 8.33 T and 1.9 K has been evaluated and measured [6] to be 1.5 K. Since more than 1 K is reserved for heating due to beam losses, it means that even a minute movement of few micrometers is capable of producing, by friction, a local heating that can drive the magnet to quench.

For these reasons, a new model is being developed, relying on the contact capabilities of ANSYS® to represent interfaces between different materials, and choosing to model individual turn and to implement friction and the non-linear stress-strain behavior of insulated cables.

A model of the LHC dipole magnet cross-section had already been developed at CERN, mainly for magnetic analysis [7], but the structure was represented by blocks of

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Mirko Pojer is with CERN, Accelerator Technology Department, CH-1211 Geneva 23, Switzerland and Ecole Polytechnique Fédérale de Lausanne – Programme Doctoral en Physique (phone: +41-22-767378; fax: +41-22-7676300; e-mail: mirko.pojer@cern.ch).

Arnaud Devred is with CEA/Saclay, DSM/DAPNIA/SACM, 91191 Gif-sur-Yvette, CEDEX France and CERN, Accelerator Technology Department, CH-1211 Geneva 23, Switzerland (e-mail arnaud.devred@cern.ch).

Walter Scandale is with CERN, Accelerator Technology Department, CH-1211 Geneva 23, Switzerland (e-mail: walter.scandale@cern.ch).

insulated cables lumped into circular sectors, and friction was neglected. Enhancing the complexity of the modelization with individual turn segmentation and interaction between matching surfaces is a necessary step towards a better understanding of reality. This is even more important in the coil ends, where the Lorentz forces tend to stretch the coil axially: the inter-faces between insulated cables and G10 end spacers, and the hard bending of the Rutherford-type cable make it rather difficult to apply the proper load and mechanically stabilize the coil.

III. MODEL

A. *Salient Model Features*

Prior to challenging thermo-electromagnetic developments in two or three dimensions, a 2-D pure mechanical finite element model has been developed. This model describes the straight part of the LHC dipole coil cross-section; it has been developed in ANSYS®. The main features of the new model are: separated coil turns (representing insulated cables), friction between each coil turn and its surrounding elements, non-linear and (eventually) hysteretic stress-strain behavior of the insulated cable between loading and unloading paths.

Since we are only interested in the interaction of insulated cables with each other and with the surrounding boundaries, it was decided to model the coils only. In particular, to test the feasibility of this model, we tried to reproduce the coil dimension measurements which are performed in industry, prior to collaring, with applied load up to nearly 100 MPa.

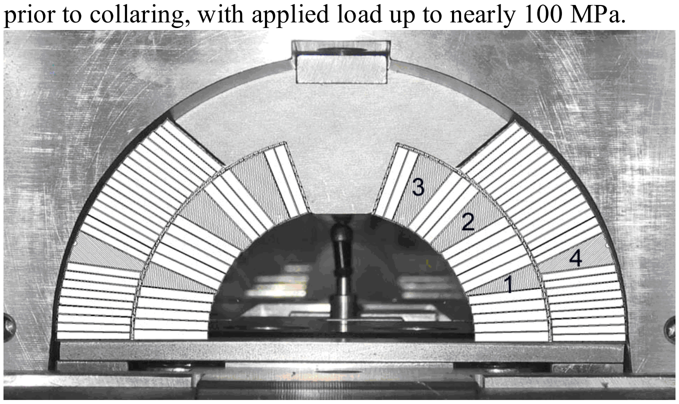

Fig. 1. Picture of the mould used in industry for Young's modulus measurements, with sketch of a pole.

In Fig. 1, a sketch of a pole cross-section is superimposed to the picture of the mould which is used in industry to measure Young's modulus. This is exactly the configuration that we want to reproduce: the two coil layers with individual turns, the interlayer spacer in between and the stainless steel mould which closes and presses onto the pole. Due to symmetry, only a half pole is modeled as presented in Fig. 2.

The Rutherford cables are represented with their keystone angle and sharp corners. The copper wedges have rounded external surfaces. Each layer is built by piling up cables and wedges over their respective nominal winding radii (see Fig.2).

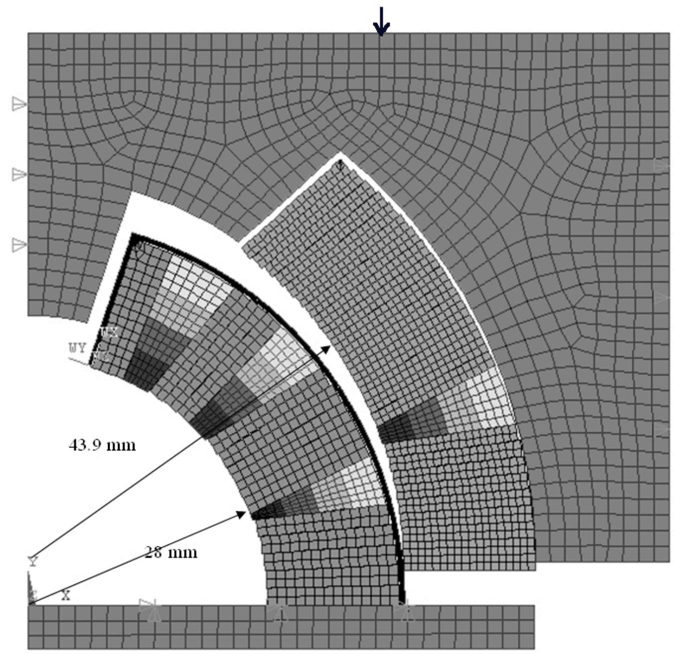

Fig. 2. Model of a half pole during Young's modulus measurements. The inner and outer layer coil turns are divided up into blocks by copper wedges and the two coil layers are separated by an insulating spacer. Constraints on the stainless-steel mould are also shown, as well as the applied pressure on the upper plate.

By design, there is certain an interference between some of the insulated cables and the interlayer spacer; this is the reason why the two layers appear separated in the FE model of Fig. 2. This is not a pure geometrical abstraction: even in reality, when the layers are coupled, they don't match perfectly and the first pressure step just brings them to the design configuration.

The mesh of the cables has been chosen so that the number of elements is equal to the number of strands in each one: 28 in the inner layer cable and 36 in the outer layer one. A 2-D plane quadrilateral structural element type has been used for the whole model (PLANE42).

B. *Material Properties*

In spite of the complex structure of the cables, they are modeled as quadrilaterals with homogeneous material properties (insulation included). This choice is in accordance with the measurements of the elastic modulus performed at CERN on straight stacks of insulated cables [8]. In addition, we assume that the Young's modulus, *E*, is the same in both azimuthal and radial directions.

The ANSYS® function MELAS has been chosen to represent the piece-wise linear elastic properties of the insulated cables, where the Young's modulus is very low at low pressures and increases as the stress is increased.

The copper wedges have been assigned an homogeneous but anisotropic elastic modulus averaged over the copper and the insulation; they have been divided into four radial sectors with increasing *E* from small to large radii, to take into account the increasing proportion of copper with respect to insulation. A summary of the material properties implemented in the model can be found in Table II.

TABLE II
SALIENT MATERIALS PROPERTIES

	Ex [GPa]	Ey [GPa]	Shear modulus [GPa]	Poisson Ratio
Inner layer cable	3.1 @ 100MPa*		4.3	0.1
Outer layer cable	4.0 @ 100 MPa*		4.0	0.1
Copper wedge 1	77.6	13-41	15-36	0.34
Copper wedge 2	77.6	30-51	29-41	0.34
Copper wedge 3	77.6	35-53	32-42	0.34
Copper wedge 4	75.1	24-47	25-39	0.34
Inter-layer spacer	10	10	4.3	0.3
Steel mould	190		-	0.3

*As explained in the text, the Young's modulus of the superconducting cables is non-linear in the whole range.

C. Contact Description

Another important feature of this new model is that none of the components are been bonded together; any two mating boundaries have been defined as complementary inside a *contact pair*. Two kinds of ANSYS® elements have been used to model the contacts: either surface-to-surface contact elements (CONTA172-TARGE169) or node-to-surface contact elements (CONTA175-TARGE169). In most cases the first kind has been used. However, the second kind has been used for the radial contacts of all cables, for which it provides a better response.

Each contact is governed by the normal and transversal contact stiffness (which determines the repulsion force between the two boundaries and the sliding opposition), the allowable penetration, the allowable slip in transversal motion and the friction coefficient (five parameters for a total of 15 different contact types on our model). This excessive number of free parameters has been reduced by imposing a maximum penetration of 1 μm on all contacts and by neglecting the friction at the interfaces with the surrounding mould; the first condition is imposed by common sense, while the second one can be satisfied in reality by properly lubricating the mould surfaces. The values of the friction coefficient are: 0.4 for the contacts between insulated cables, and between insulated cables and copper wedges; 0.1 for the contacts of cables and copper wedges with the inter-layer spacer. These are standard values which produce a faster convergence of the simulations, even if they are still preliminary.

To determine the suitable initial values for the contact parameters, series of tests has been performed, using simple structures: we started with two objects in contact, with the same or different materials, and we ended up with structures more and more complex. Simple structures permit to reduce the calculation time, while keeping all the information needed for the complete model. A sensitivity analysis for the parameters has also been performed on these simple cases. A similar analysis has to be performed for the pole model.

To simulate the elastic modulus measurements, the bottom of the mould is set at a given position and the upper part is lowered vertically and an increasing load is applied to it (see Fig. 2). The options to perform a transient analysis (ANTYPE,4) and to include large deflection effects (NLGEOM,1) have been selected; the loads are linearly interpolated and ramped for each step (KBC,0).

IV. SIMULATION RESULTS

Since the measurements of the elastic modulus in industry are performed either on single layers or on assembled poles (and sometimes on both), the two processes have been simulated. A comparison between measurements and simulations is shown in Fig. 3.

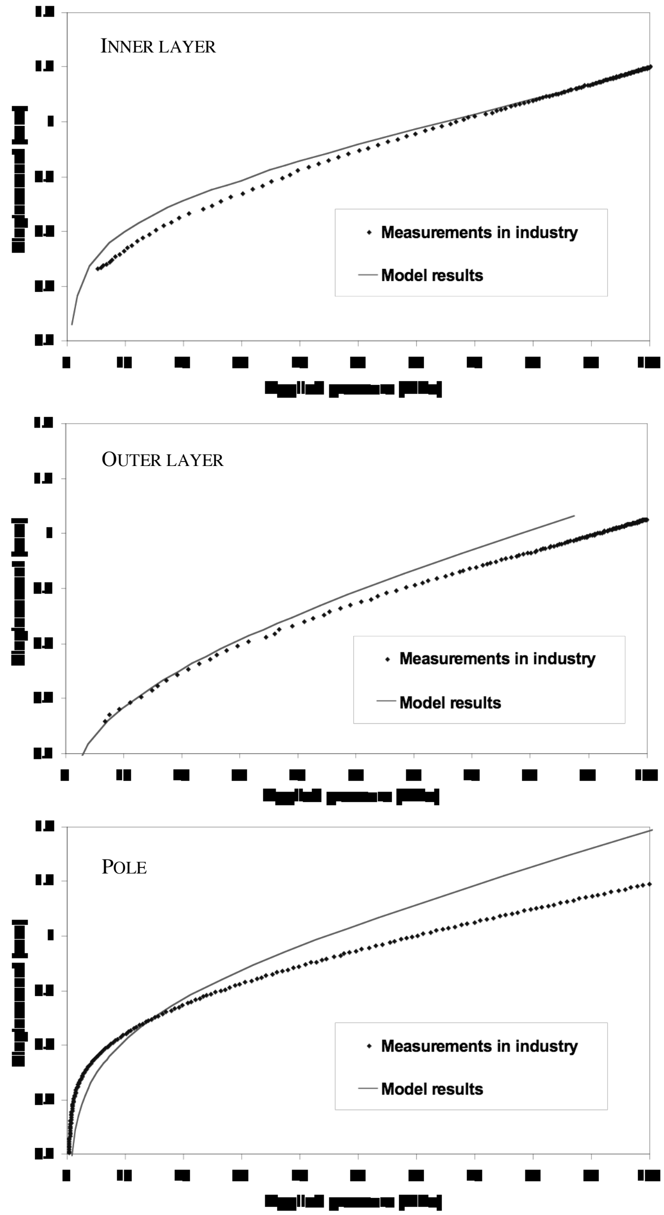

Fig. 3. Comparison between measurements in industry and FE simulations.

The single layer model is identical to the one described above, with the only difference that the mould has a cavity accommodating one layer at a time.

For the half pole analysis, some important features are:

- number of nodes, 6645
- number of contact elements, 54
- number of iterations for a typical case, 7365
- CPU time, 10 hours (with a 3 GHz processor PC).

A first important preliminary remark is that it is difficult in industry to fix an absolute zero for the measurement: for instance, in the case of a pole and zero applied pressure, the outer layer is not in perfect contact with the inner one, mainly because of mechanical imperfections. The experimental data and simulation results have been thus shifted arbitrarily in order to approximately superimpose the curves. What is important, in any case, is not the absolute but the relative behavior between low and high pressure values.

For single layers, the correspondence between measurements and simulations is quite good, with a maximum error of 5% for the inner layer and 8% for the outer one. Note that the simulated inner layer behaves as a somewhat softer material at low loads and is more rigid at high loads, while it is the opposite for the outer layer. Both results are anyway satisfactory.

The model is less accurate for the complete pole, where the difference between measurements and simulations reaches 20%. This can be only partially explained by an overestimation of the elastic deformation of the outer layer.

In any case, the model better reflects the elastic modulus of the pole than analytical calculations: the weighted sum of the Young's modulus of the two layers gives in fact an overestimation of the pole Young's modulus by 50%.

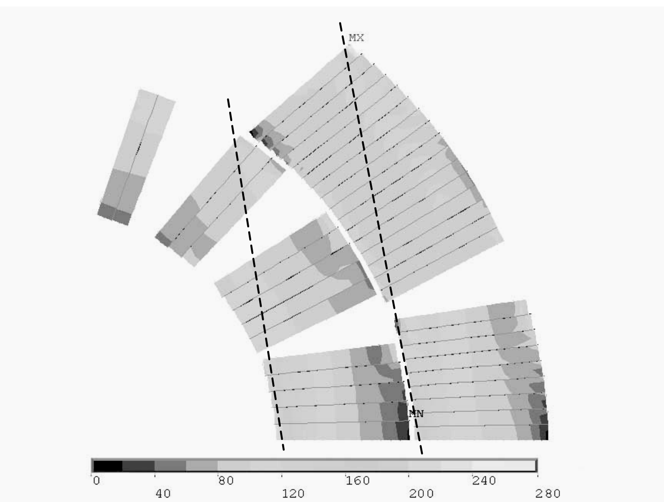

Fig. 4. Von Mises stress distribution for 100 MPa of applied pressure.

Another important observation can be made: at high pressure values there is a concentration of stress in the outer layer along an axis passing through the uppermost right corner down to the lowest left one; a similar one is also apparent for the inner layer (see lines in Fig. 4). This produces a stress gradient in the last uppermost cable in both layers, which has an average value as high as 100 MPa in the outer layer and nearly 50 MPa in the inner one. These gradients may strongly influence cable stability.

V. Future Developments

We can add few remarks. First of all, the conductor geometry that we used for the two layers is the nominal one, defined at 40 MPa and 1.9 K; this means that bigger cables should be used in the model. However, the solution of the single layer case with an over-dimensioned cable has shown the same qualitative behavior. The same analysis for the pole is still under way.

Another important point is that, as mentioned, the material used for the cables has been considered as isotropic; measurements performed at BNL [9] have shown that this is not the case. An implementation of the model to take into account the anisotropy of the material is under development.

The evaluation of the influence of friction, and in general a sensitivity study of all the contact parameters on the result is also in progress.

Future developments will be aimed at reconstructing the whole cycle the poles undergo during collaring, with implementation of the unloading phase. However, the branch of the unloading part is not unique and depends on the peak stress value upon loading. Hence, we must either use a different value for each turn, or rely on average values.

VI. Conclusion

A new 2-D finite element model for the LHC dipole coil cross-section has been developed, with the aim of representing its fine structure. A comparison of the model with available experimental data has proven its soundness. Nevertheless, some open questions have still to be investigated.

This new model provides a good starting point for future mechanical and possible electromagnetic analysis, including the development of a 3-D model.

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