Development of a Displacement sensor for the CERN-LHC Superconducting cryo-dipoles

Daniele Inaudi
SMARTEC SA
Via al Molino 6,CH-6916 GRANCIA, Switzerland
Tel: +41 91 993 09 24, Fax: +41 91 993 09 40
email: inaudi@smartec.ch, Web: www.smartec.ch

Branko Glisic, Sirine Fakra
IMAC - Stress Analysis Laboratory
EPFL – Swiss Federal Institute of Technology Lausanne
CH-1015 Lausanne, Switzerland

Walter Scandale, Juan Garcia Perez, Jaques Billan
CERN - European Laboratory for Particle Physics
1211 Geneva 23, Switzerland

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 or 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 firs 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. 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.
The extreme environmental conditions and the geometry have imposed several conditions to the displacement sensors.
Fist, 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.

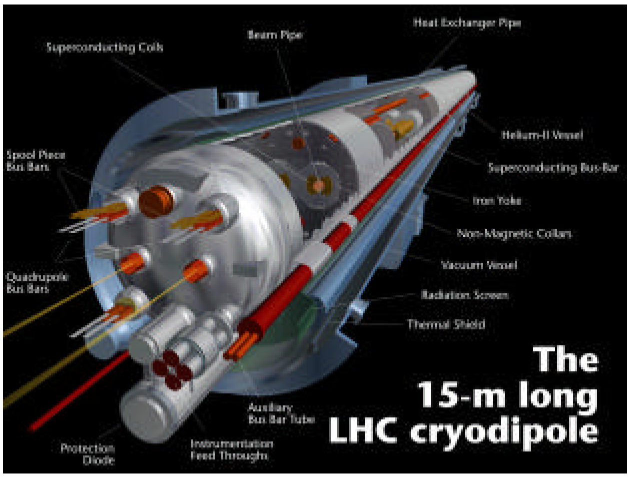

Figure 1: Concept of the LHC cryodipole (CERN, 30.04.99)

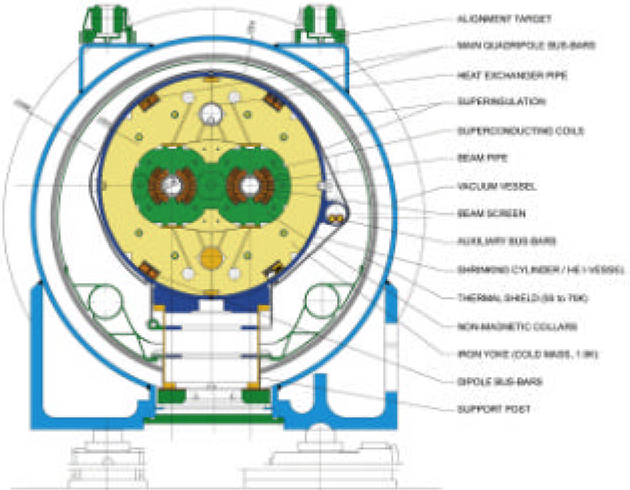

Figure 2: Cross section of the LHC dipole magnet.

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 displacement of its extremities. This was the main goal of this work.

2. SENSOR DESIGN

This solution 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 an 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]. 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.

The sensor works as follows: 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 ferrule 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 ferrule, 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 ferrule are conjugated points with respect to the lens-mirror system, the light is always reflected back to the fiber fore after two passes, independently from the mirror tilt. The intensity of the re-coupled light will off course depend on the aperture-matching and will be reduced with increasing rotation of the mirror [3, 4]. 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.

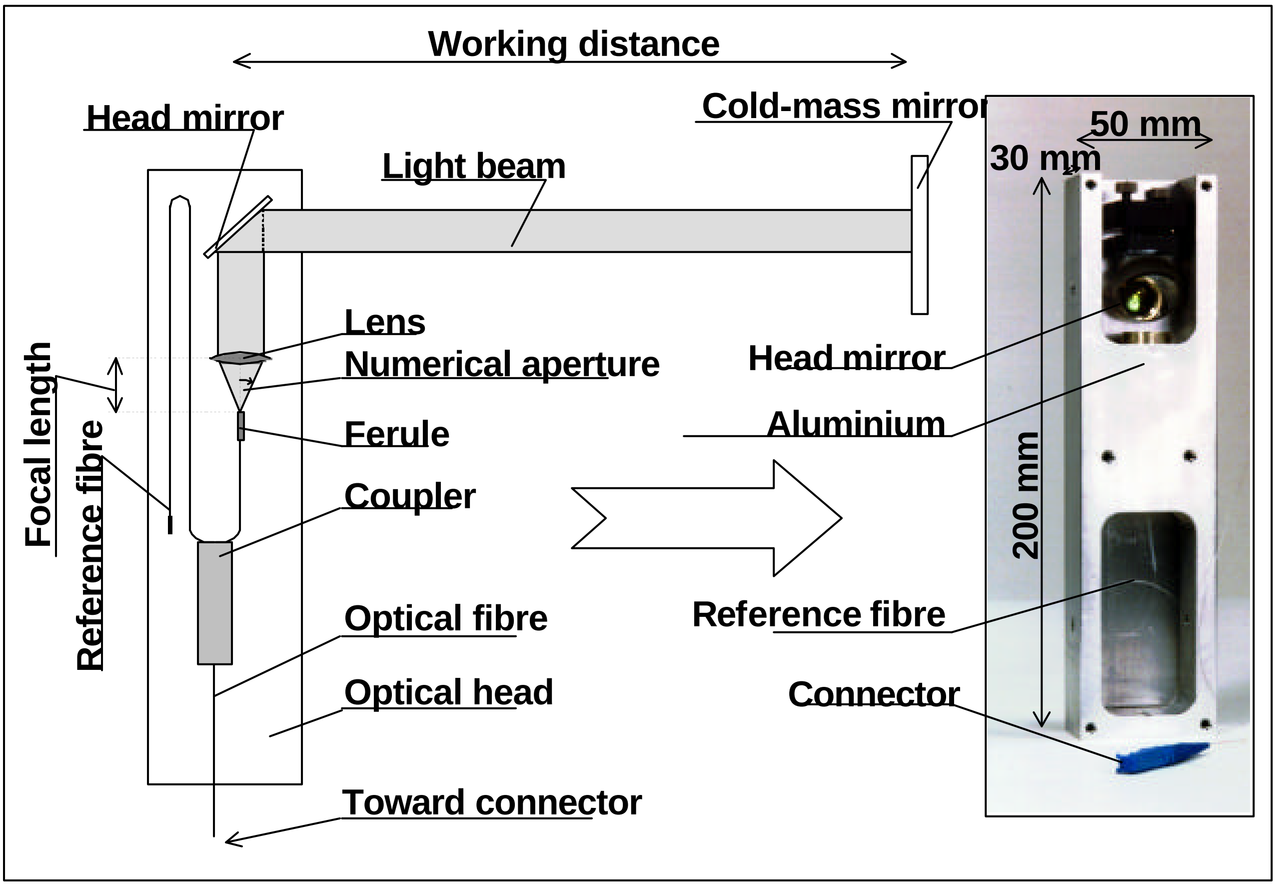

Figure 3: Setup and picture of the sensor head

3.
4. LABORATRY TESTING

The following preliminary tests were carried out in order to certify the sensor before installation in the cryodipole prototypes:

Resistance of the cold-mass mirror in low temperature conditions

The resistance 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.

5. APPLICATION

The first two measurement heads have been installed in a test dipole in April 2000. The installation proceeded without problems ant the optical alignment required less than 30 minutes (see Figure 4). A few days later the dipole was provided with end-caps and was displaced from the assembly hall to the testing hall. Figure 5 shows the recorded displacements during transportation. It can be noticed that most readings are symmetrical, indicating a rigid body motion of the cold-mass inside the vacuum vessel. Dissymmetrical deformation might be the result of temperature changes or deformations of the vacuum vessel. It can be noticed that a residual displacement of about 0.1 mm vas recorded at the end of the transport operation.

TODO

Figure 4: Sensor installation

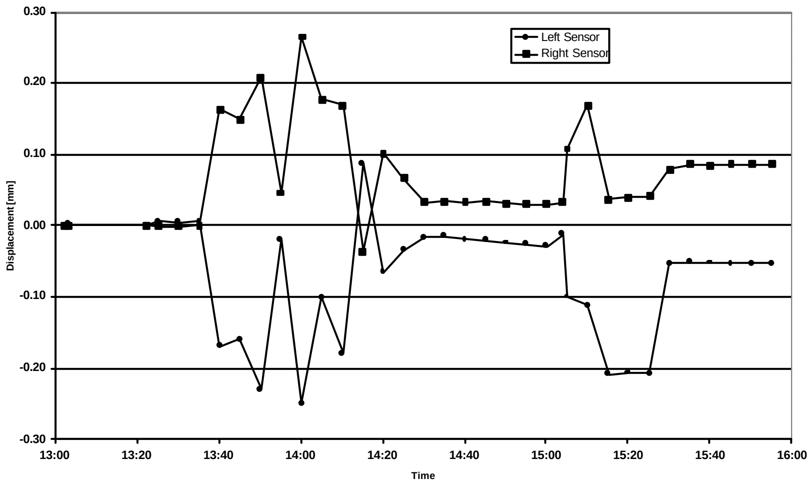

Figure 5: Measurements during dipole transport.

6. CONCLUSIONS

The presented sensor extends the use of the SOFO system, which is usually used to measure elongations in structures using an imbedded fiber. For the measurement of the internal displacements of the CERN-LHC cryodipoles the fiber was replaced by a direct path in air and a bulk optical setup. The use of a double-pass optical setup allow the measurement even in the presence of significant rotations of the target mirror.
The sensor was successfully tested n conditions similar to the ones that will be encountered in the real experiment and in particular vacuum and cryogenic temperatures for the target mirror.
The first two sensors systems have been installed in a prototype cryodipole and have measured the displacements of the cold-mass during transportation.

ACKNOWLEDGEMENTS

The Authors are indebted to Marzio Rossi, Raymond Délez and Gianluca Ballerini for helping in the design and construction of the optical heads.

REFERENCES

[1] http://lhc.web.cern.ch/lhc/

[2] “Field testing and application of fiber optic displacement sensors in civil structures” D. Inaudi, 12th International conference on OFS ’97- Optical Fiber Sensors, Williamsburg, October 1997, (invited paper)

[3] D. Inaudi "Fiber Optic Sensor network for the Monitoring of Civil Engineering Structures", Ph.D. Thesis, EPFL No. 1612, Swiss Federal Institute of Technology, Lausanne, 1997

[4] L. Thévenaz et al. "Birefringence Measurement in Fibers without Polarizer", journal of Lightwave Technology, Vol. 7, No. 8, August 1989, pp 1207-1212