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High accuracy continuous position determination of large accelerator components

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Abstract
We propose a new solution to continuously determine the position of large accelerator components within a 0.03 mm accuracy. These components are magnet assemblies having a length of approximately twelve meters, a diameter of one meter and a weight of up to 18 tons and are situated around the experiments. The solution consists in a combination of wire positioning sensors performing vertical and radial offset measurements, with respect to a stretched wire considered as a straight reference of alignment, and hydrostatic levelling sensors performing vertical offset measurements with respect to a water surface. Both types of sensors are based on a capacitive technology, allowing non-contact measurement with a sub-micrometric resolution. The configuration of alignment sensors and the implementation of the associated measurement networks are introduced, before detailing the concept of position determination and the associated results obtained.

Large scale metrology, position determination, capacitive sensors

1. Introduction

CERN, the European Laboratory for Particle Physics, is the world's largest laboratory to perform research in fundamental physics. It provides a unique range of particle accelerator facilities. The Large Hadron Collider (LHC) is its flagship, with a circumference of almost 27 km. The LHC particle accelerator has four interaction regions situated around the experimental areas of the detectors ATLAS, ALICE, CMS and LHCb. The low beta quadrupoles located in this area are of particular interest for physics as they squeeze the beams, with their set of focussing and defocussing magnets, to a beam diameter of 16 µm, and they bring them into collision in the experiments.

The low beta quadrupoles can be approximated to cylinders with a length of twelve meters, a diameter of one meter and a weight of up to 18 tons. These high performance superconducting quadrupoles are an assembly of the external vacuum vessel, called cryostat, in which are supported one or two cold masses. These magnets provide a field gradient of 240 T/m at 1.9 K along the integrated beam pipe in which circulate the particle beams. The alignment tolerances for this set of three quadrupole magnets, also called triplet, are tighter compared to the rest of the LHC and thus their position needs to be followed continuously.

Stretched wires, hydrostatic levelling systems and their associated sensors, are used to continuously determine the position between the low beta quadrupoles situated on the left and the right side of the experiment, as well as provide the position information to the experiment itself.

Firstly, the strategy, methods and measurement requirements are introduced. In the next step, the sensors are presented together with the remote validation concepts that have been developed at CERN. Afterwards, the remote alignment process based on the measurements is explained together with the key results. Lastly, an outlook on the High Luminosity LHC (HL LHC) continuous position determination concept will be given.

2. Continuous position determination

For a smooth operation of the LHC, the continuous position determination of the low beta quadrupoles is required. A specific configuration of alignment sensors has been put in place to allow the real-time analysis of movements in six degrees of freedom. The continuous position determination is required to provide a relative position of the set of three low beta quadrupole cryostats that is better than 10 µm, and to provide around the experiment, from the left to the right side, a position that is better than 150 µm [1]. As it is not possible to access the cold mass and the beam pipe once the quadrupoles are installed, it is the position of the cryostat that is monitored. More particularly, reference points on the cryostats are determined during the manufacturing process with respect to the mechanical aperture of the beam pipe and the magnetic axis of the magnet. These reference points are later equipped with alignment sensors and their sensor supports designed for this dedicated position.

This specific zone of the low beta quadrupoles in the LHC tunnel, covered by the continuous position determination system, has a length of approximately 40 m along each side of the experiment and extends to a total length of 140 m, without having a direct line of sight in between the two sides. The harsh radiation environment in this area of the accelerator required the design of robust systems and sensors in order to minimize interventions for maintenance on the equipment and thus limit exposure of personnel to radiation. Based on this constraint, the sensors were designed with remote electronics and tested in a thorough process for their radiation tolerance [2, 3].

2.1. Alignment systems configuration

The alignment system installed for radial and vertical measurements is the Wire Positioning System (WPS), based on stretched wires that form the straight reference along each set of low beta quadrupoles, in order to provide the relative position of the cryostats independently for each side.

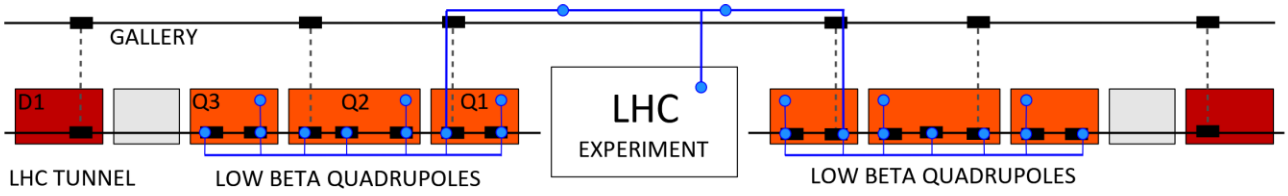

Figure 1. Layout of the LHC continuous position determination system with the hydraulic network and HLS (blue), the WPS with stretched wires and sensors (black) and the wire to wire measurement system (grey, dashed line).

A third wire is stretched in a parallel gallery to the magnets and is crossing the experimental cavern. The layout configuration is shown in figure 1. In addition, the geometry of one triplet, with respect to the other triplet, is determined by having three distance measurements between the two wires on each side, called wire to wire measurement. This measurement is carried out as a combination of mechanical measurements using invar rods installed in three boreholes linking the LHC tunnel to a parallel gallery that is connected to the experimental cavern together with the WPS sensor measurements [4].

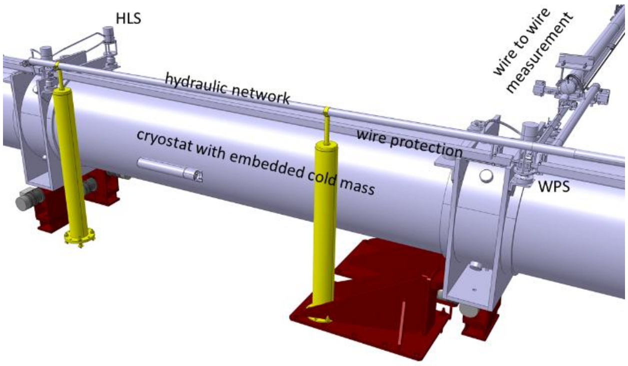

Figure 2. Layout of the LHC continuous position determination system configuration on one cryostat

Two WPS sensors are installed on the reference points of each cryostat, as presented in figure 2, providing information on four degrees of freedom of the cryostat: pitch and yaw rotations as well as vertical and radial translation. As a second measurement system, Hydrostatic Levelling Sensors (HLS) provide redundant measurements determining the vertical translation plus the pitch and the roll of the cryostats [5, 6]. The height reference is propagated by an equipotential water surface to which the sensors are carrying out vertical offset measurements. This system is, similarly to the WPS system, operated on both sides of the experiment and linked through the experimental cavern.

To evaluate WPS measurements in the vertical direction, the wire sag has to be taken into account [4]. The wire shape is calculated using the parabola as expressed in the equation hereafter and illustrated in figure 3,

$$f(x) = y_0 + \frac{4f}{l^2}(x - x_0) + \frac{h - 4f}{l(x - x_0)}$$

where wire sag at a given position x is f(x). The horizontal distance l and the vertical distance h are the offset from the reference coordinates X_0 and Y_0 at one extremity.

The height observations from the HLS are introduced as a reference in the compensation model to determine the observed sag f which is defined as the maximum difference between the straight connection line d between the wire extremities and the wire. The sag f is defined according to the following equation.

$$f = \frac{g \cdot q \cdot l^2}{8T}$$

The parameters used are the local gravity g, the linear mass of the wire q, the horizontal distance of the wire l and then tensile force T applied to stretch the wire.

The third position determination system implemented monitors continuously the longitudinal position. The distance offset measurement sensors (DOMS) carry out relative distance measurements to the cryostat with respect to their fixation on the floor. This system is used to follow the relative position evolution of the cryostats during vacuum cycles, machine cool down and operation.

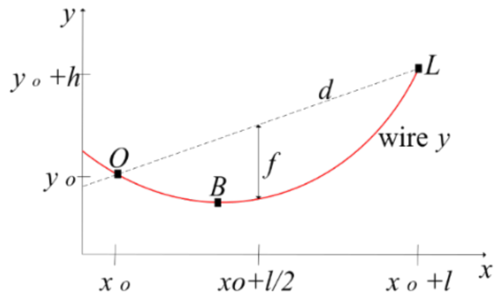

Figure 3. Parameters of the wire sag model

2.2. Sensors

The sensors have mandatory remote electronics that are located separately with respect to the sensor at a distance of maximum 30 m. They were thus qualified as an inseparable set of sensor, cable and electronics, to provide the desired resolution of 10^{-7} m, together with the required radiation hardness and magnetic field tolerance [2, 3]. The measurement range of the sensors is typically of 10 mm.

There is a total number of 229 sensors installed for the triplet continuous position determination in the LHC. The operating principle of all sensors is based on capacitive measurements whereas the sensor's electrode forms a capacitor together with the reference surface of the object to be measured. In the case of the WPS sensors, the stretched wire is the counterpart, in the same way as it is the water surface for the HLS, and a metallic surface is used for the DOMS [7].

The sensor functionalities have been enhanced by CERN compared to the relative calibration of the manufacturer. For all types of sensors, an absolute calibration concept has been developed, allowing the calibration of the sensors on automated benches to be better than 10 µm [7, 8]. The voltage signal output of the sensor is translated in metric measurement results by using polynomial functions up to order six. In the case of WPS sensors, where no reliable reference surface was identified, isostatic interfaces were introduced [8].

The sensors are installed on the external reference points of the cryostat using a common support, as presented in figure 4. This support is also thoroughly calibrated as it is part of the measurement chain allowing the position determination of the cryostat. For the determination of the sensor support parameters, portable coordinate measuring arms or laser trackers are used.

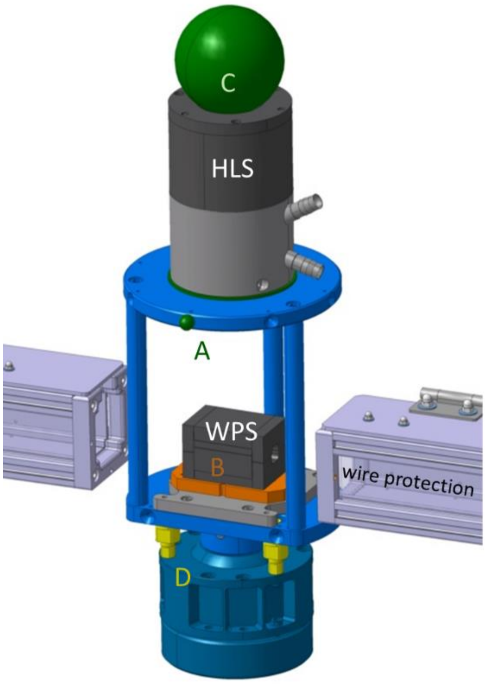

Figure 4. Alignment sensors support with HLS, WPS and the key features: additional fiducials (A), isostatic interface plate (B), HLS reference surface (C) and position locking (D)

2.3. Remote Alignment

The continuous position determination is completed by a remote alignment approach, using stepper motors with a resolution of better than 2 µm and load sensors to follow the load evolution of the cryostat, in combination with the position determination sensors. In accordance with each sensor support position, the motorized jacks are installed under the magnet assemblies. The motors displace loads of up to 9 t per jack and a designated position better than 10 µm can be achieved [10].

3. Operational tool for beam physics

The system was initially designed to be used for a remote positioning of the cryostats when no particle beam is circulating in the LHC. Correspondingly, alignment outside maintenance periods is only foreseen in the exceptional case that the use of beam orbit corrector magnets has limited effect on the modification of the particle beam trajectory.

Nevertheless, the beam operation team at the CERN control centre has a permanent display of the WPS sensor readings relative to the position at the beginning of the yearly LHC operation. The information is used to trigger a software-based beam injection interlock, meaning that no particle beam can be transferred to the LHC, in the event that any sensor is more than 250 µm away from its reference position. The aim is to avoid injecting a probe beam accidentially into cold masses or experiments during beam commissioning. As the yearly relative movements of the cryostats are in general less than 150 µm, this safety mechanism never got triggered during LHC operation.

However, spontaneous position changes of more than 400 µm are observed when the internal cryostat pressure or temperature varies, for example in the case of a beam quench. This observation is illustrated in figure 5, with the pressure reading inside the cryostat and the radial WPS sensor reading showing a strong correlation. In the twelve years of LHC operation, it has been observed that these events can create permanent position changes of maximum 100 µm after returning to the initial state.

Figure 5. Correlation between cryostat pressure and radial WPS position

In October 2016, the triplet on the right side of the CMS experiment observed radial movements of 200 µm that resulted in a reduced number of particle collisions in the particle detector. The remote alignment was carried out successfully with a probe beam at 450 GeV, bringing back the cryostats to the initial position. This remote alignment with beams was a world premiere, using continuous position determination and remote alignment systems, for a machine repositioning with circulating beams. In figure 6, the screenshot of the CERN control centre display shows the misalignment of the triplet, the movement of the cryostats observed, as well as the realignment to the nominal position.

This demonstration of the working principle strengthened the concept of the continuous position determination concept for HL-LHC and smoothened the way to consider a full remote alignment system.

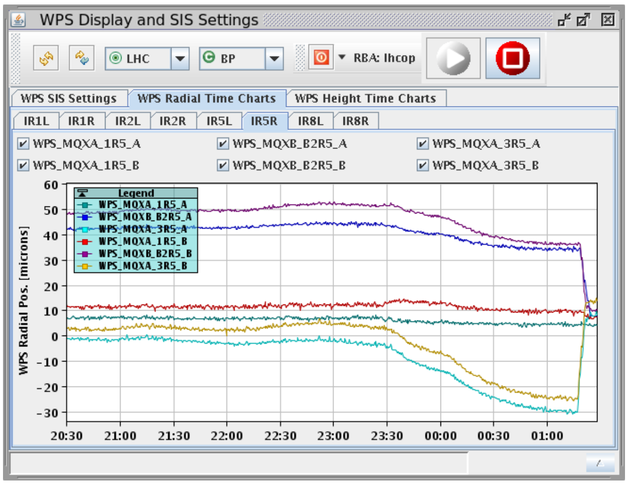

Figure 6. Remote alignment of the low-beta triplet with probe beam

4. System consolidation

The continuous position determination system was initially designed as a relative measurement system [1]. The use of the system and the according adjustments have been made during the concept and installation phase for the sensors and the systems.

For the HL-LHC era, the accelerator sections around ATLAS and CMS will be further developed. The machine configuration for the triplets around ALICE and LHCb will remain the same. Thus, a consolidation program was established for the LHC maintenance shutdown in the period from 2018 to 2021. This consolidation work reflects the experience gained in the last fifteen years on the continuous position determination sensors, their mechanical interfaces and the mechanical robustness of the systems in the LHC environment.

The new type of sensor support, as seen in figure 4, is composed with the key features of seven additional reference points, A, that allow the establishment of a local coordinate system for the sensor support, using retroreflector balls and laser tracker measurements. These reference points allow the definition of the WPS sensors' isostatic interface's position, B, and the mechanical interface of the HLS sensors, C. The reference points can also be used to determine any deterioration of the position with respect to the cryostat. The new supports have a supporting system, which mechanically limits the possible displacement of the support due to external forces, D. In addition, the sensor calibration is split into mechanical constants, e.g. to the external interface, and a sensor reading calibration function as a new calibration approach for the sensors can be deployed using mobile calibration benches in the LHC tunnel.

The combined measurement results for the position determination and the geodetic compensation models are discussed in the following paragraphs. The a priori accuracy at one sigma for a measurement is considered to be of 30 µm in the referential frame of the cryostat. This value is composed of the sensor calibration contribution known to 10 µm by using the calibration methods developed at CERN, the laser tracker measurements for the mechanical determination of the supports and the chosen geodetic referential system.

The evaluation of one network shows an a posteriori accuracy for the vertical positions of 31 µm as a combination from the HLS and WPS measurements. The hydrostatic levelling system linking from one side to the other side of the experiment is composed of several networks. The complete network analysis results in an accuracy, for the point transfer from the left side triplet to the right side triplet, of 40 µm.

The radial measurement network, based on the wire measurements, is configured without any redundancy. Thus, the same determination accuracy as for the vertical measurement is assumed along one triplet. The evaluation of the wire sag, based on the equations presented in section 2.1, allows the calculation of the wire's shape to an accuracy of 30 µm with an uncertainty of 49 µm.

In the case of the ATLAS and CMS experiments, the radial link between the two triplets is established with the additional wire to wire measurements and the long reference wire running through the cavern, as illustrated in figure 1. The radial position around the experiment is determined with an accuracy of 55 µm.

The laser tracker measurements for a single point determination on a cryostat have been achieved with an accuracy of 20 µm, combining through a bundle adjustment to a network accuracy for the laser tracker network of 50 µm for one triplet.

5. Future applications

The HL LHC installation, foreseen from 2025 onwards, will require an extension of the continuous position determination network from 40 m on each side of the experiment to 250 m. To achieve the required alignment of 500 µm along the 500 m of accelerator, internal monitoring of the cold masses will be introduced, as well as extensive improvements in the design of the HL LHC sensor supports, their calibration and validation methods for the sensors and systems [11-13]. The internal cold mass monitoring system will be based on frequency scanning interferometry [14].

A full remote alignment system will be included to continuously determine and remotely align the position of the main, as well as of the intermediate accelerator components, along this beam line [15]. This concept will become a fundamental operational tool for HL LHC as it will allow the remote alignment of these accelerator sections in order to take into account indentified offsets between the experiment and the accelerator alignment, and compensate for unforeseen movements of the tunnel.

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