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Stability of the Horizontal Curvature of the LHC Cryodipoles During Cold Tests

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F. Seyvet, A. Tovar-Gonzalez, E. Wildner

Abstract

The LHC will be composed of 1232 horizontally curved, 15 meter long, superconducting dipole magnets cooled at 1.9 K. They are supported within their vacuum vessel by three Glass Fiber Reinforced Epoxy (GFRE) support posts. Each cryodipole is individually cold tested at CERN before its installation and interconnection in the LHC 27 km circumference tunnel. As the magnet geometry under cryogenic operation is extremely important for the LHC machine aperture, a new method has been developed at CERN in order to monitor the magnet curvature change between warm and cold states. It enabled us to conclude that there is no permanent horizontal curvature change of the LHC dipole magnet between warm and cold states, although a systematic horizontal transient deformation during cool-down was detected. This deformation generates loads in the dipole supporting system; further investigation permitted us to infer this behavior to the asymmetric thermal contraction of the rigid magnet thermal shield during cool-down. Controlling the helium flow rate in the thermal shield of the cryomagnet enabled us to reduce the maximal deformation by a factor of approximately two, thus increasing significantly the mechanical safety margin of the supporting system during the CERN cold tests.

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***Abstract*—The LHC will be composed of 1232 horizontally curved, 15 meter long, superconducting dipole magnets cooled at 1.9 K. They are supported within their vacuum vessel by three Glass Fiber Reinforced Epoxy (GFRE) support posts. Each cryodipole is individually cold tested at CERN before its installation and interconnection in the LHC 27 km-circumference tunnel. As the magnet geometry under cryogenic operation is extremely important for the LHC machine aperture, a new method has been developed at CERN in order to monitor the magnet curvature change between warm and cold states. It enabled us to conclude that there is no permanent horizontal curvature change of the LHC dipole magnet between warm and cold states, although a systematic horizontal transient deformation during cool-down was detected. This deformation generates loads in the dipole supporting system; further investigation permitted us to infer this behavior to the asymmetric thermal contraction of the rigid magnet thermal shield during cool-down. Controlling the helium flow rate in the thermal shield of the cryomagnet enabled us to reduce the maximal deformation by a factor of approximately two, thus increasing significantly the mechanical safety margin of the supporting system during the CERN cold tests.**

***Index Terms*— LHC, superconducting accelerator magnets, cryodipole, cryogenics.**

I. INTRODUCTION

The LHC cryodipole is supported in its cryostat on three support posts spaced in order to limit the vertical sagitta. In its initial baseline design the central post was free to move transversally, therefore limiting constraints both to the cold mass and the post itself. However, experience during production showed that cold masses showed displacements in the horizontal plane. In order to avoid this behavior, it was decided to block the transversal degree of freedom of the central post. This proved to be efficient in stabilizing the cold mass horizontal curvature. However, a transient horizontal deformation was observed during one production cold test measurement and reported to the LHC Main Ring Committee (MARIC), which recommended increasing the statistics via additional measurements. This paper presents the results from the action decided by the MARIC. It describes the test set-up and provides the test results and data analysis for eleven cryodipole measurements, along with recommendations and conclusions.

II. METHODOLOGY AND TEST SET-UP

The measurements are performed at CERN on the cryodipole production cold test benches in the following sequence. The cryodipole is initially at room temperature, fully connected to the Cryogenic Feed Box (CFB), and under vacuum. The central jack of the cryodipole supporting system is taken off, so that it is assumed to be simply supported at its extremities, and free to bend in the vertical and horizontal directions. Taking off the central jack is the basis of this work: now that the LHC cryodipoles have their central support blocked laterally [1], during the cold tests a sagitta change of the cold mass is transmitted mechanically to the vacuum vessel via the blocking system of the central support, and measurements of the vacuum vessel shape give an indication of the cold mass deformation. The cryodipole components and the central support post blocking system are presented in Fig.1.

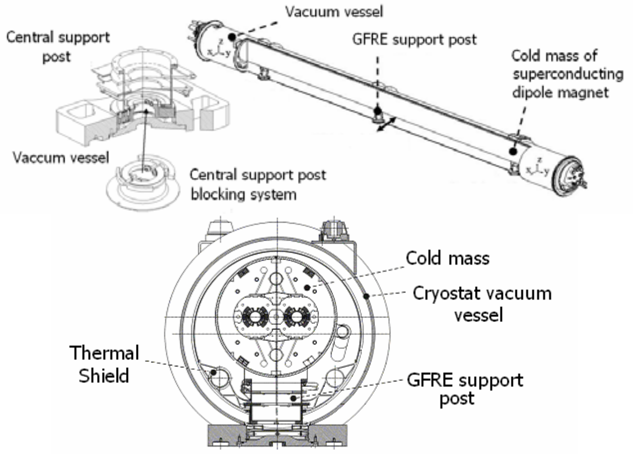

Fig. 1. Cryodipole components and central support post blocking system.

Ideally, the determination of the dipole cold mass sagitta requires the measurement of the beam tube geometry, which is very difficult during cool-down. Uncontrolled temperature differences and tolerances of the anticryostat add significant errors on measurements. On the other hand, with the central support blocked, the cryodipole mechanical structure becomes hyperstatic and any transient deformation of the cold mass reacts on the vacuum vessel, whose shape can be easily measured externally. Therefore, the bending of the vacuum vessel is monitored by measuring the 3-D displacements of seven points distributed on its outer surface as a function of time: the four vacuum vessel fiducials (E, M, S and T) and two additional points on the cryodipole mid plane A-A, which

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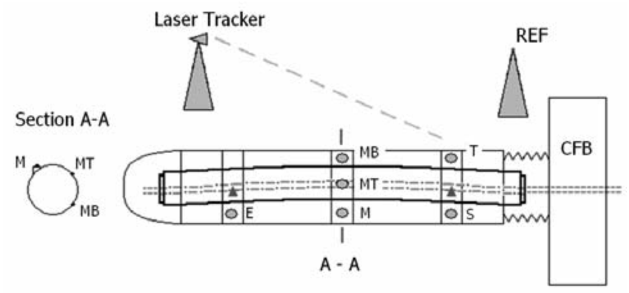

Fig. 2. Cryodipole test set-up (top view).

allow investigating potential torsional behavior of the cryodipole. A schematic representation of the test set-up is presented in Fig. 2. The measurement is done with a laser tracker identical to the one used for the fiducialisation of the LHC cryomagnets [2]. Its accuracy is estimated to be better than 0.1 mm/m and the sampling rate varies from thirty seconds to one minute, so that all the points have been measured once every seven minutes. Data recording begins when the cool-down starts and ends when the cold mass temperature has reached 100 K, below which thermal contraction becomes minimal. This process lasts for approximately twelve hours. For every cryodipole, the following additional data, presented in Fig. 3, are monitored and recorded as well during the cooling process:

- The helium temperature at the cold mass inlet and outlet (line N-M1&M2 circuit) and at the thermal shield outlet (line C'-E circuit).
- The global helium flow rate in both the thermal shield and the cold mass (FT265 sensor).

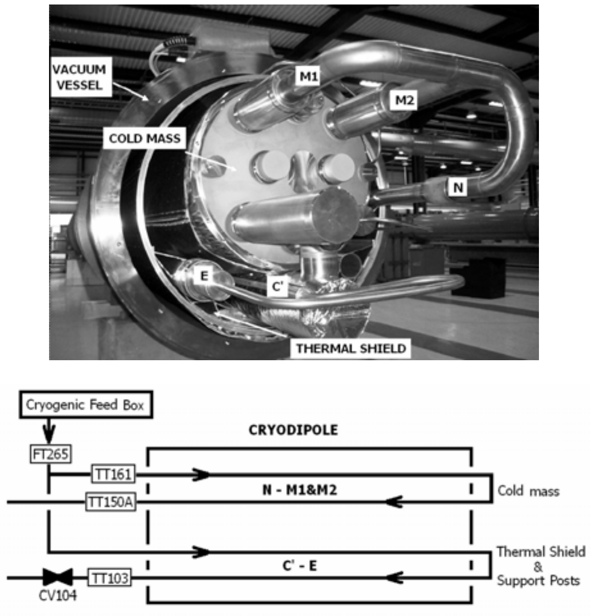

Fig. 3. Cryodipole cooling circuits and sensor positioning.

III. EXPERIMENTAL DATA

A. Data analysis

Six cryodipoles have been measured during the first test campaign. An important transient horizontal displacement of the cryodipole middle section A-A (between 0.3 and 0.8 mm) has been recorded, while the fiducials (E, S and T) and the external reference remained stable (+/-0.2 mm). This transient horizontal displacement is always in the same direction (towards the LHC ring center). During the cool-down process, the cryodipole sagitta decreases and the cryodipole always comes back to its original position within +/- 0.2 mm. This confirms that cryodipoles with the central foot transversally blocked do not display any change of curvature between the warm stage and after cool-down to 1.9 K, which was not the case before blockage.

The maximum displacement peak occurs when the helium flow rate is increased stepwise. Each time there is a new step in the helium flow rate, a new displacement peak appears. Moreover, the peak value is dependent on the temperature of the magnet at that moment: the colder the dipole, the smaller the peak displacement. This is particularly well illustrated for the measurement of cryodipole 1112, presented in the top graph of Fig. 4. The peak displacement always occurs at the early stages of the cool-down, within the first two hours, and it is consistent with the thermal contraction coefficient of metals, higher at high temperature than at cryogenic temperatures [3]. The measurement points distributed on the circumference of the central section A-A of the cryodipole, demonstrate the same horizontal displacement amplitude

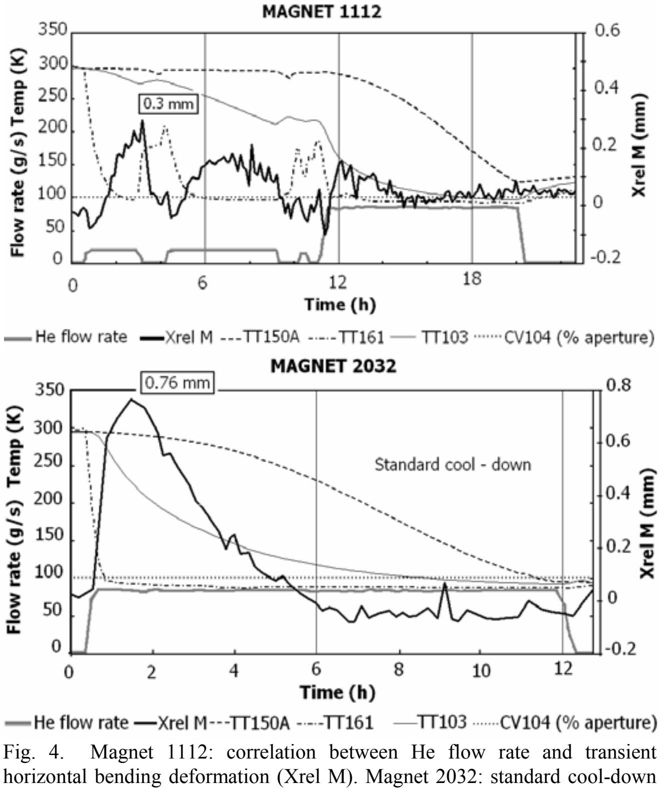

Fig. 4. Magnet 1112: correlation between He flow rate and transient horizontal bending deformation (Xrel M). Magnet 2032: standard cool-down process.

within +/- 0.1 mm. It can be concluded that there is no torsion of the cryostat during cool-down and therefore, the deformation of the vacuum vessel can be analyzed as pure bending of a simply supported beam. The value of interest is the resulting horizontal sagitta of the vacuum vessel, calculated as the relative horizontal displacement of point M with respect to the arithmetic average of the displacements of the extremity fiducials E and S (noted *XrelM* below), see Fig. 2.

The *standard cool-down process*, presented in the bottom graph of Fig. 4 for magnet 2032, has been previously detailed [4], and it can be summarized as follows:

- The helium flow rate entering the cryodipole is increased from 0 to 85 g/s stepwise. Then, the helium temperature at the cold mass circuit inlet (TT161) is decreased from 300 K to 100 K in approximately 30 min.
- The magnet is kept under these conditions until the outlet temperature reaches 100 K. This process lasts for twelve hours.
- Further cooling decreases the temperature of the cryodipole to 1.9 K.

Under these conditions, a repetitive cryodipole bending deformation (*XrelM*) of 0.76 +/- 0.01 mm is obtained. This value can be conservatively assumed to be the maximum deformation, as long as the cool-down procedure is not changed. Bending beam type calculations lead to an equivalent force of 21.2 kN, applied on the central support post, causing a sagitta change of 0.77 mm on the vacuum vessel. It is important to note that the *maximum admissible shear load* on the support post is 25 kN, under combined loading of the unit both in compression, under the dipole weight, and in shear [5]. Thus, the safety margin for the integrity of the supporting system is only 15 %. The relation between the helium flow rate and the maximum bending deformation of the cryostat is presented in Fig. 5. In case of change of the cool-down profile via an increase of the helium flow rate, the vacuum vessel deformation will be larger, imposing a larger force on the supporting system, and the limited safety margin of 15 % does not allow for greater loads on the system. A similar conclusion can be drawn concerning the inlet helium temperature profile: an increase of the gradient will generate more thermal constraints on the system and it is thus expected to increase the deformation of the vacuum vessel. On the other hand, the transient vertical displacements of all measured points remain relatively stable and small, with amplitudes below 0.3 mm for all cryodipoles. This motion can be explained by the fact that the reference point displays vertical displacements up to 0.15 mm: the accuracy of the laser tracker in the vertical direction is limited due to vertical ground motion. This behavior might be attributed to the magnet installation or removal in the cold test hall. The temperature gradient (day/night) could influence as well the vertical position of the fiducials (approximate calculation for a cryostat of steel with 0.9 m of radius shows that for a 10°C temperature change, the thermal contraction of steel could lead to a vertical motion of 0.12 mm [3]). We cannot exclude some stress relaxation of the lamination packs, which in some cases might influence slightly the deformation of the cryodipole. The small vertical displacements measured can be quite safely attributed to external factors and are not further investigated (especially considering that they are of no concern for the mechanical rupture of the support post).

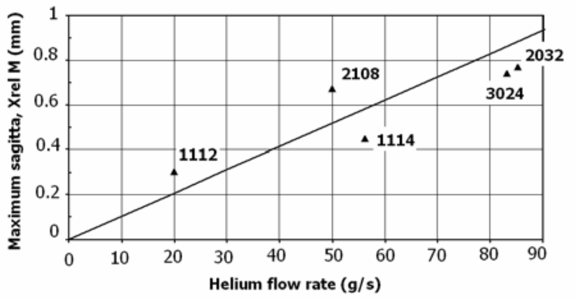

Fig. 5. Peak transient horizontal sagitta versus Helium flow rate for 5 cryodipole cool-downs.

B. Determination of the origin of the transient deformation

The observed transient horizontal deformation of the magnets with the central foot blocked could obviously be caused by transverse thermal gradients induced by cooling flow asymmetries in the cryodipole transverse section. The test benches input helium in the cryodipole via two different cooling circuits. The first circuit consists of the line N, linked hydraulically to the lines M1 and M2, for the cool-down of the cold mass. By design, the cooling gas flow through the cold mass should be evenly distributed via channels in its transverse cross-section, thus resulting in no transverse thermal gradient. The second circuit consists of the line C' linked hydraulically to the line E (line E circuit), for the cool-down of the thermal shield and the support posts, see Fig. 3. Unlike the cold mass, the line E circuit is asymmetric with respect to the cryodipole cross-section, inducing transverse temperature gradients. In order to verify the origin of the transient deformation observed, a test was performed during which these circuits were fed sequentially. The thermal shield active cooling circuit was initially deactivated, and the

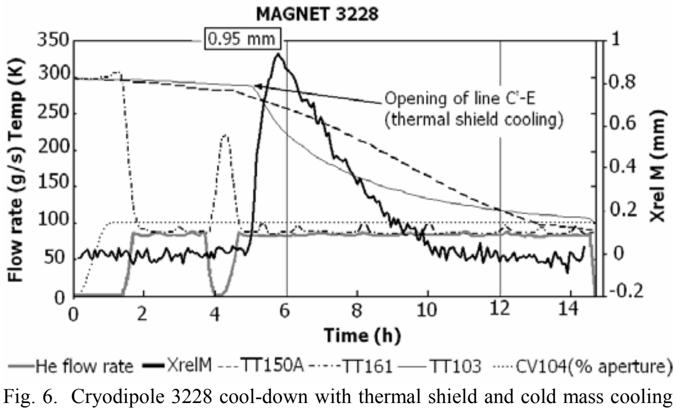

Fig. 6. Cryodipole 3228 cool-down with thermal shield and cold mass cooling decoupled.

TABLE I
BENDING RIGIDITY COMPARISON

EIz	Cold Mass	Vacuum Vessel	Thermal Shield [a]
[N m^2]	160 10^6	292 10^6	32 10^6

[a] Obtained from calculations based on CERN EDMS drawing LHCQBA_S0057

standard cool-down process then followed. Unlike in previous tests, no deformation during this initial period could be observed. As soon as the valve closing the thermal shield circuit was opened, the cryodipole started to deform (see Fig. 6), thus pointing unambiguously to the thermal shield transverse asymmetric cooling. The horizontal bending rigidity of the cryodipole cold mass, vacuum vessel and thermal shield are presented in Table 1 [6]. The thermal shield bending rigidity is twenty times lower than the bending rigidity of the vacuum vessel. The strong asymmetrical cooling of the thermal shield causes the thermal shield to deform, applying a force on the support foot which is mechanically transmitted to the vacuum vessel and the cold mass. The ratio of approximately twenty between the rigidities of the thermal shield and the cold mass suggests that, to obtain 0.8 mm of horizontal deformation of the vacuum vessel, an unconstrained thermal shield should deform by approximately 20 mm. This has been indeed calculated on LHC cryostat theoretical thermal models [7].

C. Reduction of the cryodipole transient bending deformation

Additional tests were performed with the aim of reducing the cryodipole transient bending deformation without delaying the cool-down time, so as to increase the mechanical safety margin on the central post. During the standard cold tests, it could be observed that the temperature at the outlet of the thermal shield (TT103) was lower than the temperature at the cold mass outlet (TT150A). This temperature difference was reduced by servo-controlling the aperture of valve CV104, situated at the thermal shield outlet. Results for magnet 2098 are illustrated in the top graph of Fig. 7, where the temperature gradient between the cold mass and the thermal shield outlet has been minimized. In this example, a maximal horizontal bending deformation of 0.26 mm has been measured, representing a 66 % reduction with respect to the previous standard cool-down tests. The present case showed that although increasing the gain on the valve servo loop strongly reduced absolute cryodipole deformations, it also induced instabilities leading to an overall significant increase of the cool-down time. A compromise was therefore found on further tests (see example in the bottom graph of Fig. 7), and with a reduced servo loop gain at the expense of a slight increase of the transient deformation, the baseline cool-down time was restored. With these settings, on three repetitive consecutive tests, the reduced cold mass transient deformation led to a 60 % increase on the mechanical margin for the cold mass supporting posts. This is now permanently applied in series testing of some forty-five cryodipoles per month.

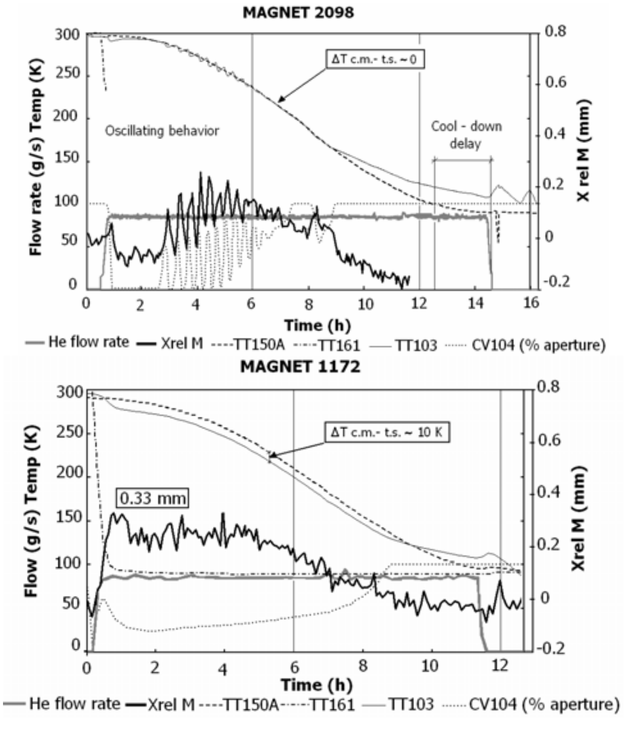

Fig. 7. Cool-down of cryodipole 2098 with $\Delta T_{\text{CM-TS out}} \sim 0$. Cool-down of cryodipole 1172 with $\Delta T_{\text{CM-TS out}} \sim 10$ K.

IV. CONCLUSION

The methodology to detect potential change of the horizontal curvature of the cryodipole cold mass during cold tests by measuring the vacuum vessel deformation with a laser tracker instrument has been validated. The cryodipole transient horizontal displacement has been reduced by a factor of two with respect to the standard cool down process, by controlling the temperature gradient between the cold mass and thermal shield outlet, and without any delay of the cool down time. The strong asymmetrical cooling of the cryodipole thermal shield has been found responsible for this transient bending deformation. The safety margin to ensure the mechanical stability of the support posts has been increased by 60%. This new controlled cooling process is being presently applied for the series testing of the LHC cryodipoles.

REFERENCES

[1] F. Seyvet *et al.*, “Improvement of the geometrical stability of the LHC cryodipoles when blocking the central support post,” presented at the Particle Accelerator Conference, Knoxville, Tennesse, USA, May 16-20, 2005, Paper ID: 1578-MPPT041.

[2] M. Dupont, D. Missiaen, P. Winkes, “The laser tracker: a major tool for the metrology of the LHC,” presented at the 8th International Workshop on Accelerator Alignment, Geneva, Switzerland, October 4-7, 2004.

[3] *Cryogénie. Ses applications en supraconductivité*, Institut International du Froid, Techniques de l’Ingénieur, Paris, 1995, p.43.

[4] A. Tovar Gonzalez, “Cryo Feed Box CFB Operator Guide,” Version 1.0, CERN, 2003.

[5] D. Simek, “Dipole support post mechanical tests,” CERN AT-CRI Test Report 2003-11, EDMS id. 411325, 2003.

[6] F. Seyvet, “Control of horizontal geometry of LHC cryodipole via its supporting system,” CERN AT-CRI Technical Note 2004-09, EDMS id. 478552, 2004.

[7] G. Peon Hernandez, “Design of components for the LHC cryostat”, Ph.D. Dissertation, University of Saragossa, 1997.