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GEOMETRICAL POSITION OF THE LARGE HADRON COLLIDER MAIN DIPOLE INSIDE THE CRYOSTAT

M. La China, J. Garcia Perez, G. Gubello*, C. Hauviller, W. Scandale and E. Todesco

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The superconducting dipole of the Large Hadron Collider (LHC) is a cylindrical structure made of a shrinking cylinder containing iron laminations and collared coils. This 15 m long structure, weighing about 28 t, is horizontally bent by 5 mrad. Its geometrical shape should be preserved, from the assembly phase to the operational condition at cryogenic temperature. When inserted in its cryostat, the dipole cold mass is supported by three posts also providing the thermal insulation. Sliding interfaces should minimize the interference between the dipole and the cryostat during cooling down and warming up. Indeed, a possible non-linear response of the sliding interface can detrimentally affect the final dipole shape. This paper presents the results of dedicated tests investigating interferences and of specific simulations with a 3D finite element model (FEM) describing the mechanical behaviour of the dipole inside the cryostat. Comparison between measurements and FEM simulations is also discussed.

CERN, Geneva, Switzerland
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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
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The superconducting dipole of the Large Hadron Collider (LHC) is a cylindrical structure made of a shrinking cylinder containing iron laminations and collared coils. This 15 m long structure, weighing about 28 t, is horizontally bent by 5 mrad. Its geometrical shape should be preserved, from the assembly phase to the operational condition at cryogenic temperature. When inserted in its cryostat, the dipole cold mass is supported by three posts also providing the thermal insulation. Sliding interfaces should minimize the interference between the dipole and the cryostat during cooling down and warming up. Indeed, a possible non-linear response of the sliding interface can detrimentally affect the final dipole shape. This paper presents the results of dedicated tests investigating interferences and of specific simulations with a 3D finite element model (FEM) describing the mechanical behaviour of the dipole inside the cryostat. Comparison between measurements and FEM simulations is also discussed.

1 INTRODUCTION

In a superconducting machine like the LHC during the required thermal cycles to reach the operating temperature at 1.9 K, the thermal contraction of the cold mass will induce a change of shape in each dipole. Consequently, being the magnets linked together, that deformation will provoke mechanical interference between the extremities of two adjacent dipoles. Should these phenomena induce a uncontrolled modification of the dipole shape, we will have to face two detrimental consequences: firstly the mechanical aperture available for the LHC beam will be reduced. Moreover the transverse position of the multipolar correctors welded at each dipole end to compensate the persistent currents at injection, will be shifted away from the beam closed orbit. It will be rather difficult to measure this in realistic conditions. However we can learn something by studying the effect of external forces applied at the dipole ends. Hence we worked out a dedicated test in a pre-series cryo-dipole. The test was performed at room temperature and the results compared to FEM simulations.

In Section 2 we present the experimental set up whose results are discussed in Section 3. In Section 4 we describe the 3D finite element model and Section 5 we compare the experimental test with the FEM simulations. Conclusions are summed up in Section 6.

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2 TEST DESCRIPTION

The mechanical interference between dipole ends induced by thermal cycles is reproduced in the test as a transverse load applied in the dipole end covers. The load is horizontally applied in the transverse direction respect to the dipole axis and is generated by mean of an hydraulic actuator fixed to the cryostat. The cold mass displacement is monitored by a 3D laser tracker before, during and after the application of the load. This instrument, used in conjunction with a special reflector (travelling in one of the magnet apertures), can provide the axis shape. This allows a detailed comparison with the results coming from a finite element model reproducing the cold mass under the same loads and constraints.

During the first load cycles, to confirm the cryostat steadiness assumption and, if necessary, to correct the measurements, the laser tracker was used in conjunction with centesimal comparators and interferometric devices providing the cryostat distances from external fixed points as well as from the cold mass.

3 TEST RESULTS

The first result of our test is the elastic response of the cold mass to successive transversal loads applied in the magnet-magnet interconnection. The applied forces have been increased up to 15.4 kN and the measured displacement *d* of the horizontal axis during and after the loads is plotted in Figure 1 as a function of the axis position *s*.

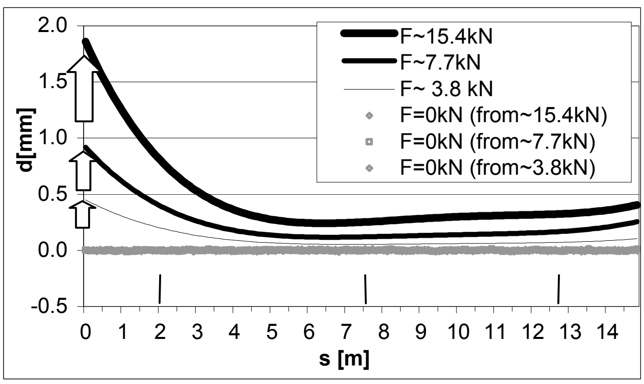

Figure 1: Axis shape under load and rest conditions.

The dotted lines represent the axis contour after the removing of each increasing load. Since all the unloaded profiles fully overlap, we can exclude any permanent residual displacement. The three vertical lines give the approximate location of the three supports.

In Figure 2 the transverse displacement *d* of the cold mass end where the external force is applied is plotted versus the load *F* itself. The force-displacement relation is clearly linear. Therefore, we work out an elastic coefficient as the slope of the force versus displacement relation. Once the data are corrected from the cryostat deformation, its value becomes 8.8 ± 0.3 kN/mm (with a 95 % confidence level).

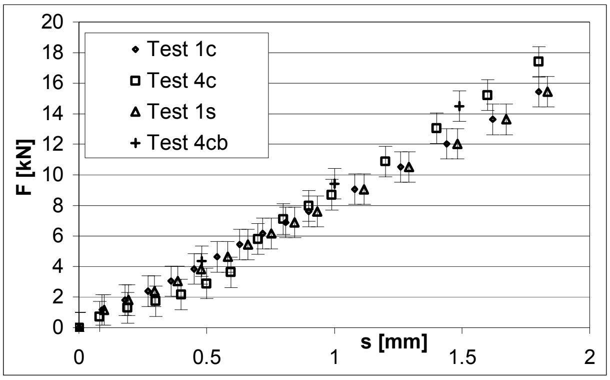

Figure 2: Loaded end displacement vs. applied load.

4 FEM DESCRIPTION

A 3D finite element model has been developed to analyse the mechanical behaviour of the cold mass on its support posts. The code ANSYS5.7 has been used to describe the FEM. The cryostat was assumed to be rigid and stable and hence ignored. The cold mass is modelled as a revolution body. Its section, shown in Figure 3, is spanned over a 5mrad arc of circle with a 2812.36 meters radius. The dipole section is made of the stainless steel collar (inner core), the iron yoke (surrounding the core) and the stainless steel shrinking cylinder represented by the external circumference. In such model the major simplification is the iron yoke and stainless steel collar described as continuous bodies instead of longitudinally packed laminations. This simplification has been taken into account by defining equivalent properties for the yoke and the collar materials. The two young's moduli in the longitudinal direction have been properly worked out [1] to provide the expected cold mass flexural rigidity (of 180 MPa m^2 [2]). No contact interfaces were implemented between the collar and the yoke and between the yoke and the shrinking cylinder. They are, in fact, simply supposed to be welded together (we checked that this assumption does not affect the FEM behaviour with respect to the real cold mass behaviour).

The G.F.R.E. (Glass Fibre Reinforced Epoxy) support posts were modelled as thin cylinders. As shown in Figure 4, they are joined on the top to a stainless steel pad welded on the shrinking cylinder and in the bottom to a stainless steel collar embodying the sliding interface to the cryostat. As for the real posts, the two supports closer to dipole ends are allowed to slide longitudinally and are blocked transversally, whilst the central support is constrained in the longitudinal direction but can slide in transversal direction. By design, the sliding of the posts is assumed to be frictionless. However, we also considered simulations where the friction is large enough to block the sliding of the supports.

The material properties used in the FEM description are listed in the Table 1.

Table 1: Material properties

Component	Material	Young's modulus	
		Longit.	**Transv.**
Shrinking cylinder	Stainless steel	200 GPa	200 GPa
Yoke	Iron	6.6 GPa	200 GPa
Collar	Stainless steel	6.6 GPa	200 GPa
Supports	G.F.R.E.	17 GPa	17 GPa

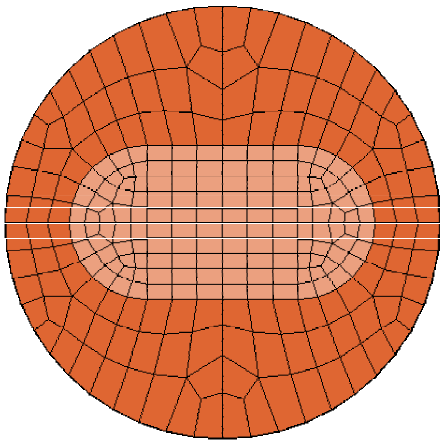

Figure 3: Cold mass FEM section.

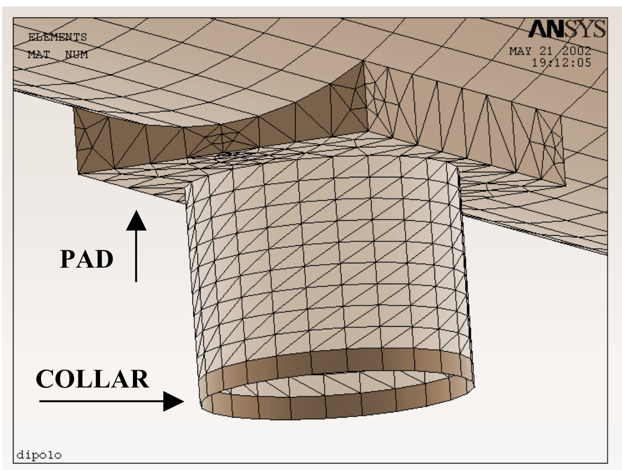

Figure 4: FEM of the support post

5 COMPARISON OF MEASUREMENTS AND FEM SIMULATIONS

In Figure 5 we show the horizontal deviation of the dipole axis corresponding to a load of about 15.4 kN. The narrow black line gives the measured value of the deviation in a pre-series cryo-dipole. The thick black line represents the result of a simulation with frictionless sliding supports. Finally the grey line shows the result of a simulation where the supports are locked.

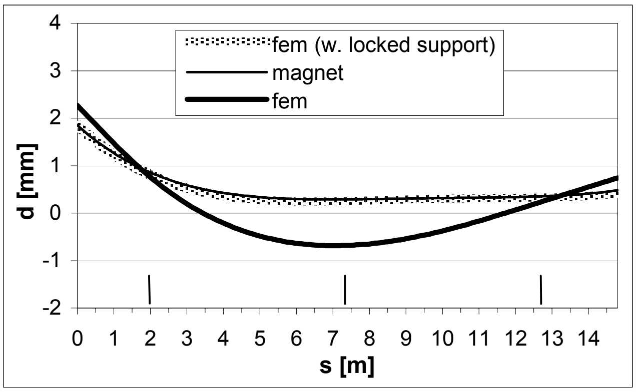

Figure 5: Test-fem comparison

The model with sliding posts predicts large deviations of the dipole shape, which should exhibit a large curvature and a considerable negative shift at the position of the central post (in the opposite direction with respect to the applied force). Instead, the dipole axis, as measured by the laser tracker during the test, does not show such a shape. The observed curvature is drastically smaller and the shift at the location of the central post is positive. The FEM model with the central support fully blocked gives simulation results in excellent agreement with the experimental data. The expected value of the transversal force of about 5.5kN applied on the central support seems insufficient to provoke its sliding. This value is obtained from the finite element model as the reaction of the central support constrain.

Indeed, the support-cryostat interface is vertically loaded by about 105 kN, hence a static friction coefficient of 0.05 would be sufficient to prevent any movement for the applied transversal force. Being the expected friction coefficient of about 0.08 [3], the model with the blocked support can be considered rather realistic.

In a second test, we loaded both the dipole ends with transversal forces of about 23 kN per side. The results are shown in Figure 6. Through the comparison of experimental results (thin black line) with the finite element model (thick black line for frictionless support interfaces and grey line for locked support interfaces), it can be argued that no transversal sliding of the central support occurs even in this case. The model provides an estimate of the resulting transversal force applied on the central support of about 17 kN. This means that to prevent sliding of the central post the friction coefficient should by equal or greater than 0.17, i.e. by far in excess of the above mentioned expected value of 0.08. On-going investigations should clarify why the sliding interface of the central support is so sticky and suggest possible remedies.

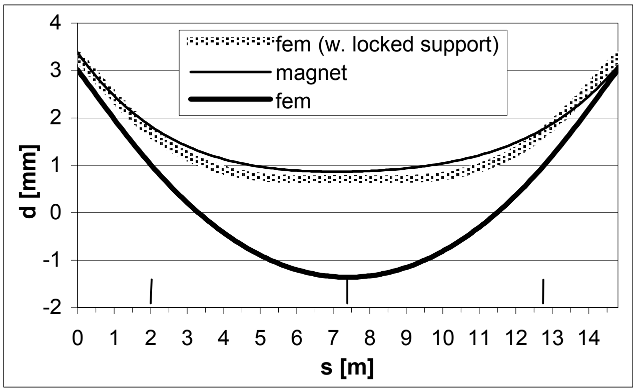

Figure 6: Test-fem comparison

6 CONCLUSIONS

We performed dedicated experiments on a pre-series cryo-dipole by introducing transverse forces similar to those expected in realistic conditions during dipole operation or during cryo-dipole alignment in the LHC tunnel. The experimental results revealed two important facts. On the one hand, the deformation of the dipole and of its supports is still elastic, hence no residual deformations should be expected. On the other hand, we observed a strong interference of the cold mass with the cryostat itself through the sliding cold posts. Using FEM simulations we could point-out that the possible source of the interference is a large friction coefficient in the sliding interface. The test was done at room temperature and cannot be easily repeated in operational conditions at cryogenic temperature.

Should the strong interference dipole-cryostat be confirmed by further tests, there will be two important consequences. On the one hand, the frictional interference is expected be beneficial during cryo-dipole transportation, since it will limit the internal degrees of freedom and hence reduce the possibilities of deforming or displacing the cold mass from its nominal position. On the other hand, during thermal cycles the effect of friction is a potential mechanism to produce erratic displacements of the central post and hence to introduce possible change of shape of the cold mass axis and of the position of the multipolar correctors welded at its end. This may be rather detrimental for the reproducibility of beam control.

7 REFERENCES

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[2] M. La China, "Steady state and transient thermo-mechanical analysis of the LHC superconducting dipole",2001, master thesis, unpublished.

[3] V. Parma, private communication, 2002.