Displacement Measurements in the Cryogenically Cooled Dipoles of the New CERN-LHC Particle Accelerator

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ABSTRACT

All evidence indicates that new physics, and answers to some of the most profound scientific questions of our time, lie at energies around 1 TeV. To look for this new physics, the next research instrument in Europe's particle physics armory is the Large Hadron Collider (LHC). This challenging machine will use the most advanced superconducting magnet and accelerator technologies ever employed. LHC experiments are being designed to look for theoretically predicted phenomena.

One of the main challenges in this new machine resides in the design and production of the superconducting dipoles used to steer the particles around the 27 km underground tunnel. These so-called cryodipoles are composed of an external vacuum tube and an insert, appropriately named the cold mass, that contains the particle tubes, the superconducting coil and will be cooled using superfluid Helium to 1.9 K. The particle beam must be placed inside the magnetic field with a sub-millimeter accuracy, this requires in turn that the relative displacements between the vacuum tube and the cold-mass must be monitored with accuracy.

Due to the extreme condition environmental conditions (the displacement measurement must be made in vacuum and between two points with a temperature difference of more than 200°C) no adequate existing monitoring system was found for this application. It was therefore decided to develop an optical sensor suitable for this application. This contribution describes the development of this novel sensor and the first measurements performed on the LHC cryodipoles

1. THE LHC DIPOLES

The LHC will consist of two colliding synchrotrons installed in the 27 km tunnel previously used by the LEP accelerator[1]. They will be filled with protons and two superconducting magnetic channels will accelerate them. To bend 7 TeV protons around the ring, the LHC dipoles must be able to produce fields of 8.36 Tesla. Superconductivity makes this possible. The LHC machine will contain around 2000 main ring superconducting magnets cooled at 1.9 K by super-fluid pressurized helium, mainly 15 m-long dipoles with their cryostats and 6 m-long quadrupoles. Figure 1 shows the concept of one of the 15 m-long LHC cryodipole.

The magnet dipole enclosed in the Helium Vessel with heat exchanger and cold bore tubes, forms the dipole cold-mass. The work temperature of the cold-mass is 1.9K. The cryostat of the dipole magnet consists of the three supports to position the cold mass, a radiation screen and a thermal shield both equipped with multi-layer super-insulation, and a vacuum vessel.

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The dipole cold-mass assembled into the cryostat forms the Cryodipole Magnet. Figure 2 shows a cross section of the LHC 15 m cryodipole in the plane of an extremity support post.

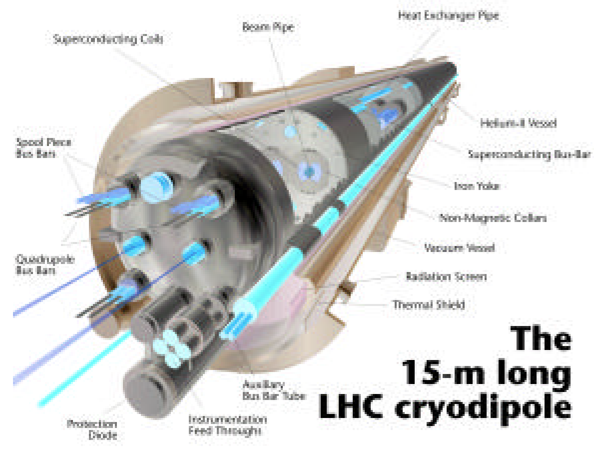

Figure 1 : Concept of the LHC cryodipole (CERN, 30.04.99).

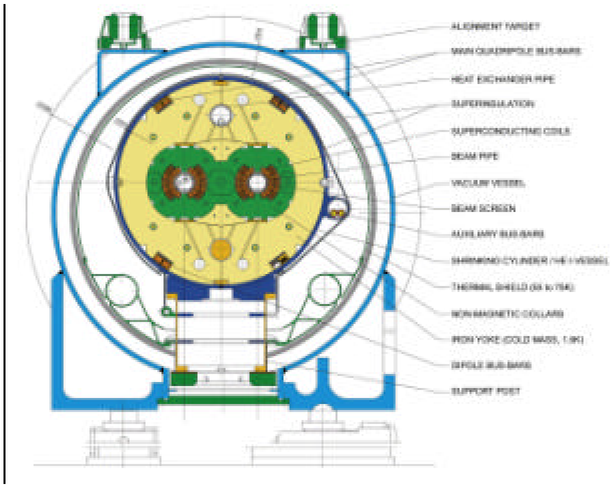

Figure 2 : Cross section of the LHC dipole magnet.

The extreme environmental conditions and the geometry have imposed several conditions to the displacement sensor. First, since the longitudinal displacement is so important (20 mm), it is not possible to install an optical fiber between the vacuum vessel and the cold mass. Therefore it was decided to use a light beam propagating in the space between an optical head installed on the inner wall of the vacuum vessel and a mirror attached to the external surface of the cold mass. Optical fibers are used as reference path in the optical head and to bring the light in / out of the vacuum tube.

To insure the correct functioning of LHC it is necessary to know the real position of the cold mass in to the vacuum vessel. This allows to position the particle beam relative to the surveying points placed on the external face of the vacuum tube. During cooling and increase of the magnetic field, the cold-mass changes its size, shape and position. The expected longitudinal deformation of the 15m long cold-mass will be of the order of 20 mm, caused mainly by thermal contraction. More difficult and more important is the determination of the horizontal and vertical displacement of its extremities. This was the main goal of this work.

2. SENSOR DESIGN

This solutio n requires the use of a mirror attached to the cold mass. This mirror must survive undamaged to temperatures down to 1.9K. The optical head consists of a reference fiber, a coupler, ferule, mirror and lens. The transversal dimension of the optical head is limited to 30 mm because of space limitations.

The optical head, installed in interior of the vacuum vessel is to be connected with the reading unit, which is in exterior, hence a special vacuum feed through must be conceived. All parts of the sensor must survive the vacuum without significant outgas. The sensor must guarantee a correct measurement even if the cold-mass mirror is subjected to tilt. The working distance of the sensor is approximately 150 mm.

A schematic representation of the optical head and a picture of it are presented in Figure 3. The optical path and the reference fiber have about the same optical length and constitute a Michelson interferometer. This interferometer is demodulated using an existing SOFO path-matching readout system[2,3]. The Reference fiber is thermalised to the vacuum vessel and is therefore at constraint temperature during all operations.

The optical head is attached to the internal side of vacuum vessel. It consists of the coupler, reference fiber, ferule, lens and the head-mirror. All parts of the optical head are encased in an aluminum Armour. The other mirror is fixed on the cold mass. The optical head, including the reference fiber, is thermalised to with the vacuum vessel hence it works under almost constant room temperature. Thee cold-mass mirror is subjected to temperatures as low as 1.9K (~ -271°C). Tests showed that an high quality mirror with gold coating could survive these extreme conditions without damaging[4].

The sensor works as follows[3,5]: The broadband light coming from the SLED source @1330nm in the SOFO reading unit is split by the coupler. One path goes into the reference fiber while the second leaves the fiber trough a metallic ferule is collimated by the lens and pointed by the head mirror towards the cold-mass mirror. It reflects off the cold-mass mirror, goes back to the ferule and is collimated on a point on the ferule, close to the optical fiber end, but not on it. The reflected light travels back to the cold-mass and is finally reflected and collimated back in the optical fiber. Since the fiber core and the reflection point on the ferule are conjugated points with respect to the lens-mirror system, the light is always reflected back to the fiber core after two passes, independently from the mirror tilt[3]. The intensity of the re-coupled light will of course depend on the aperture-matching and will be reduced with increasing rotation of the mirror[3,6]. This setup ensures a back-coupling with high tolerance on the cold-mass mirror rotations and independence on its longitudinal translations. In general, a longer focal length of the lens will improve the angle range, but increase the head and beam size. It was found that a lens with a focal length of 25.4 mm would allow a sufficient back coupling efficiency at the design working distance of 150 mm. The total dimensions of the optical head are 30x50x200 mm. The dimensions of the cold-mass mirror are 50x50x10 mm.

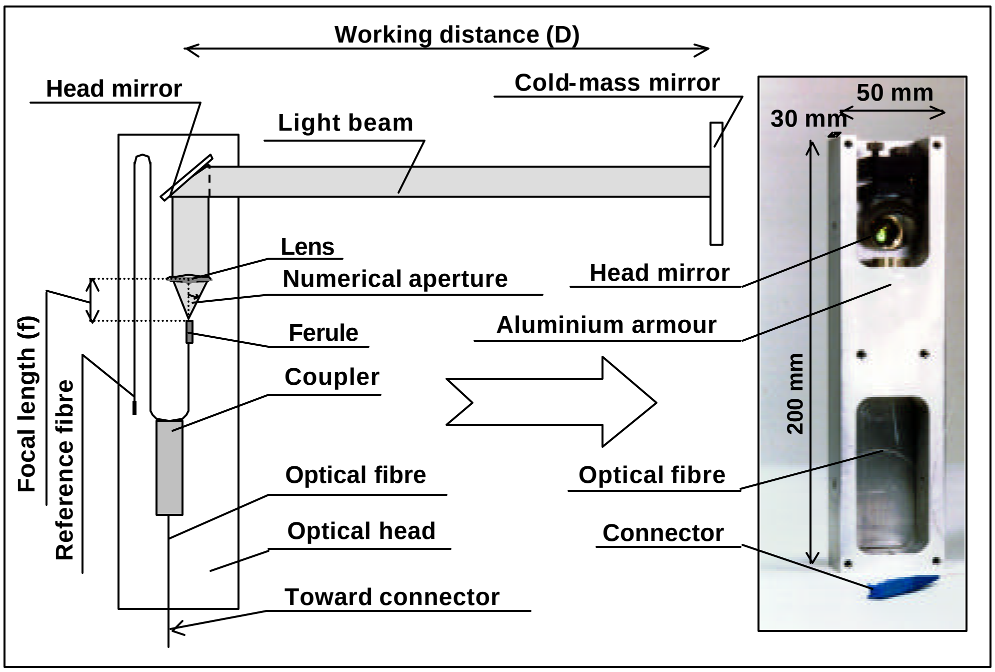

Figure 3: Setup and picture of the sensor head.

3. LABORATRY TESTING

The following preliminary tests were carried out in order to certify the sensor before installation in the cryodipole prototypes[4,5]:

Reflectance of the cold-mass mirror in low temperature conditions

The reflectance of the cold-mass mirror at low temperatures was tested at three different temperatures, at 75K using liquid nitrogen, at 20K using a cryostat and at 4.2K using liquid helium. After all three tests there was no noticeable change compared to a reference gold-coated mirror.

Vacuum testing of the optical head.

The Vacuum tests were also successful. A change in the optical path was observed and can be explained by the change of refractive index between air and vacuum.

Acceptable tilt range

The maximal permitted tilt angel was determined by simulating a mirror tilt with a rotation stage. In reality, the installation of the cold mass into the vacuum vessel, its cooling and the application of the electromagnetic field have as a consequence a torsion and an horizontal bending of the cold-mass. Thus the cold-mass mirror may be exposed to horizontal and vertical tilts. If the tilt exceed a certain value, the back-coupling efficiency might become insufficient to carry out a measurement. The usable measurement area is divided in two zones with a blind area in-between. This interruption is expected and corresponds to the light beam returning directly into the fiber after a single round trip. Therefore the area that is considered as exploitable for measurement begins after the interruption and finishes when the signal fades. This area cover the range of about 230". This is higher than the maximal tilt that can be tolerated in the cryodipole. The sensors should therefore cover the whole utilization spectrum without the need of realignments.

4. APPLICATION

Our system measures absolute variations of the distance between the mirrors, welded on the cold mass, and the optical heads, fixed on the cryostat. Displacements of the dipole relative to the cryostat in the plane perpendicular to the magnet longitudinal axis can be monitored by measuring distances between cold mass and cryostat inner wall in three points. Three optical heads are installed at around 500 mm from the magnet ends, as shown in Figure 4: two of them are placed along a horizontal diameter of the cold mass and allow measuring diameter variations (given by the sum of measured distance changes) and horizontal center displacements (given by the semi-difference of the measured distance changes). The third head measures the vertical distance between the lower part of the cold mass and the cryostat: this provides a measurement of vertical displacements of the magnet center, once the variation of the dipole radius is subtracted.

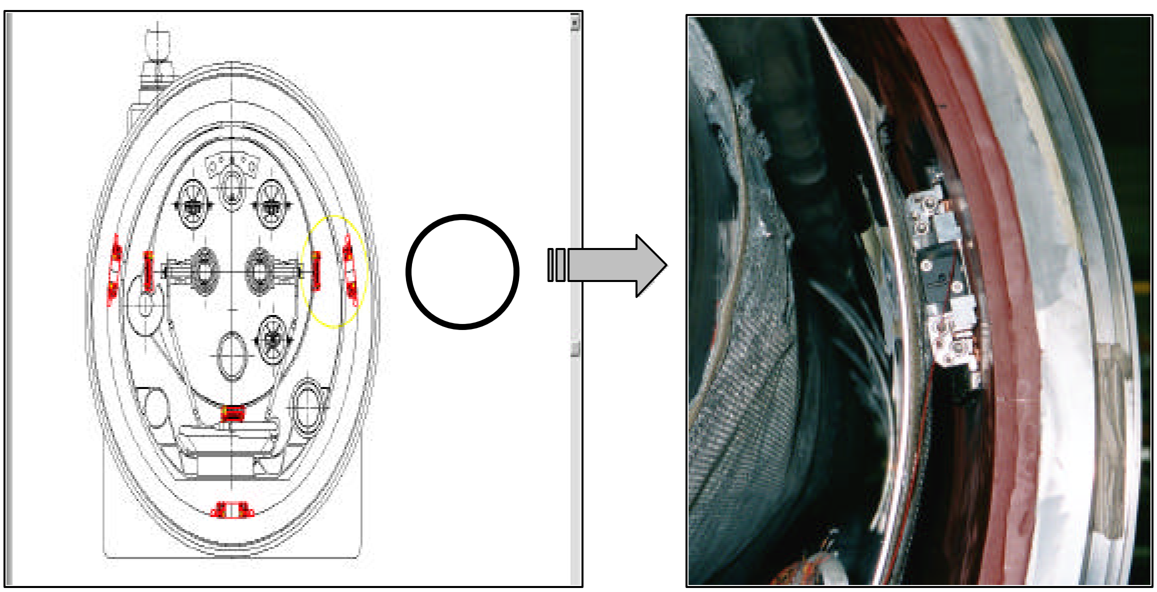

Figure 4: Installation of the optical heads on the cryostat and of the mirrors on the cold mass. They are longitudinally located at around 500mm from magnet ends.

This experimental set-up enables us to measure cold mass displacements relative to the cryostat and diameter variations in different situations, such as transportation, thermal cycles, magnet energization and quenches [7].

4.1 Dipole displacement during transportation

After cryostating, the dipoles have to be installed in the underground tunnel: one is interested in monitoring displacements during transportation. Examples of vertical and horizontal displacements of the dipole relative to the cryostat during the transportation by truck between two CERN buildings are given in Figure 5. Measurements are taken about every minute. We indicate the various operations performed, namely the loading on the truck, the transportation, the unloading from the truck, the installation on temporary feet, a quiet period (during which the dipole was sitting on the floor) and the final installation on the nominal feet. The largest displacement is observed when the magnet is lifted with a crane to be loaded and unloaded from the truck. Maximum displacements up to around 0.5mm and 0.3mm were measured, in vertical and horizontal directions, respectively. On the other hand, the final offsets between starting and final positions (with the nominal feet configuration) are smaller, i.e. around 0.2 and 0.05mm, respectively. The band-width of the system is insufficient to follow the fast cold mass vibrations during the transportation and the measured displacements might underestimate the real maximum movements.

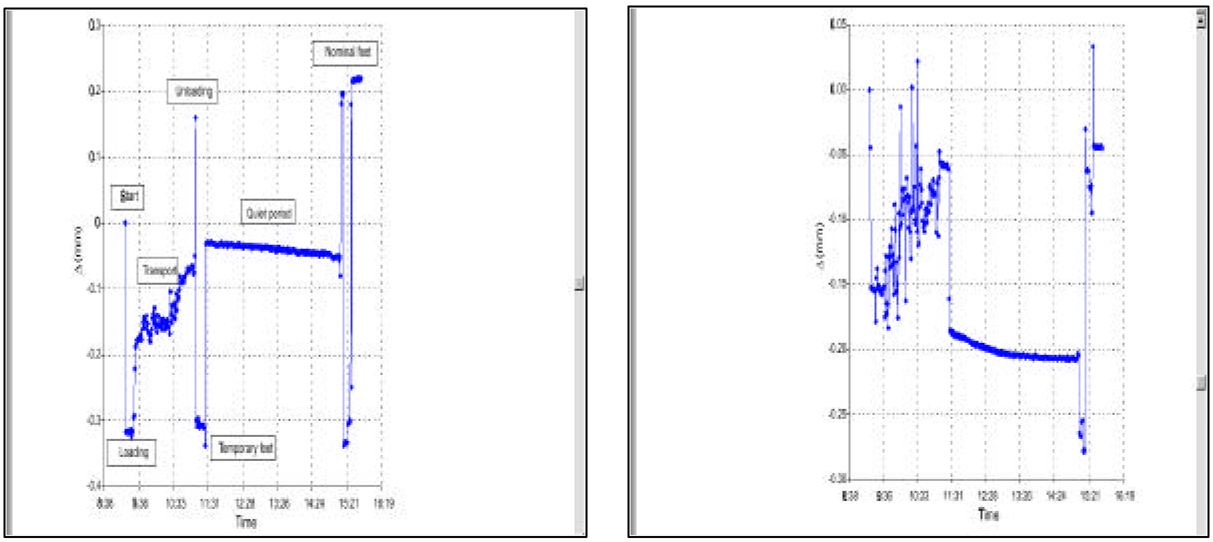

Figure 5: Vertical and horizontal displacements of the dipole prototype MBP2O2 during transportation.

4.2 Deformations during thermal cycles

One would like to monitor dipole displacements during cool down to check whether the alignment at room temperature is maintained at 1.9K. We measured cold mass displacements relative to the cryostat and diameter variations during several thermal cycles performed on the dipole prototypes.

A typical plot of dipole displacements and diameter variations as a function of the time during a standard thermal cycle is given in Figure 6: starting from the 1.9K operational temperature, the cold mass is warmed up and then cooled down again at 1.9K. Diameter variations, center displacements (both in vertical and horizontal directions) and the temperature on the considered magnet end are given as a function of time. Notice that the vertical head was not available for the whole temperature range, since unexpected movements of the lower part of thermal screen (see Figures 2 and 4) eventually cut the light path to the mirror.

During the transition from room temperature to 1.9K, the cold mass diameter shrinks by about 1.3mm. An example of the measured variations as a function of the temperature is given in Figure 7, for both ends of one prototype (data refer to a warm up cycle). The measured value is consistent with the expected one, assuming the known thermal coefficients for iron and stainless steel.

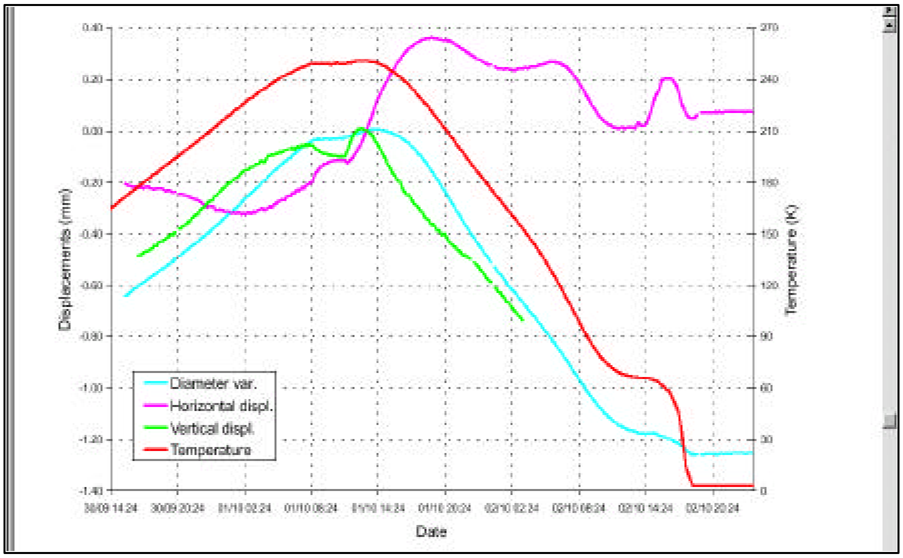

Figure 6: Horizontal and vertical displacements of the center of the cold mass and diameter variations as a function of the time during a thermal cycle performed on the MBP2A2 prototype between September 30 and October 2, 2000.

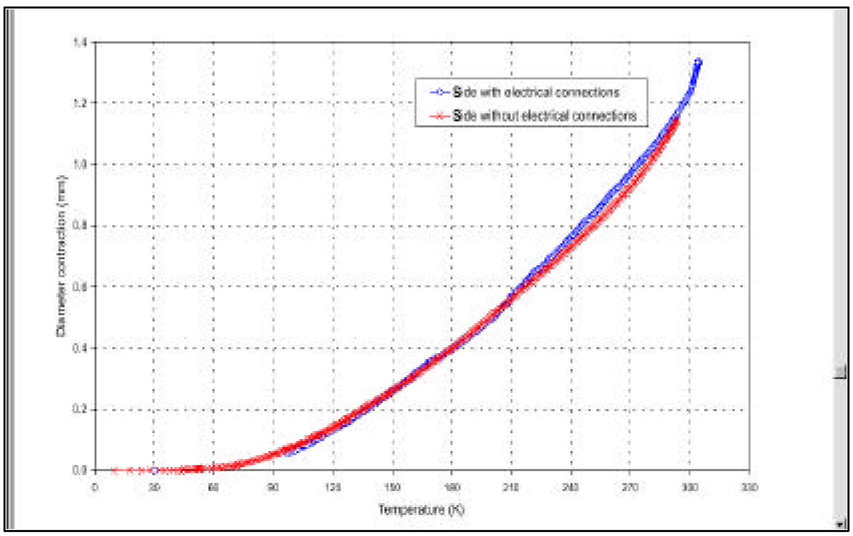

Figure 7: Diameter variation as a function of the temperature for the two sides of the MBP2A2 prototype. Zero diameter refers to value at 1.9K.

Center displacements as a function of the temperature measured on both ends of a prototype are shown in Figure 8. A similar pattern is found in the two cases, but the two shifts have rather different values. Final offsets with respect to the position at room temperature are up to 0.3mm, i.e. of the order of tolerances on corrector alignment [8].

One should wait for more statistics to see whether such a feature is systematic and possibly try to compensate for it. During the whole thermal cycle, larger displacements of the dipole end center are found, up to more than 2mm. This is a potential problem for the interconnections between two consecutive magnets.

Vertical displacements up to more than 1mm have been observed in the temperature range where the acquisition system has been working, i.e. from room temperature to around 150K. They are mainly induced by the contraction of the dipole feet. Further variations are expected at least down to 100K.

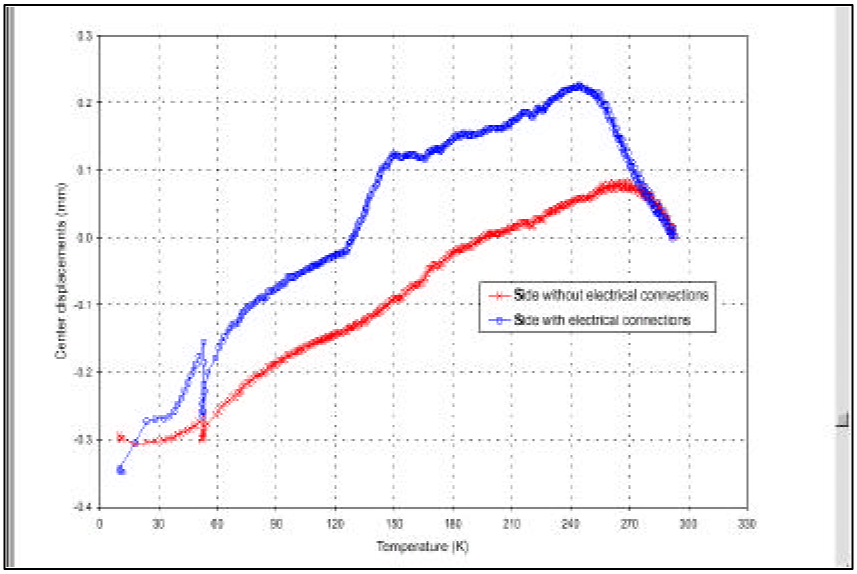

Figure 8: Center displacement as a function of the temperature for the two sides of the dipole prototype MBP2A2 prototype. Zero position is the one at room temperature.

4.3 Deformations during energization

During the magnet energization, electromagnetic forces arise in the coil, which depend on the square of the exciting current. At the nominal current, in the straight part of the dipoles, there are outwards horizontal forces are of the order of 3MN/m. Moreover, in the dipole ends, forces with a longitudinal component of the order of 0.5MN also arise[1].

We measured small dipole deformations when the current is ramped up to the nominal value of 11.75kA. The horizontal diameter increases by around $60\mu m$, according to the mentioned quadratic dependence on the exciting current I (see Figure 9). The order of magnitude of such a variation is in agreement with an estimation based on mechanical properties of the dipole. Also the center of the cold mass end moves, up to around $80\mu m$, and it features a quadratic dependence on I as well.

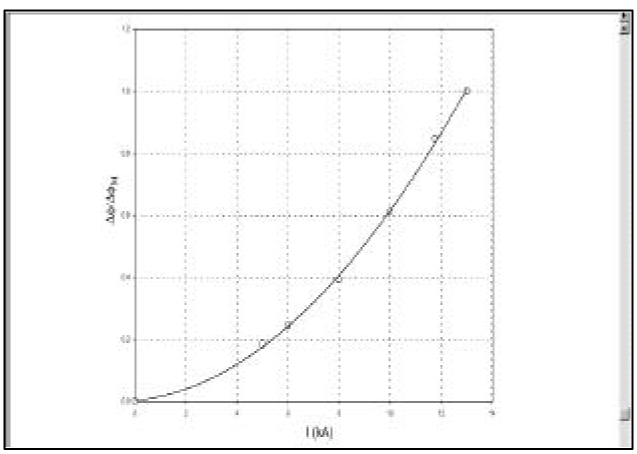

Figure 9: Diameter variation as a function of the exciting current, measured on one side of the prototype MBP2O1. Variations are normalized to the their maximum value $\Delta\phi_M$ at 13.4kA.

4.4 Movements after a quench

A *quench* is a sudden transition of a superconductor to the normal-conducting state. At the operational field, a current of 11.75kA flows in the cables and an energy of around $7\cdot10^6$J is stored in the magnet. When a quench happens, part of such energy is dissipated by Joule effect in the cable and the magnet warms up. The temperature in the cable can easily increase up to 300 degrees and that leads to an increase of the temperature of the whole cold mass, which depends on the magnet protection and rises in general up to around 30K[9].

With our optical system, we could measure displacements of the dipole end center due to the quench-induced warm up of the cold mass. An example, concerning a provoked quench at the nominal current is given in Figure 10. Due to the limited bandwidth of our system, it is impossible to observe the fast transient at the very beginning of the quench.

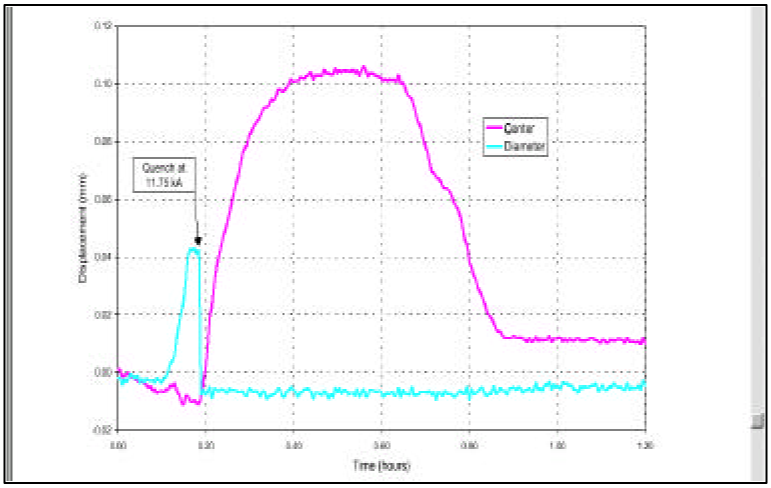

Figure 10: Displacement of one end of the prototype MBP2O1 after a provoked quench at 11.75kA.

After the quench, the center cold mass end starts moving and it slowly recovers its original position, while the refrigeration system absorbs the released energy and recovers the operational temperature of 1.9K. The temperature increase of the cold mass depends both on the current flowing in the cables and on the parameters of the quench protection system. By analyzing quenches at different currents, leading to different temperatures, we found that the original center position is recovered within few micrometers, with typical time constants from 20 to 50 minutes, which depend on the maximum temperature increase and on the efficiency of the refrigerating system.

Notice that the cold mass diameter, which increases because of the electromagnetic forces, suddenly recovers its original value after the quench (within few micrometers) and it is almost not affected by the magnet warm up: actually, we are in a temperature range (from 1.9 to about 30K) where the material dilatation is not relevant.

5. CONCLUSIONS

We described the principle, the constructive details and the first results of a novel device intended to measure transverse displacements between the cold mass and the cryostat of an LHC dipole. The device is fully operational in all the required conditions, i.e., at room temperature and pressure, during transportation and at 1.9K in vacuum at the dipole operational conditions.

The sensitivity and the precision of the measured displacements is fully satisfactory for the needs of the LHC project, i.e. displacements of the order of magnitude of a few 0.01mm can be easily detected.

The band-width of our device is rather limited, thus one can detect displacements in a quasi-steady-state situation. Indeed this allowed us to observe with high precision displacements during thermal transient of several hours.

The long-term exploitation of this device in a test cell-lattice of LHC will eventually provide us useful information on the fine alignment of the LHC dipoles in operational conditions.

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