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A Simplified Structural Model for the Analysis of Shape Deformations of the LHC Superconducting Dipole Cold Mass

M. La China, E. Wildner, W. Scandale

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CERN, Accelerator Technology Department, Geneva, Switzerland

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CERN
CH - 1211 Geneva 23
Switzerland

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A Simplified Structural Model for the Analysis of Shape Deformations of the LHC Superconducting Dipole Cold Mass.

Marco La China, Elena Wildner, Walter Scandale

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***Index Terms*— Superconducting magnets, large scale superconductivity, structural models, LHC project.**

I. INTRODUCTION

THE LHC main dipole is a superconducting twin-aperture magnet. It has the shape of a 15.2 m long and 0.57 m wide, weighing about 30 t [1]. The 8.3 T nominal field is reached at 11.8 kA, at the operational temperature of 1.9 K [2].

In our study we consider the dipole Cold Mass (Fig. 1) that is the assembly composed by the electrical and magnetic components as coils and sheets of iron and steel packed inside a shrinking cylinder that serves as a vessel for the refrigerating helium and provides the mechanical rigidity to the structure.

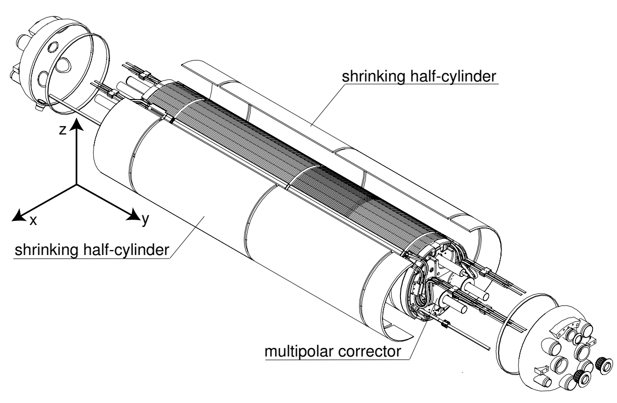

Fig. 1. Cold Mass assembly (short prototype).

In this paper, after an outline of the structural model based on slim beam theory, we describe some aspects of the LHC main dipole series production and testing, for which the model is of valuable help.

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All authors are with CERN, European Organization for Nuclear Research, AT Department, Geneva 23, CH-1211 Switzerland. Mail to: marco.la.china@cern.ch; phone:+41 22 76 79023; fax:+41 22 76 76300.

II. THE THIN BEAM MODEL

The length over diameter ratio of around 30 allows us, as first approximation, to look at the Cold Mass as a thin beam and thus to consider the bending moment as the main cause of deformations and to apply the pure bending theory. The flexural rigidity is therefore the most relevant parameter to characterize the Cold Mass structural behavior but the internal structure complexity prevents from deducing it in an analytical way. The flexural rigidity value that we currently use in the equivalent beam model was therefore measured in dedicated tests [3]. The slight horizontal curvature for our study can be ignored and the negligible cross-talk between deformations in horizontal and vertical plane allows us to implement a bi-dimensional model. The beam constraints are represented by the three Cold Mass support posts that are placed approximately at 2.2, 7.6 and 13 m from one extremity. The model is therefore a 2D slim beam on three supports that for convenience is divided, by the three supports, into four connected beams and can be solved through the “three moments equation” (derived for the first time by Emile Clapeyron in 1857). Parameters used in the model are given in Table I.

III. BLOCKING THE CENTRAL SUPPORT POST

To evaluate the quality of the Cold Mass shape we refer to two parameters: the sagitta of the curved part and the positions of the extremities, that is where the multipolar corrector magnets are hosted. The curved part should give a nominal sagitta of 9.14±2 mm at room temperature whereas the multipolar correctors should be in average within 0.3 mm from the theoretical beam trajectory [4].

The analysis of the Cold Mass series production shows that the nominal shape, obtained in the industries, undergoes a systematic degradation throughout the successive pre-operative stages and exceeds, in few cases, the tolerance limits [4]. The corrective action, implemented at CERN, consists in the modification of the faulty shape via the blocking of the central support in an appropriate position [5]. The drawback of this effective procedure is the time needed for the fine adjustment, customized for each magnet, to find the optimum support post position. As the three producing firms show three distinct degrees of change in shape, a possible alternative is based

TABLE I
MAIN PARAMETERS OF BEAM MODEL.

Param.	Value	Units
Flex. Rig. EI	180	[MPa m^4]
Length	15.2	[m]
Lin. Dens.	$1.7{\cdot}10^3$	[Kg/m]
Supp. pos.	2.2, 7.6, 13	[m]
Stiff. K_{supp}	$24{\cdot}10^6$	[N/m]
Stiff. K_{bell}	$1.4{\cdot}10^6$	[N/m]

TABLE II
EFFECT ON EXTREMITY POSITIONS OF DIFFERENT KINDS OF SHAPE CORRECTION.

Corrective action	Mean [mm]	STD [mm]
None	0.263	0.467
Per Magnet	0.001	0.081
Per Firm	0.008	0.371

on the definition of a support post position unique for all the magnets produced by the same firm. To check the effectiveness of such a procedure we simulated the new correction on each produced magnet and we evaluated the effect in terms of extremity positions. By this simulation we computed, for each magnet, the optimum position of the central support post then we average the value within the magnets produced by the same firm and we adjust the magnets by this 'position per firm'. If, after the correction, at least one of the correctors of each magnet exceeds the nominal position by more than 0.87 mm [4], the magnet is individually corrected in the optimum position.

In Table II we report the average position of the Cold Mass extremities without the correction, with the old 'per magnet' correction and with the new 'per firm' one. It can be noticed that the value averaged over all the magnets is very close to zero with both the old and the new correction whereas the dispersion associated to the new correction is close to the original without correction. As the tolerances on the multipolar correctors are set at 0.3 mm on the systematic and at 0.5 mm (at $1\,\sigma$) on the random component [6], the margin for the future production in case of no corrective action is very narrow. Therefore, as the new correction reduces considerably the average and, to a lesser extent, the dispersion, the tolerance respect is much better guaranteed also for the forthcoming production.

IV. GEOMETRIC DATA MANIPULATION

Cold Mass geometry checks are performed at several different stages on different benches and locations. As the Cold Mass structure is relatively flexible, the measuring bench support configurations can induce temporary shape modifications comparable to the imposed tolerances, of few tenths of millimeters. It is therefore mandatory to disentangle the intrinsic features of magnet shape from the deformations associated to the specific boundary conditions. Since we are interested in detecting the shape downgrading from industry to CERN, we used the model to filter out the deformations potentially induced by the different measuring benches. Operatively we proceeded as follows: first we deduced, from the two measurements, the relative misalignments between the supports within each one of the two measuring benches; second we used the model to compute the deformation of the Cold Mass induced by the variation of the relative misalignments between supports; third we subtracted those deformation from the second measurement (step called WP08) to obtain a shape consistently comparable to the first one (step called ITP20). In Fig. 2 we can see the effect of the correction for the aperture 1 of magnet 1058. The plot contains the tube axis shape in the horizontal plane as measured in the industry (ITP20) and at CERN before (WP08old) and after (WP08new) the virtual correction. It is therefore evident that the critical curvature change and the associated offset of the extremities between the industry and the CERN measurement (ITP20 and WP08old) is a feature related to the different alignment of the three supports (whose position is represented by the three crosses) between the measuring benches.

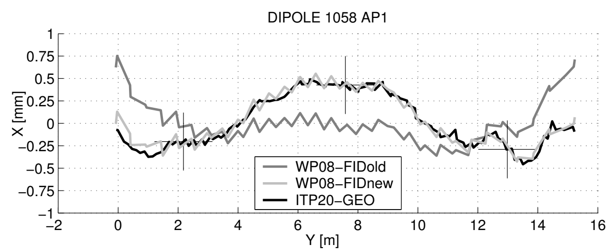

Fig. 2. Correction of Cold Mass deformation in the horizontal plane induced by different measuring benches. Crosses indicate support positions.

V. A STUDY ON THE VERTICAL SAGITTA

The quality of the Cold Mass vertical shape is strictly correlated to the maximum sagitta between the supports induced by the gravity. The values measured in the cold masses up to now produced generally exceed the expected 0.3 mm [7] reaching values even three times larger and this can produce detrimental effect on machine performance. The average values resulting from the analysis of the vertical sagittas in each Cold Mass were two times bigger than the nominal. To see if such a feature was related to poor structural properties (namely an insufficient flexural rigidity) of the produced Cold Mass we used the analytical model to disentangle the deformations induced by gravity from the intrinsic shape imperfections. Operatively we studied a group of magnets for which one of the measurements was taken on a bench with only two supports instead of the nominal three so that, by comparing measurements on two and on three supports, we were able to identify the gravity effect and to subtract it from the measured shape.

For each magnet we took the average between the two apertures and we fitted the model on it. We did it for the two and three supports cases and we obtained two values of the flexural rigidity and two sets of residuals distributed along the axis representing the original magnet shape. The analysis results given in Table III concern the flexural rigidity and the support positions. In fact in the magnet model the deflection induced by gravity depends on the following parameters: Cold Mass density, length and flexural rigidity (EI); support longitudinal and vertical position. In the best fit procedure we

TABLE III
VALUES OF FLEXURAL RIGIDITY (EI) COMPUTED FROM MEASUREMENTS OF COLD MASS ON TWO AND ON THREE SUPPORTS (31 MAGNETS)

	3 Supp.		**2 Supp.**		
	Mean	STD	Mean	STD	Units
E1	133	26	141	16	[MPam^4]
Z_{s1}	1.84E-4	7.65E-5	7.28E-4	1.19E-4	
Z_{s2}	8.25E-5	1.31E-4	7.21E-4	0.98E-4	[m]
Z_{s3}	1.81E-4	8.95E-5	-	-	
Y_s1	2.44	0.13	3.69	0.09	
Y_{s2}	7.60	0.21	11.47	0.12	[m]
Y_{s3}	12.76	0.22	-	-	

longitudinal and vertical position. In the best fit procedure we fixed the density and length of the Cold Mass and we left as independent variables the support positions along with the flexural rigidity. Indeed for the two and the three support cases we had 5 and 7 variables, respectively.

It can be noticed that the agreement between the flexural rigidity values on three and two supports is well within the related dispersions but both values are smaller than the expected 180 MPa m^4. The vertical support positions Z_{sz} result misaligned by few tenths of millimeter, which is in both cases realistic and the spread of the horizontal support positions Y_{sz} is compatible with the temporary supports used in the industries whose size can vary between 10 and 40 cm. Generally, in each magnet, the computed flexural rigidities are slightly smaller for the three than for the two supports case and the average discrepancy is 4±1%. This can be related to the effect of shear between laminations that we didn't take into account considering the high length over diameter ratio of the Cold Mass. Such a ratio is smaller when the Cold Mass is on three supports rather than on two so that the effect of the shear, is bigger in the first than in the second case. Currently we are investigating, by means of a specific model, if the shear effect could also be responsible for the discrepancy between data and the expected El value of 180 MPa m^4. The original shapes extracted from the measurements on two and on three supports generally match, within the measuring error, and in some cases highlight local imperfections as shown for example in Fig. 3 at Y ≅ 6 m.

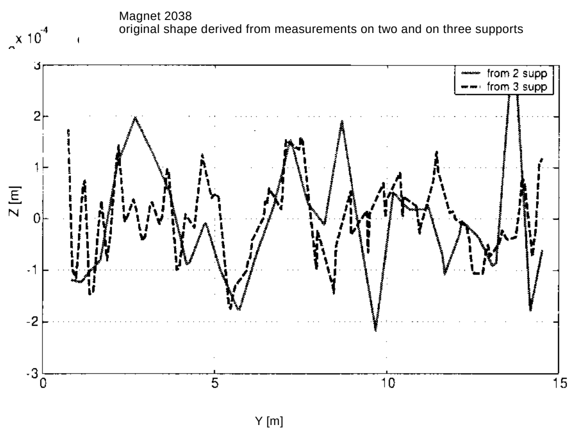

Fig. 3. Original axis shape of magnet 2038 derived from measurement on two and on three supports (solid and dashed line, respectively).

VI. The Geometry of Interconnected Magnets

In the LHC lattice the dipoles are interconnected by specifically designed bellows that must ensure the continuity of the vacuum enclosures and of the various electric and cryogenic circuits. This interconnecting bellows must also compensate for the thermal expansion/contraction of the magnets (around 46 mm each) and for their possible transverse misalignment. Ideally the transverse misalignment should be taken over by the bellows without affecting the position of the magnet extremities. In reality this is not feasible since the bellows have a non-negligible transversal stiffness; the extremities of misaligned magnets are therefore subjected to elastic forces transmitted by the bellows that can modify their initial position. To evaluate the final geometry of interconnected dipoles we used a 2D model of the Cold Mass in which the composite supports and the interconnections are implemented as springs. The mechanical behavior of the interconnection, extensively described in [8], is strongly nonlinear and temperature and history dependent. In fact the bellow metallic foldings enter the plastic field right after the first deformation cycle considerably increasing the stiffness thanks to the kinematic hardening effect [9]. In our simulation we considered the lateral stiffness (see Kb_{ell} in Table I) subsequent to the first cycle as it was validated in previous test [10]. The composite support equivalent stiffness for a transversal load is nevertheless a value that strongly depends on the actual bending moment transmitted by the Cold Mass on the top of the support rather than only on the composite material properties. As the transmitted moment cannot be easily computed a priori, we chose a value (see K_{supp} , in Table I) accordingly to previous tests on the cryostated dipole in similar conditions, as described in [11] and [12]. It must be noticed that a comparison with experimental data [10] showed how these assumptions slightly affect the result precision in the Cold Mass central part rather than in the extremity regions.

The Cold Mass geometries before and after the connection can be seen in Fig. 4 where the curves represent the geometry in the horizontal plane of three Cold Masses of an LHC half cell and the stars highlight the flange positions. The solid lines show the geometry as individually measured in the fiducialization procedure before the pre-installation stocking, whereas the dashed lines are the simulated geometry after the interconnection. The cell quadrupoles located before the first (3213) and after the third (3187) dipole have not been modeled and the dipole extremities are unconstrained. The displacement of the extremities connected between the dipoles can exceed a tenth of millimeter. This effect can be considered relevant faced to the tolerance on the multipolar correctors, hosted in the dipole extremities (see III). When the original extremity offsets are opposite w.r.t. the neutral axis, the displacements go in the desirable direction as it happens in the connection between magnet 3213 and 1200 and the advantage is both in terms of average and dispersion of the final positions. Alternatively when the original offsets have the same sign there is no improvement on the average whereas the dispersion is still reduced. A Montecarlo simulation showed that globally an improvement of 25 % for the average and 10 % for the standard deviation (at $1\,\sigma$) of the extremity positions should be achieved when the magnets are connected. In Fig. 5 we provide a graphic tool to easily estimate the final position of the extremities of two connected dipoles.

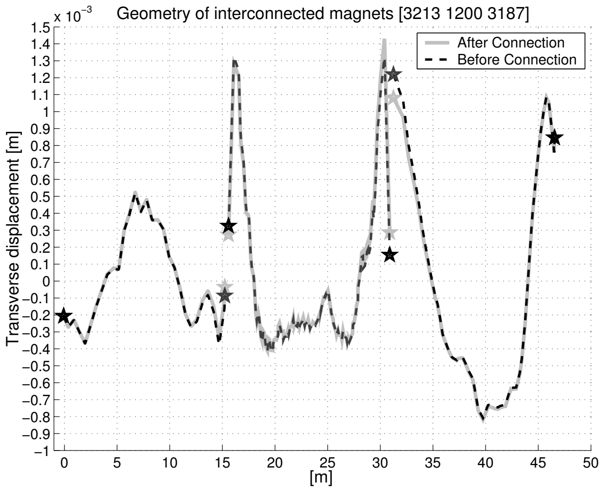

Fig. 4. Shapes of magnets 3213 1200 and 3187 before and after the connection.

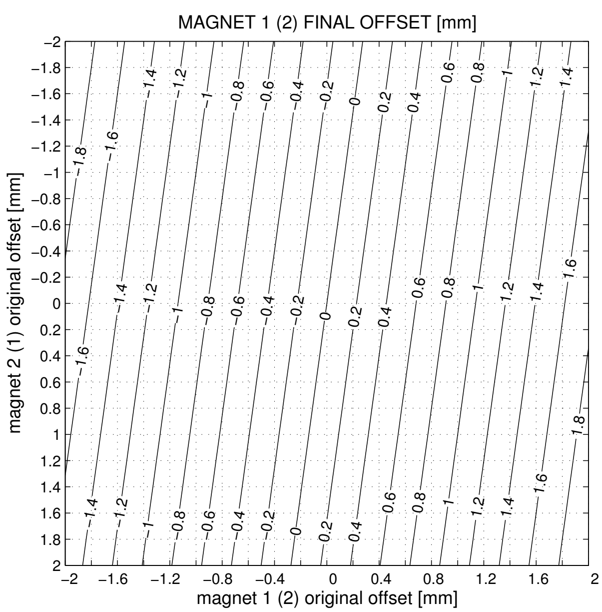

Fig. 5. Final position of the connected extremities of two consecutive magnets. The final offset of magnet 1 (or 2) extremity is given by the intersection of its original offset taken on the horizontal axis and the original offset of magnet 2 (or 1) extremity taken on the vertical axis.

VII. Conclusions

In this paper we outlined a simplified model used to understand the mechanical behavior of the produced dipoles and as a tool in the statistical evaluation of the quality of the geometry. We described some of the most relevant applications in which the analytic nature and the simplicity of the model make it the appropriate tool to get the job done in the given time frame.

A first task was to estimate the efficiency of a possible modification to the shape correction procedure; by means of a simulation applied to all the produced magnets we showed the feasibility of a time-saving approach.

Secondarily we described how we used the model to filter out the noise associated to geometric measurements, necessary to monitor the Cold Mass shape change through the successive pre-operative stages. We identified the noise as deformations induced by different boundary conditions that made the data inconsistent for analysis purposes and we were able to purge the data.

Another exercise aimed at understanding the over-sized vertical sagitta affecting the produced dipoles. We disentangled the effect of gravity and the shape imperfections and we found, on one hand, that the intrinsic waviness of the produced shape is in part responsible for the vertical sagitta, on the other hand, Cold Masses feature an apparent flexural rigidity smaller than the expected one and the reasons are currently under investigation.

The last application allowed us to predict the magnet shapes once interconnected to form the LHC lattice. We found that the shape modifications have a beneficial effect rather concentrated in the extremities that can improve their alignment both in terms of average and of dispersion around the theoretical values.

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