HL-LHC ALIGNMENT REQUIREMENTS AND ASSOCIATED SOLUTIONS

H. Mainaud Durand, S. Bartolome Jimenez, T. Dijoud, M. Duquenne[1], A. Herty, K. Kucel, V. Rude[1], M. Sosin, CERN, Geneva, Switzerland
[1]also at ESGT-CNAM, Le Mans, France

Abstract

To increase by more than 10 times the luminosity reach w.r.t. the first 10 years of the LHC exploitation, the HL-LHC project will replace nearly 1.2 km of the accelerator during the Long Shutdown 3 scheduled in 2024 [1][2][3]. This paper presents the HL-LHC alignment and internal metrology requirements of all the new components to be installed: magnets, beam instrumentation and vacuum devices, RF cavities and more. As for the LHC, a combination of Hydrostatic Levelling Sensors (HLS) and Wire Positioning Sensors (WPS) is proposed for the alignment of the main components, but they will be deployed on a longer distance (210 m instead of 50 m), generating technical challenges for the installation of the stretched wire and for the maintenance of the alignment systems [4]. Innovative measurement methods and instrumentation are under study to perform the position monitoring inside a cryostat of cold masses and crab cavities, in a cold (2 K) and radioactive (0.1-1 MGy/year) environment, as well as to carry out remote measurements in the tunnel of the intermediary components. The proposed solutions concerning the determination of the position and the re-adjustment of the components are detailed in this paper.

INTRODUCTION

In the LHC, ad-hoc methods and tools have been developed and implemented to perform the metrology and alignment of the components in the Long Straight Sections (LSS). Micrometric measurement systems have been put in place to monitor the position of the Inner Triplet (IT) cryostats. It consists of WPS and HLS sensors, coupled with motorized jacks to adjust remotely the cryostat when needed. These alignment systems are combined with standard methods of measurement (levelling in vertical plus offsets to a wire in radial) for the remaining components of the LSS [4].

New solutions of alignment and new configurations of alignment systems are proposed for the HL-LHC project, to answer beam dynamics requirements. They also take into account the lessons learnt in the LHC and integrate the environmental conditions that will be more stringent.

This paper first reminds the solutions chosen for the LHC with the associated results and lessons learnt. Then it states the requirements for the HL-LHC project, before presenting the solutions retained and the status of the associated R&D studies.

LHC REQUIREMENTS AND SOLUTIONS

Actual LHC Requirements

In the LHC, the requirements of alignment refer to the position of the external alignment targets (fiducials) installed on the magnets cryostats and other accelerator components. The position of these targets, w.r.t. mechanical axis of the cold mass, was determined during the fiducialisation process at room temperature at CERN. A measurement uncertainty of the order of ±0.1 mm was achieved [5]. The magnets were then transferred in the tunnel to be pre-aligned w.r.t. the geodetic network within ±0.3 mm. Once the magnets were interconnected and cooled down below 80 K, their smoothing took place within an accuracy of ±0.15 mm over 110 m [6]. Since then, the smoothing of the main LSS components takes place every year, during the end year technical stop, fulfilling the same requirements.

The alignment of the intermediary components (beam instrumentation and vacuum modules) is carried out using the adjacent quadrupoles as reference of alignment.

The requirements concerning the Inner Triplet (IT) located on each side of the four experimental areas are specific [7]. The positioning errors of the IT fiducials from left to right side of Interaction Point (IP) are ±0.2 mm (1σ) in radial and ±0.1 mm (1σ) in vertical. The position error of the fiducials inside each IT is of the order of ±3 μm plus a drift of 1 μm per month, according to 5 degrees of freedom (radial and vertical translations, plus the 3 rotations).

Chosen Solutions

Standard alignment is achieved by performing levelling measurements in vertical and offsets w.r.t. a stretched wire in radial. Both solutions fulfil the requirements.

The remote determination of the position of IT is performed using a combination of 2 WPS and 3 HLS per cryostat (plus one additional HLS sensor to monitor the sag of Q2 with a longer cryostat), as shown in Figure 1 [4].

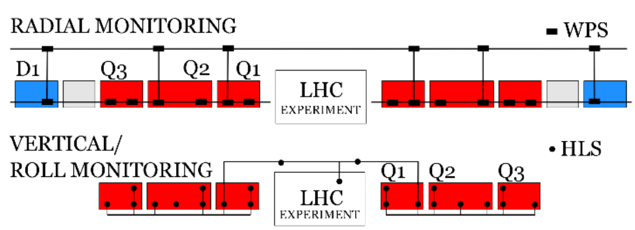

Figure 1: Configuration of LHC alignment systems

The remote adjustment of the IT cryostats is carried out by motorized jacks with a resolution of displacement for both radial and vertical axes below 10 μm [4].

Lessons Learned

WPS readings data are analysed by the machine operation team in the CERN Control Center, including well-defined references for all WPS sensors. Based on this

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estimate, non-negligible movements can be tackled in two ways:

- A remote re-alignment using WPS readings and motorized jacks. The first remote alignment of IT cryostats was achieved successfully in October 2016 with beam.
- A magnetic correction.

It has also been observed that WPS readings do not correlate very well with the cold mass position. As a matter of fact, WPS sensors are located on top of the cryostat, and the link between the cryostat and cold mass is not known precisely enough. Therefore in future an inner monitoring of the cold mass position w.r.t. the cryostat would be really useful.

Using the WPS and HLS readings, the alignment of the IT cryostats can be observed accurately during vacuum and cooling-down phases. Important misalignments have been observed due to mechanical loads originated by pressure changes during the cooling-down. The possibility to perform remote adjustment once the cooling-down is carried out and when no access in the area is possible (for safety reasons, the access to IT is only possible when there is no liquid helium inside) is really a plus [8].

The position of the quadrupoles cryostats inside the IT is known very accurately using the alignment systems, but the position of the IT quadrupoles w.r.t. other components of the Matching Section (MS) was not determined with sufficient accuracy, especially in radial. The wire offset measurements, that need to be carried out between the IT and the MS components, could not achieve the requested accuracy for two reasons: firstly there is no possibility to protect the stretched wire from air current in such an area; secondly, it is very difficult to access to the standard fiducials of the IT cryostat, hidden by the alignment systems networks (wire protection and hydraulic network).

Considering the high radiation environment, a major improvement has been implemented in the LHC on the alignment systems: their remote validation to guarantee the readings of sensors [9].

HL-LHC REQUIREMENTS AND ENVIRONMENTAL CONDITIONS

HL-LHC Requirements

The deviation of the orbit from the reference orbit has been estimated to specify the orbit corrector strength, and more particularly the deviation of the mechanical axis of magnets from a straight line [10]. The quadrupoles from Q1 to Q5 were considered in this analysis. The quadratic sum of the independent contributions includes:

- The fiducialisation error, e.g. the determination of the mechanical axis of the quadrupoles w.r.t. their external fiducials: ±0.1 mm.
- The error of smoothing of the quadrupoles. This error can be divided into 2 parts: the mechanical axis of each quadrupole included in a cylinder with a radius of 0.1 mm as shown in Figure 2, and the left to right axis included in a cylinder with a radius of 0.15 mm, Figure 2.
- The misalignment between alignment campaigns taking place every year during the Year End Technical Stop, integrating ground motion and mechanical stresses encountered during the vacuum and cool-down phases, of the order of ± 0.17 mm per year.

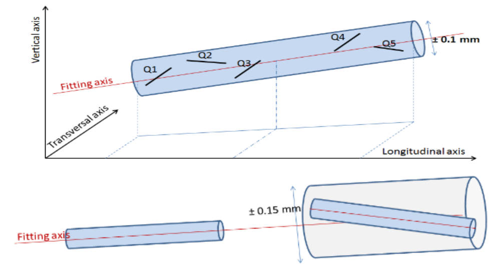

Figure 2 (top): Smoothing errors of quadrupoles from Q1 to Q5, (bottom): left to right error of IT misalignment.

The estimated deviation is ±0.27 mm and the value of ±0.5 mm for the transverse misalignment of the quadrupoles from Q1 to Q5 was considered as worst case scenario, leading to a quite large contribution to the overall corrector strength budget of the MCBXF correctors [10].

Ground Motions and Access Restrictions

A very high level of radiations will complicate the access to the components, with residual doses estimations after 1 week of machine cool-down ranging from 50 μSv/h to 2500 μSv/h for the MS components [11].

Yearly vertical measurements in the ATLAS and CMS caverns and in the tunnel area provide a mapping of the ground motion and allow performing a realistic extrapolation to HL-LHC. Concerning ATLAS, maximum displacements of +0.25 mm/year have been observed near the center of the cavern floor. Same maximum displacements have been recorded between the cavern and the tunnel up to 100 m on each side of the Interaction Point (IP). No particular displacements are detected on the components installed 100 m after IP1. Concerning CMS, the most important displacements (4 mm over 10 years) are seen at the level of the new caverns excavated specifically for the LHC, located between 80 m and 130 m on both sides of IP5 [12].

During Long Shutdown 2 foreseen in 2019-2020, a new gallery will be excavated approximately 10 m above the LHC tunnel in order to install the new equipment associated with the HL-LHC LSS. Some important ground motions could result from such civil engineering works and simulations are being performed. This will mainly concern D2 and Q4 components in the LHC during Run 3, as well as 3 major components of the HL-LHC project after Long Shutdown 3: D2, crab cavities and Q4.

HL-LHC ALIGNMENT SOLUTIONS

Main Components from Q1 to Q5

Alignment sensors will be installed on all major components of the LSS between Q1 and Q5, including the Corrector Package, the Target Absorber Neutral (TAXN) and the crab cavities' cryostats. Remote adjustment systems will support these major components to allow a fine remote tuning of the position of components once the cooling-down has been carried out. The same configuration, as for the present LHC, is proposed: 2 WPS and 3 HLS per cryostat, on a longer distance (210 m instead of 50 m). The longitudinal position of each cryostat w.r.t. the tunnel ground floor will be monitored using a capacitive sensor.

In order to have a better knowledge of the position of the cold mass inside its cryostat, the IT cold mass position will be monitored using Frequency Scanning Interferometry (FSI) [13]. Such a system performs absolute distance measurements within a micrometric uncertainty of measurement between a collimating optics and a target in a harsh environment. The vacuum compatible optics is planned to be installed on the cryostat and oriented towards the cold mass where the targets are installed. Specially developed optics and reflective targets have undergone with success specific irradiation and cooling-down tests [14]. The configuration of distance measurements is under study; it will consist of redundant lines of sight as foreseen for the monitoring of the crab cavities inside their cryostat [15].

Optimization studies are under way in order to:

- Carry out remotely the stretching of the alignment wire considering the high level of radiations.
- Increase the reliability of the electronics and hardware (cables, connectors, data acquisition) of the capacitive sensors, to get the possibility to perform remote diagnostics.
- Identify an alternative solution of HLS based on the Fabry-Perrot technology. This option would extend the maximum length between a sensor and its electronics to kilometres, while for the present capacitive technology this length is a limiting factor (in the order of a few tens of meters) [16].
- Replace the HLS sensors, used to determine the roll, by radiation hard inclinometers.
- Develop a direct connection between deep references and the HLS network. The deep references are 20-30 m vertical invar rods anchored to the stable rock, with a levelling interface on top, used as long term reference for the levelling in the tunnel.

Connecting the Machine Tunnel on the Two Sides of a HL-LHC Experimental Cavern

The vertical determination carried out using HLS sensors located in the caverns fulfils the requirements and will be kept for the HL-LHC project. The radial determination, currently based on invar rods and capacitive sensors (see Figure 1), will be replaced by a more accurate and simple solution using FSI. The collimator part will be associated to the WPS located in the survey galleries, to measure the distance to a Corner Cube Reflector installed on the tunnel WPS. As both wires and WPS sensors are located in different air pressure areas, a viewport will be installed at the end of the galleries boreholes. Tests of correction of the FSI measurements through such a viewport are under way.

Case of the Intermediary Components

The intermediary components are shielding masks, coupled to the quadrupoles Q4 and Q5, collimators located between D2 and Q4, external BPMs close to D1 and D2, and vacuum modules. Some realignment of the intermediary components will be needed during the life of HL-LHC, when the levels of remnant dose will be high. It will be therefore important to be able to measure the position of these intermediary components w.r.t. the adjacent quadrupoles as remotely as possible.

Three solutions are under investigation:

- The use of WPS sensors for some of these components (collimators, external BPMs and masks), measuring w.r.t. the wire stretched between Q1 and Q5.
- The adaptation of the train developed for the remote measurement of the collimators of point 7, combining offset measurements to a stretched wire and photogrammetry measurements w.r.t. permanent targets equipping the intermediary components and the adjacent quadrupoles [17].
- The development of a new method based on micro-triangulation and FSI, using a stretched wire to limit the propagation error in the tunnel [18].

After having performed the measurements, the capability to perform a "fast" readjustment will be needed. The "fast" adjustment solution for such components is based on a support developed previously for the CLIC quadrupoles: a Stewart-type platform, allowing the micrometric adjustment of 5 degrees of freedom [19]. The 5 adjustment knobs are located on the same side of the support towards the corridor where temporary motors can be plugged in less than 5 minutes, limiting the personnel activity in the area.

CONCLUSION

New solutions of alignment are proposed for the HL-LHC project, answering the tighter alignment requirements from beam dynamics and taking into consideration the lessons learnt in the LHC. The alignment systems based on HLS and WPS sensors will be installed on the main components from Q1 to Q5 and will be combined with motorized jacks to perform remote alignment. A special care will be put on the intermediary components (shielding masks, independent BPMs, vacuum devices, etc.), for which several methods to determine remotely their position are under study, associated with a "fast" adjustment solution.

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