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

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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 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 first measurements performed on the LHC cryodipoles.

1. SELECTED MONITORING TECHNIQUE – SOFO® SYSTEM

The deformation monitoring system named SOFO (French acronym of "Surveillance d'Ouvrage par Fibres Optiques" - "Monitoring of Structures by Optical Fibers") has been developed by the Stress Analysis Laboratory of the Swiss Federal Institute of Technology (IMAC-EPFL) and by SMARTEC SA, Switzerland [1]. It is based on fibre optic technology and is capable of monitoring micrometer deformations (relative displacement between two points) over measurement bases up to a few meters. It is particularly adapted to monitor civil structures [2], but also finds application in very different domains [3].

The SOFO measurement system is based on low-coherence interferometry in single-mode optical fibres. The three main elements of the system are the reading unit, the standard fibre optic sensor and the data acquisition and management software [1]. All components as well as the functional principle of the system are represented in Figure 1.

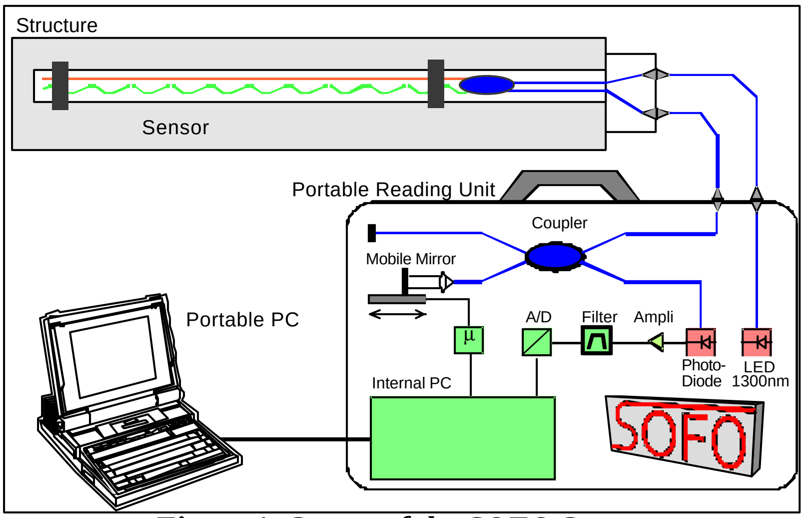


Figure 1: Set-up of the SOFO System

The SOFO reading unit is composed of a light emitting diode (LED), a low-coherence Michelson interferometer with a mobile scanning mirror, optical components and an internal PC. The sensor generally consists of two siglemode optical fibers: the measurement fiber and the reference fiber. The measurement fiber is in mechanical contact with the host structure at two points and follows its deformation (relative displacement between these two points), while the reference fiber, placed close to the measurement fiber, is loose and independent of the behavior of the structure. Any deformation of the structure will result in a change of the length difference of the two fibers.

Infrared light is emitted by the LED, sent through the siglemode optical fibre to the sensor, split by the coupler and injected into the two arms of the sensor. Then, the light reflects off the mirrors deposed on the ends of each of the fibres and returns through the coupler to the reading unit, i.e. to the compensating Michelson interferometer. The interfered light contains the information concerning the path difference between the measurement and the reference fibres. This difference is compensated using the mobile mirror and transmitted to the external PC. By successively repeating the measurements, it is possible to determinate the evolution of the deformation or displacement of the structure under observation. The Table 1 resumes the principal features of the SOFO system.

Parameter	***SOFO characteristics***
Measurement basis	20cm to 10m for Standard Sensors
Resolution	2µm
Precision	Better than 0.2% of the measured deformation
Dynamic range of the sensors	1% elongation, 0.5% shortening for Standard Sensors
Dynamic range of the reading unit	Up to 80mm in elongation and shortening
Cable length (information carrier)	Up to 5 km
Temperature sensitivity	Insensitive, self-compensated sensors
Long-term stability	Good, drift not observable over at least five years
Acquisition time	Less than 10 seconds
Automatic and remote monitoring	possible permanent, automatic and remote static monitoring
Environmental influences	Insensitive to humidity, corrosion, vibration, electro-magnetic fields

Table 1: Specifications of SOFO Measurement System

2. DISPLACEMENT SENSOR DESIGN

He use of the standard fibre optic sensor for measurement of LHC cold mass displacement is not possible, mainly due to the large longitudinal contraction of the cold mass during the cool-down (20 mm), but also due to difficult installation and to the thermal bridge it creates. Thus, a new sensor, called displacement sensor, was developed.

The extreme environmental conditions (1.9K temperature and vacuum) and the geometry have imposed several restrictions to the displacement sensor design.

2.1 Design criteria

Following design criteria are imposed to the displacement sensor:

- Since the use of the standard fibre optic sensor is not possible, 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 (called cold-mass mirror, see Figure 2). Optical fibres are used as reference path in the optical head and to bring the light in and out of the vacuum tube.
- The vacuum vessel and the thermal shield limit the only free space where the optical head can be installed, and the distance between them limits its transversal dimension to 30 mm. The optical head is thermalised to the vacuum vessel.
- The cold-mass mirror is subjected to temperatures as low as 1.9K (~ -271°C) and must survive a cool-down to 1.9K undamaged.
- The optical head, installed on the interior of the vacuum vessel is to be connected with the reading unit, which is at the exterior; hence, a special vacuum feedthrough allowing this connection must be conceived.
- All parts of the sensor as well as the feedthrough must function in vacuum without significant outgassing.
- During the cooling and operation, the cold mass is subjected to small horizontal and vertical rotations. As a result, the cold-mass mirror is subjected to tilt. A tilt can also be introduced by a poor alignment of the mirror with respect to the incoming light beam. The estimated tilt of the cold-mass mirror is less than 1mrad. The tilt influence to the measurement is restricted using double pass delay line.

- The working distance of the sensor is approximately 150 mm; such large working distance, combined with possible tilt of the cold mass mirror, can decrease significantly the intensity of the reflected beam, which is indispensable for good measurement.

All these problems are solved and presented in next subsections.

2.2 Concept of Displacement Sensor

Schematic representation and photo of the optical head without the cover as well as principle of functioning of the Displacement Sensor are presented in Figure 2.

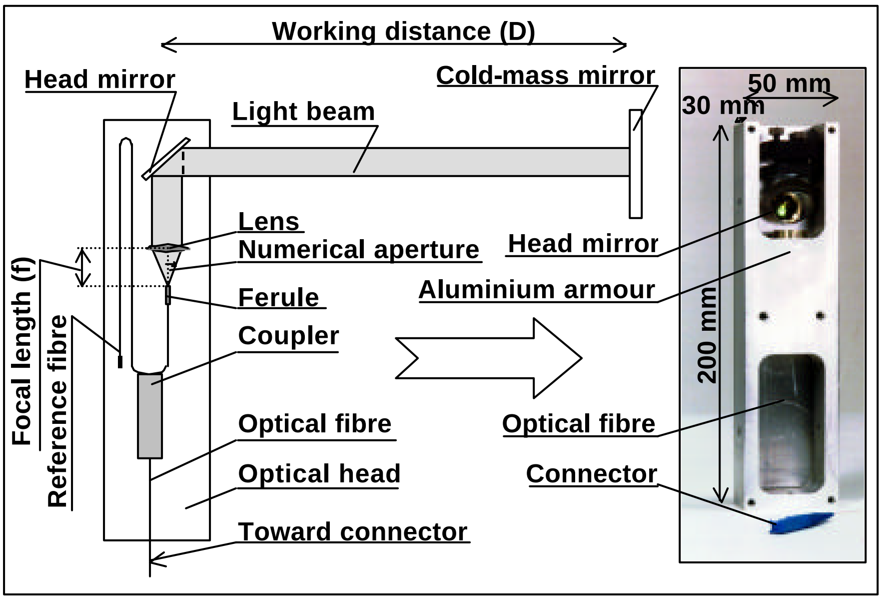


Figure 2: Schema, photo and principle of functioning of Displacement Sensor

The optical head is to be attached to the internal side of vacuum vessel. It consists of ae coupler, reference fibre, ferule, lens and the head-mirror (see schema in Figure 7.3.5). All parts of the optical head are protected by an aluminium armour. The transversal dimension of the armour is of 30 mm. The optical head, including the reference fibre, is thermalised with the vacuum vessel hence it works under almost constant room temperature. On the other hand, the cold-mass mirror has to survive at temperatures as low as 1.9K (~ -271°C). Tests showed that a high quality mirror with gold coating could survive these extreme conditions without damage. The optical path and the reference fibre have about the same optical length and constitute a Michelson interferometer. This interferometer is demodulated using the SOFO reading unit.

2.3 Concept of the feedthrough

Feedthrough is made of an FCPC connector and the corresponding mating adapter glued into an opening in the steel feed. The gluing is realised using a special vacuum-resistant resin. This resin fills up all gaps around the connector and the mating adapter. A schematic representation and a picture of the feedthrough prototype are presented in Figure 3.

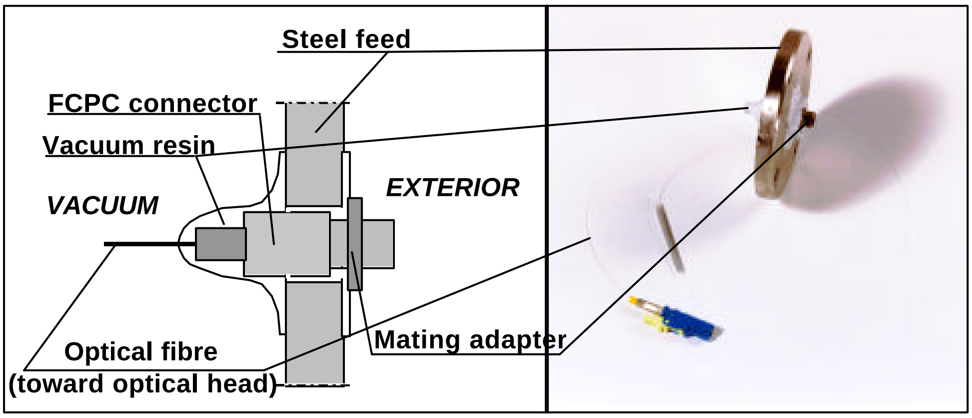


Figure 3: Schema and photo of feedthrough prototype

2.4 Functional principle - double pass delay line

The sensor functions as follows: The broadband light coming from the reading unit is split by the coupler. One path goes into the reference fibre while the second leaves the fibre trough a metallic ferrule which is collimated by the lens and pointed by the head mirror towards the cold-mass mirror. The light reflects off the cold-mass mirror, goes back to the lens and is collimated on a point on the ferrule, close to the optical fibre end, but not on it. The reflected light travels back to the cold-mass and is finally reflected and collimated back in the optical fibre. Since the fibre 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 fibre core after two passes, independently from the mirror tilt (see Figure 4).

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 [1,4]. This set-up 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.

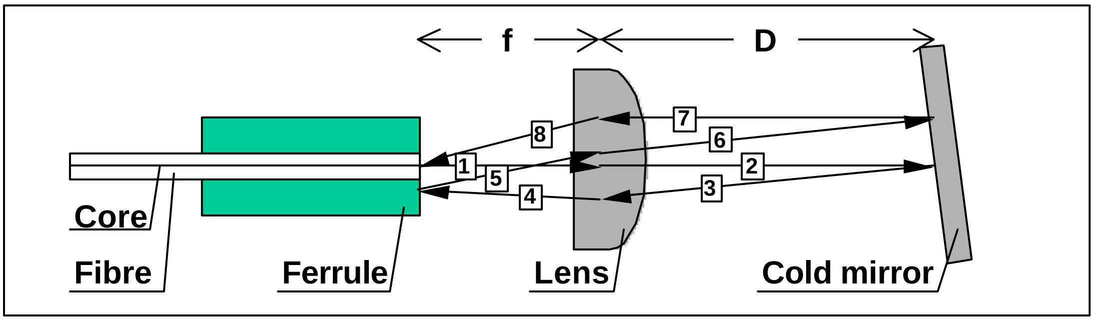


Figure 4: Double pass delay line

2.5 Laboratory tests

The following preliminary tests [3,4] were carried out in order to certify the sensor before installation in the cryodipole prototypes:

- Back coupling efficiency of the sensor
- Resistance of the cold-mass mirror in low temperature conditions

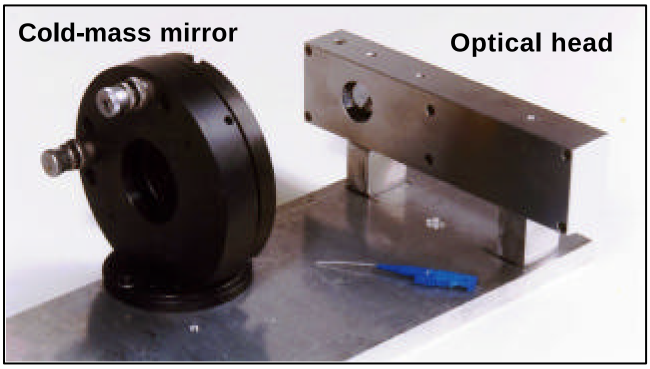
- Behaviour of the materials constituting the prototype under vacuum
- Influence of vacuum to the optical head - cold-mass mirror alignment
- Acceptable tilt range

The back coupling efficiency of the sensor represents the intensity of light that comes back into the reading unit after course through the double pass delay line. The intensity of back light depends on the distance between the optical head and the cold-mass mirror, the angle between the incoming light beam and axis perpendicular to the cold mass mirror (tilt of the mirror), the lens focal length and the numerical aperture of the fibre. The aim of this test was to examine the functional principle, and to determine the properties of the optical components of the sensor allowing good measurements for the foreseen working distance (150mm) and tilt (1 mrad).

The back coupling efficiency was tested using a set-up consisting of an optical head and a cold-mass mirror, both mounted on displacement table. The distance between the optical head and the cold mass mirror is altered and controlled using a micrometer. Results obtained using this set-up are compared with theoretical results presented in Figure 7. The ferule with numerical aperture of 0.25 and the lens with a focal length of 25.4 mm allow sufficient back coupling efficiency at the working distance. The dimensions of the optical head are 30x50x200 mm. The dimensions of the cold-mass mirror are 50x50x10 mm.

The resistance of the cold-mass mirror in low temperature conditions is tested at three different temperatures, at 75K using liquid nitrogen, at 20K using a cryostat and at 4.2K using liquid helium. The first two tests are carried out at IMAC and the third one at CERN. After all three tests there was no noticeable change when compared to a reference gold-coated mirror.

The behaviour under vacuum of the materials constituting the prototype is tested at IMAC using a small vacuum chamber. The set-up consisting of the optical head, the cold-mass mirror and the feedthrough is placed into the vacuum chamber. The set-up and the vacuum chamber are shown in Figure 5.



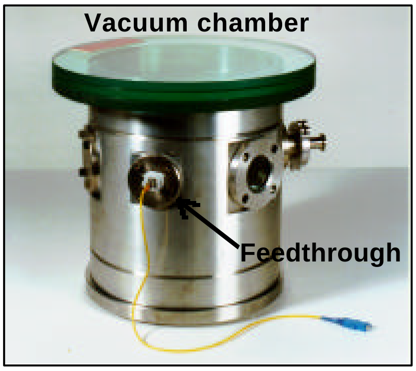


Figure 5: Optical head and cold-mass mirror placed in vacuum chamber, and chamber it-self with installed feedthrough

Two phenomena are tested, the outgassing of all components and the leaking of the feedthrough. Firstly, only the optical head and the cold-mass mirror are placed into the vacuum chamber, and vacuum is established. Afterwards, the feedthrough is installed and the experience is repeated. No outgassing was observed during the first test. The pumping set-up did take approximately the same time to reach the final pressure ($2\cdot 10^{-6}$) in the vacuum chamber as for the empty chamber. Results of both tests are presented in Figure 6.

During the second test a small outgassing is observed: in Figure 6 a longer stagnation at a $1\cdot 10^{-5}$ mbar pressure is noticed. The ultimate pressure is reached in 550 minutes instead of 300 minutes. This outgassing is small enough to be neglected in the LHC conditions (15 m long vessel). Moreover, the feedthrough does not leak since the pressure continues to decrease when the released gas is pumped out.

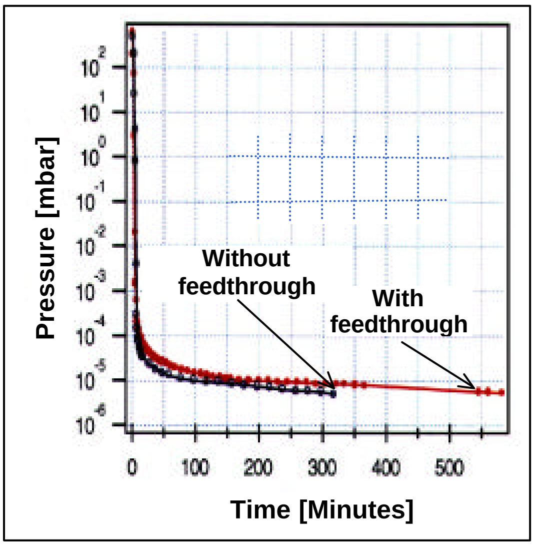


Figure 6: Vacuum tests of the prototype and the feedthrough

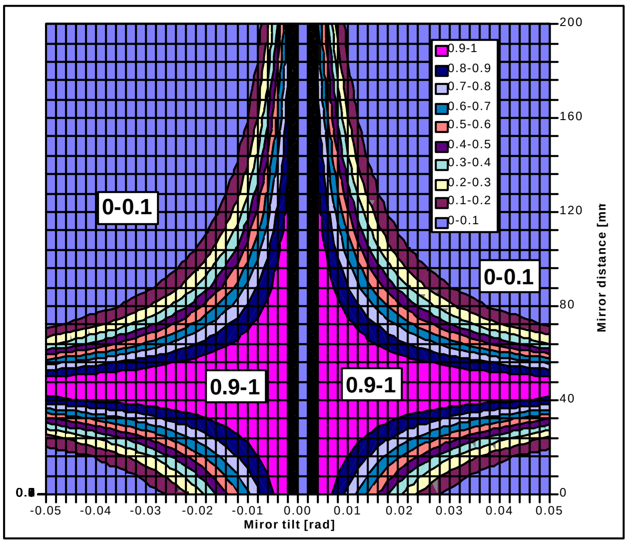
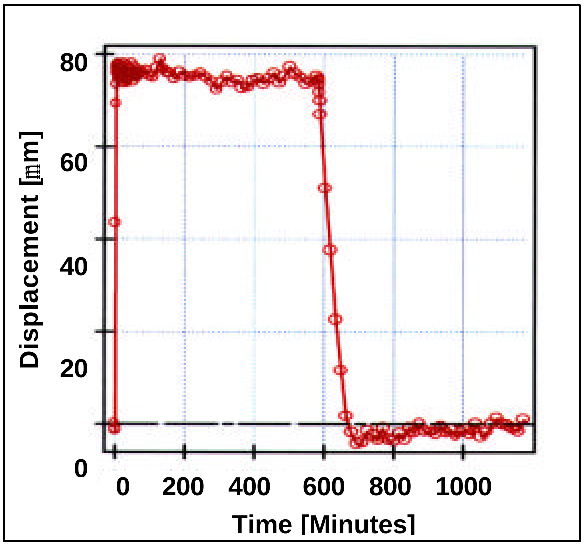


Figure 7: Theoretical back coupling efficiency of the sensor

The influence of vacuum to the optical head - cold-mass mirror alignment is tested using the same set-up as in previous test. The cold-mass mirror was aligned at atmospheric pressure and fixed at working distance of approximately 140 mm. The pressure is firstly decreased by pumping until the pressure of $5.4\cdot 10^{-5}$ mbar is reached, and afterwards increased to the initial (atmospheric) pressure. Measurements are repeated during both phases of the test, and results with respect to time and to pressure are presented in Figures 8 and 9 respectively.



Figures 8: Displacement Sensor measurements with respect to time

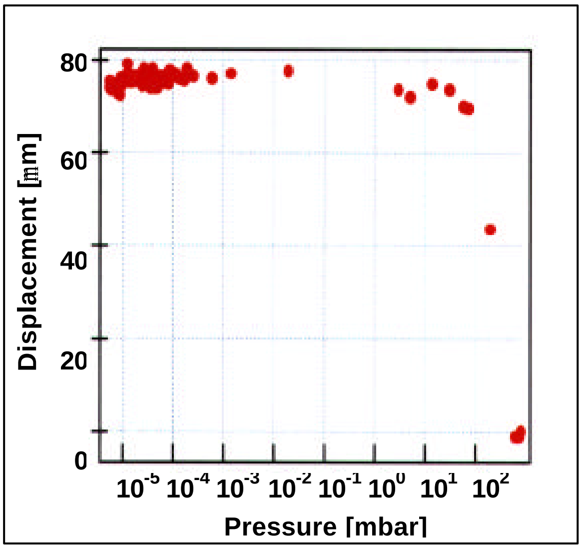


Figure 9: Displacement Sensor measurements with respect to pressure

A change of approximately 80µm is noticed when the pressure is changed. The origin of this difference is the change of the speed of light between air and vacuum. This change will not influence the measurements because it is easily corrected using an appropriate coefficient in the reading unit. On the other hand, there was no loses of the optical signal, the measured value was stable during the periods of stable pressure and when the atmospheric pressure is re-established the measurement went back to zero. Therefore, the optical alignment is not influenced by vacuum.

The acceptable tilt range 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 magnetic 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 exceeds a certain value, the back-coupling efficiency might become insufficient to carry out a measurement.

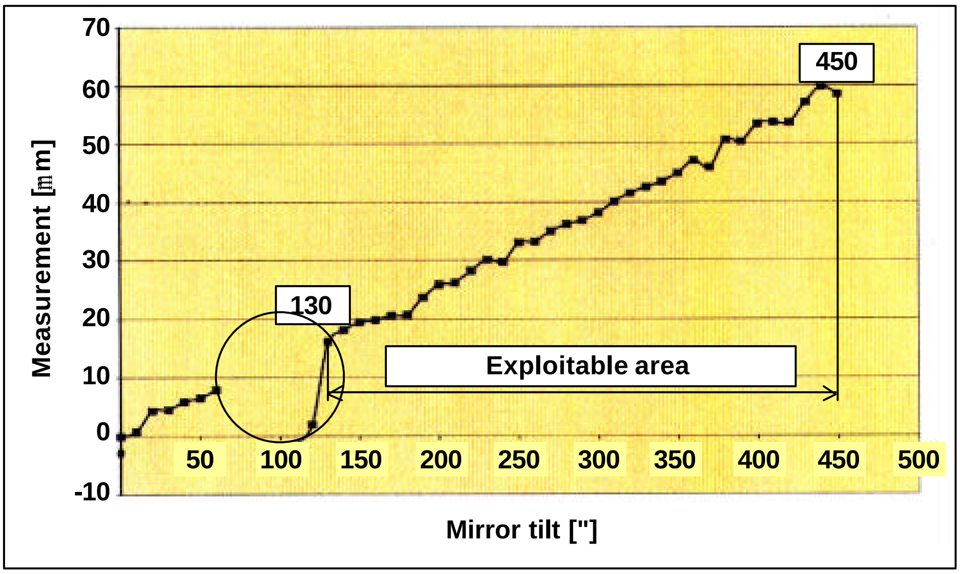


Figure 10: Vertical tilt measurements

The set-up used for this test is similar to the that shown in Figure 7.5.5. The cold-mass mirror is attached to the support which horizontal and vertical tilt is controllable and measurable. The tilt is imposed to the mirror and measurements are carried out with the optical head. Results for horizontal tilt are shown in Figure 10.

In both figures the correlation tilt - measurement is linear. This is caused by eccentricity between the light beam and axis of rotation of the mirror. Since the aim of the test is to determine the tilt range which allows return of the light to the optical head, this eccentricity is not of importance.

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 fibre cladding 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, indicated in Figure 10, cover a range of 230" (1.12 mrad) for horizontal and 320" (1.55 mrad) for vertical tilt. These values are higher than the maximal tilt that can be tolerated in the cryodipole. The sensors should therefore cover the whole utilisation spectrum without the need of realignments.

7.7 REFERENCES

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