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Long Term Stability of the LHC Superconducting Cryodipoles after Outdoor Storage

F. Seyvet, G. Arnau Izquierdo, A. Bertarelli, O. Denis, P. El-Kallassi, E.D. Fernandez Cano,
P. Fessia, S.D. Ilie, J.B. Jeanneret, D. Letant, A. Poncet, P. Pugnat, F. Savary, S. Sgobba,
A. Siemko, E. Todesco, D. Tommasini, R. Veness, B. Vullierme, E. Wildner

Abstract

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CERN
CH - 1211 Geneva 23
Switzerland

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Abstract—**The main superconducting dipoles for the LHC are being stored outdoors for periods from a few weeks to several years after conditioning with dry nitrogen gas. Such a storage before installation in the 27 km circumference tunnel may affect not only the mechanical and cryogenic functionality of the cryodipoles but also their quench and field performance. A dedicated task force was established to study all aspects of long term behaviour of the stored cryodipoles, with particular emphasis on electrical and vacuum integrity, quench training behaviour, magnetic field quality, performance of the thermal insulation, mechanical stability of magnet shape and of the interface between cold mass and cryostat, degradation of materials and welds. In particular, one specifically selected cryodipole stored outdoors for more than one year, was re-tested at cold. In addition, various tests have been carried out on the cryodipole assembly and on the most critical subcomponents to study aspects such as the hygrothermal behaviour of the supporting system and the possible oxidation of the Multi Layer Insulation reflective films. This paper summarizes the main investigations carried out and their results.**

Index Terms— **Cryogenics, Superconducting accelerator magnets, Materials science and technology, Electrical Engineering.**

I. LHC CRYODIPOLE GLOBAL DESCRIPTION

TO achieve a final proton-proton collision energy of 14 TeV in the 27-km circumference tunnel, the LHC will be composed of 1232 horizontally curved 15 m long dipole magnets [1], generating a nominal magnetic field of 8.33 T, for a current of 11.85 kA flowing through the NbTi superconductors of the coil winding. The dipole cold masses are cooled by superfluid helium down to 1.9 K. A two-stage temperature thermal shielding system aims at intercepting the largest fraction of applied heat loads at higher temperature; it is composed of a first major heat intercept at 50 K to 75 K around the cold mass, and of a second lower temperature heat intercept at 4.6 K to 20 K designed to protect the magnet from both beam induced heat loads (by cooling the beam screen), and conduction heat transfer from the vacuum vessel through the magnet supporting system. Multi Layer Insulation (MLI) is wrapped around both the cold mass and the first major heat intercept to shield the superconducting magnet from heat radiated by the vacuum vessel at room temperature. An Instrumentation Feedthrough System (IFS) was developed for the routing of the instrumentation wires from the 1.9 K environment to the outside. The cold mass is supported within its vacuum vessel by three Glass Fibre Reinforced Epoxy (GFRE) support posts of low thermal conductivity and high stiffness; the two extremity supports are free to slide on a PTFE® coated surface to cope with differential thermal contractions of the cold mass and the vacuum vessel. A cross section of the dipole superconducting magnet in its cryostat is presented in Fig.1.

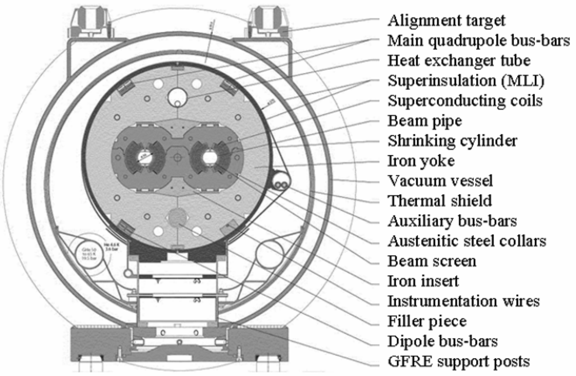

Fig. 1. Cross-section of the LHC main superconducting dipole in its cryostat.

No cryodipole components were explicitly designed to meet external storage environmental effects. Delays in the installation of the machine entailed the decision to store cold masses and assembled cryomagnets outdoors. A dedicated task force was established to study the Dipole Long Term Stability (DLTS) and determine the effects of long term outdoor storage on magnet electrical insulation and continuity, field harmonics, quench training memory, geometry stability, degradation of materials and welds. A risk assessment was finally completed.

II. STORAGE TIME AND CONDITIONS

The dipole cold masses are delivered at CERN from three manufacturers and are first stored outdoors. The magnet is then assembled into its cryostat and the performances of each individual dipole are assessed under cryogenic operating conditions. After the cold tests, a second outdoor storage period occurs. The cleaning of the beam tubes and subsequent insertion of the beam screens are performed before lowering down the cryomagnet into the 27-km circumference tunnel. Sometimes, a third outdoor storage period occurs between

Authors are within *CERN, Geneva, Switzerland*
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these last two operations. An illustration of the storage conditions of the cold masses before assembly into their cryostat is presented in Fig. 2. The conditioning of the cold masses and cryodipoles includes protection of electrical cabling, installation of leak tight covers on both magnet and vacuum vessel extremities and pressurization of the cold mass with 1.2 bar of gaseous nitrogen.

Fig. 2. External storage of LHC main dipole cold masses (winter 2005).

The distribution of the storage time for both the cold masses and the already assembled cryodipoles, at the start of the DLTS investigation early 2005, is summarized in Fig. 3. 86 cold masses or assembled cryodipoles were stored outdoors for more than one year after their delivery at CERN.

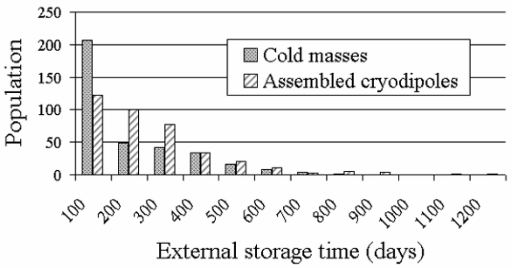

Fig. 3. Outdoor storage time for both the LHC dipole cold masses and the assembled cryomagnets at the start of the DLTS work.

III. ELECTRICAL INSULATION AND CONTINUITY

Two samples of 33 units were built to compare the electrical insulation of dipole cold masses stored outdoors for long periods, between 5 and 14 months, and for short ones, below 10 days.

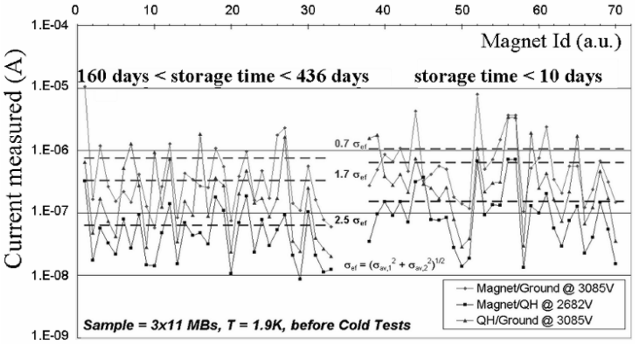

Fig. 4. Leakage current measured for dipole magnets that were stored outdoors for long and short time periods.

The leakage currents flowing in-between main insulated magnet components were measured at 1.9 K with maximum applied voltages of 2.7 kV and 3.1 kV as a function of the electrical circuits. Results presented in Fig. 4 show that the electrical insulation of the magnets is stable regardless of the magnet storage time. Furthermore, a complete electrical check is performed on each cryomagnet before their installation in the tunnel in order to ensure the electrical system integrity. The check consists of a continuity and an insulation tests. Up to now, more than 80 cryodipoles stored outdoors for periods up to one year have already passed this check successfully.

Finally, the IFS was designed to sustain external storage conditions, and specific conditioning procedures are applied that ensure the IFS functionality in the long-term.

IV. FIELD HARMONICS

The extended duration of outdoor storage was questioned to eventually enhance the creep in the coil structure [2]. Induced relaxation of the coil pre-stress would perturb the coil geometry, resulting in non-negligible variations in the magnet field quality.

A mechanical model of the dipole cross-section, previously developed and validated with experimental data [3], was used to evaluate the influence of coil pre-stress on field quality. At the nominal pre-stress of 70 MPa, a loss of 10 MPa would give +0.5 units of b3, +0.12 units of b5, -0.015 units of b7. The effect is thus modest but not negligible.

Measurements of the field quality at CERN show that the offsets between warm and cold field measurements in b3 are stable within ±0.5 units, regardless of the time of storage of the magnets. Pre-stress in the coils is thus stable in time at least within ±10 MPa; results are shown in Fig. 5. The results are very similar for b5 and b7 with stability within ±0.2 and ±0.1 units respectively.

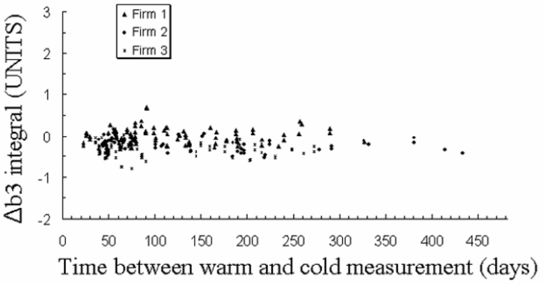

Fig. 5. Stability of the warm and cold measurement correlation with time for the b3 harmonics of the LHC arc superconducting dipoles.

V. QUENCH TRAINING

Similarly, the relaxation of the coil pre-stress in the cold mass could cause quench training degradation. In order to investigate this, a magnet displaying a relatively slow training and an initial quench below the nominal value was chosen. It was then cold tested for a second time after one year of outdoor storage. Quench training results are presented in Fig. 6. During its first cold test, this magnet initially quenched at 8.23 T, below the nominal value of 8.33 T, and seven quenches were required to reach a maximum field of 8.95 T. After the standard thermal cycle, the magnet had "memorized" the quench training and its first quench occurred at 8.76 T.

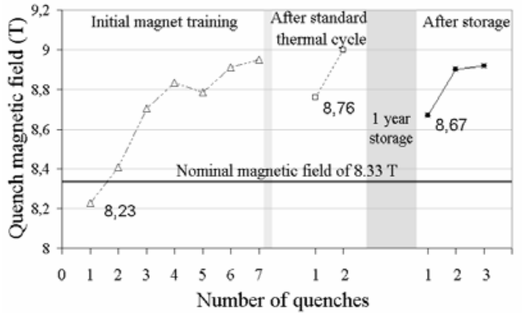

Fig. 6. Quench training of a dipole magnet after one year of outdoor storage.

During the second test, after one year of outdoor storage, the first quench of this dipole occurred at 8.67 T, a value largely above the first training quench but slightly lower than the first one after the standard thermal cycle. No important degradation of the quench training behaviour was observed for this magnet after one year of outdoor storage. For a firm statement concerning the whole population of LHC superconducting magnets, a statistical study is required.

VI. GEOMETRY AND ALIGNMENT

The geometry stability of the LHC cryodipoles has been assessed by comparing their geometry between two stages; before outdoor storage once they are assembled and cold tested; and after storage when the beam screens are inserted into the beam tubes. Measurements of 329 cryodipoles, that were stored outdoors for periods varying between one month and two years, were used to do this analysis. The position change of the cold mass extremities within the cryostat has been studied, as it is representative of both the corrector magnet alignment and the sagitta change of the dipole. Results are presented in Fig. 7. Statistically, more than 95% of the cryomagnets remained stable within +/-0.5 mm both horizontally and vertically. 8 magnets that show geometry change outside this range are under study. The mean and the standard deviation of the movements of the ends of the dipoles have been calculated using windows sliding over storage time. No indication of long term trends has been detected.

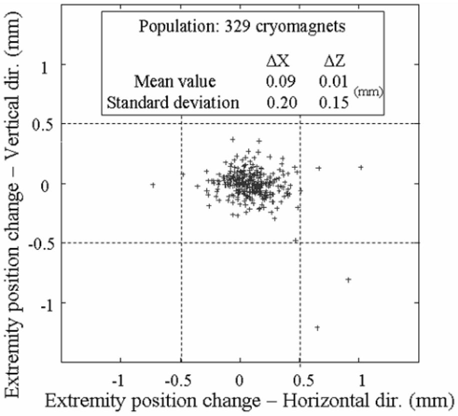

Fig. 7. Stability of the cold mass extremity positions before and after long term storage (connection side).

VII. DEGRADATION OF MATERIALS

A series of cold masses and assembled cryodipoles stored outdoors for periods of the order of one year has been inspected for potential degradation [4], with the aim to identify the components susceptible to degrade and assess the nature and importance of the degradations as well as their effects on thermal, structural, and vacuum performance of the magnets.

During the inspections, focus was put on stainless steel cold mass extremity welds, cold foot pad and bellow welds, copper heat exchanger tube and stainless steel to copper joints, copper to copper welded joints, the general aspect of the cryostat (made out of C steel), GFRE support posts and sliding surfaces of the centering pieces, helium transport lines including their aluminium to aluminium welds and bimetallic junctions, as well as the MLI.

The excessive penetration of a weld between the beam tube ultra high vacuum and the helium pressurized cold mass was specifically monitored. The risk of loss of He leak tightness of this weld is critical for machine operation and for beam-gas background in the LHC experiments. The lack of back gas shielding during this welding operation associated to a full penetration resulted in a corroded aspect of the weld root visible after some storage time. Visual inspections of every LHC cryomagnet were thus carried out and further X-rays and repair will be performed, when necessary, to ensure that only magnets adequate for LHC operation will be installed in the machine. It should be noted that this issue is coming from a cold mass manufacturing non conformity, and is thus only indirectly linked to the DLTS work.

A. *Cryodipole components, cold mass welds and bellows*

Further results from the inspections are summarized in the following. A few decilitres of liquid water were found in a cold mass heat exchanger line because of poor storage conditioning. Since one of the three producers used cast 304 H instead of cast 304 L for the cold feet pad, particular attention was paid to the possible sensitization of the Heat Affected Zones (HAZ) of the welds of this component. No corrosion of this weld was observed after outdoor storage for 9 months. On the other hand, a « rusty aspect », was locally observed in the magnet extremity welds, mainly in the HAZ. The rust extent was found to depend on duration of external storage and the cold mass assembler.

Ageing tests of welds after removing rust stains were further carried out. Furthermore, representative weld samples that were recovered from the three cold mass producers were also subjected to tests representative of the tunnel conditions, and to complementary destructive tests after a significant storage time. Finally, a storage inspection and re-conditioning campaign was launched on all cryodipoles. These efforts led to the conclusions that first, some dipole welds are indeed affected by rust but they are not critical and they can be repaired, and second, the functionalities of the LHC cryodipole components, welds and bellows remain stable in the long-term.

B. *Vacuum*

Condensation and re-evaporation cycles in the vacuum enclosures are possible during outdoor storage; the oxidation of the vacuum system was therefore investigated. Furthermore, the leak tightness of the beam screen cooling capillary was checked because of possible combined effects, during storage, of halogen residues in the system inducing corrosion, residual stresses due to welding, and temperature and humidity cycles.

Magnets stored outside for a period of one year that had already been equipped with beam screens and cooling circuits were inspected, and 3 of them were leak tested. The vacuum enclosure was found leak tight, regardless of the outdoor storage time.

C. *Thermal insulation*

The air moisture in the vacuum vessel during outdoor storage might oxidize the 40 nm aluminium coating deposited on each side of the MLI layers. Degradation of the shielding properties of the MLI protecting the superconducting magnets from radiant heat loads was thus analysed. The thermal performance of a production sample that was stored in an unprotected environment for a period of more than two and a half years has been analyzed and tested [5]. The thickness of the aluminium coat on each MLI polyester layer was determined by measuring the electrical resistivity of the sheet, and the thermal performance of two superimposed 15 layers blankets was measured with a heatmeter. Results show that the thickness of the aluminium layer was found unchanged except for the two external layers of the units, where it was found to be reduced to a minimum of 20 nm. Similarly, the overall MLI thermal performances have been degraded by 17% with respect to the test performed on a new reference sample.

A degradation of the thermal performance of a MLI sample that was poorly stored for a long time has been observed, but the degraded MLI was still found to meet the initial specifications for the operation of the LHC machine [6].

D. *Interface between the cold mass and the cryostat*

During outdoor storage, the following environmental conditions could be suspected to affect long-term behaviour of the supporting system of the cold mass inside the cryostat: moisture absorption, the night and day as well as the winter and summer thermal excursions, the change of phase of the moisture absorbed, creep phenomena under hygrothermal effects, dirt and dust.

The main risks have been identified as, first, a degradation of the friction coefficient of the PTFE® coated surface allowing sliding of the extremity support posts on the cryostat; and, second, a decrease of the stiffness of the GFRE support posts eventually degrading the alignment stability of the LHC magnets in the machine.

A specific hygrothermal ageing treatment of both GFRE supports posts and low-friction centering pieces has been defined, based on a series of humidity absorption and desorption cycles on samples of the GFRE composite material. In an environmental chamber, four supports and four centering pieces were pre-conditioned during 3 days at 40°C and 95% of humidity, and they were then subjected to 91 cycles of 8 hours each; each cycle consisting of 6 hours at 40°C and 95% humidity, and then 2 hours at -20°C.

The GFRE support posts were mechanically tested before and after hygrothermal treatment. The rigidity of the units in cantilever bending degraded by 6% after the environmental conditioning, whereas their compression rigidity remained unaffected [7]. This was shown not to affect the alignment stability of the magnets in the LHC machine.

The static friction force between the centering piece and the support post was found to increase by 45% after the hygrothermal treatment [7]. This degradation was attributed to the rust and wear-induced dust lying on the pad. It will generate increased loads in the supporting system during magnet cool down, but these loads remain five times below the admissible ones. This is thus acceptable for the machine operation.

VIII. CONCLUSION AND RISK ASSESSMENT

The long-term behaviour of the LHC main superconducting dipoles stored outdoors has been investigated, with a focus on electrical integrity, magnetic field quality, quench training, geometry, degradation of materials and welds, performance of the thermal insulation and interface between the cold mass and the cryostat. The analysis has shown that dipole cryomagnets remain functionally unaffected or weakly affected by long-term outdoor storage, even if such a constraint was not considered during the design phase. Thanks to the inspection work done, a manufacturing non conformity in a cold mass critical weld was monitored and treated, and the quality control of the storage conditions was improved.

ACKNOWLEDGMENT

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