TECHNICAL CHALLENGES FOR HL-LHC ALIGNMENT AND ASSOCIATED SOLUTIONS

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Abstract

The High Luminosity LHC (HL-LHC) is an upgrade of the LHC to achieve instantaneous luminosities, a factor five larger than the LHC nominal values. The project will involve the replacement of 1.2 km of accelerator components such as magnets, collimators and radiofrequency cavities in 2024. It relies on a number of key innovative technologies. The alignment solutions chosen to answer the requirements of the project are challenging as well. They consist of alignment systems including Wire Positioning Sensors (WPS), Hydrostatic Levelling Sensors (HLS), and Frequency Scanning interferometry (FSI) to determine the position of components, combined with motorized jacks and adjustable platforms. This paper introduces first these solutions. It then details the R&D undertaken to develop low cost alternatives of HLS and WPS sensors, to improve the measurement chain quality of the WPS sensors, to improve the installation and maintenance of the WPS system and to propose innovative solutions of adjustment. It presents the direction of studies followed and the first results achieved.

INTRODUCTION

A major upgrade of the LHC is in preparation to improve its performance and extend its reach beyond its initial mission: the High Luminosity LHC. More than 1.2 km of the current machine in the Long Straight Sections (LSS) located around both detectors ATLAS and CMS will be replaced by many high-technology components, triggering alignment challenges [1, 2, 3]. Considering alignment requirements for beam operation, the high radiation level in the tunnel and the non-negligible ground motions of a few tenths of millimetre per year between the machine and the detectors, we had to propose innovative alignment solutions. The objective is to determine the position of the accelerators' components and perform their adjustment remotely using alignment sensors and actuators within a precision and accuracy of 0.1 mm over more than 200 m in each LSS. The alignment systems should have remote diagnostics and should be designed in a way that requires low maintenance and little access in the tunnel. We also propose a continuous monitoring of the Inner Triplet (IT) cold mass and Crab Cavities inside their cryostat. Considering the number of components to be equipped, R&D was launched to develop low cost sensors and associated electronics, to propose new adjustment solutions for lighter intermediary components. The existing monitoring solutions used in the LHC are being consolidated as well as an alternative. This paper first reviews the alignment requirements for HL-LHC and presents the baseline solutions chosen. It then details the technical challenges and the associated solutions developed. The final chapter concludes on the new possibilities such developments offer in the remote alignment of accelerator components: magnet correctors used to correct ground motions can be replaced by a combination of alignment sensors and motorized solutions.

ALIGNMENT SOLUTIONS CHOSEN FOR HL-LHC

Requirements

For HL-LHC, the most challenging alignment tolerances are requested on the main quadrupoles from Q1 to Q5 along one LSS: the estimated deviation of the mechanical axis of their magnet w.r.t. a straight fitting line is ± 27 µm at 1 σ. A transverse misalignment of ± 0.5 mm at 1σ is considered as worst-case scenario [4].

Lessons learnt from LHC

The alignment requirements were similar in the LHC for the IT quadrupoles, e.g. on a smaller distance of 40 m instead of more than 200 m for HL-LHC. Alignment systems combining WPS and HLS sensors were installed on IT cryostats for the determination of their position w.r.t. five Degrees Of Freedom (DOF). Motorized jacks performed remote micrometric adjustments. Some improvements were needed [4]:

- A longer stretched wire to link the IT to the remaining components of the LSS, improving the measurement accuracy for the position of the IT w.r.t. the other components of the LSS.
- An isostatic supporting pattern for the cryostats.
- An internal monitoring of the position of the cold mass inside its cryostat at least for the IT.

The solutions proposed for HL-LHC answer these additional requirements.

Alignment solutions

Two WPS and three HLS sensors will be installed per cryostat; the stretched wire and hydraulic network will be extended from Q1 to Q5 [4]. Capacitive measurement sensors will provide the longitudinal position of each cryostat w.r.t. the ground floor.

We propose an internal monitoring of the IT cold mass position w.r.t. the cryostat based on distance measurements carried out by FSI [5].

The radial link from the left to right LSS will be established by six wire-to-wire measurement systems

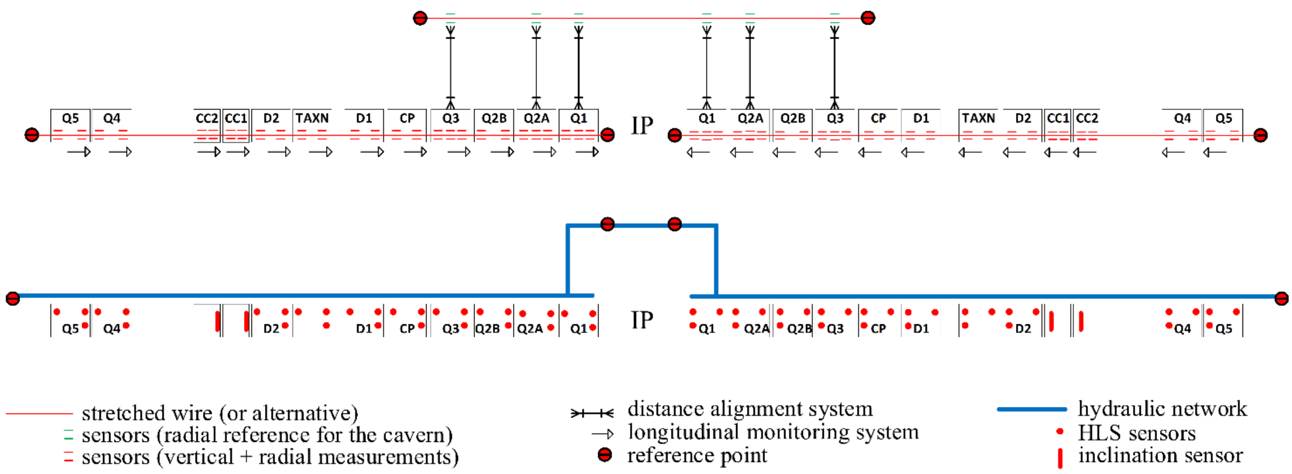

Figure 1: General layout of WPS and HLS sensors configuration

between UPS galleries and both sides of the tunnel based on FSI distances (see Fig. 1).

WPS sensors installed in the UPS galleries provide a machine reference for the cavern, as well as the HLS installed in the experimental cavern.

Technical challenges and innovations

As mentioned, capacitive WPS and HLS sensors are installed in the LHC to determine remotely the position of the cryostats. Two directions of studies have been undertaken on these sensors:

- The consolidation of the capacitive WPS (cWPS) sensors manufactured by Fogale Nanotech to improve their signal quality and ease the replacement of a wire.
- The development of low cost sensors and associated electronics allowing remote diagnostics: Interferometric HLS (iHLS) and WPS with Kapton electrodes (kWPS).

Innovative solutions to perform a five DOF adjustment was also developed in parallel.

CONSOLIDATION OF WPS SENSORS

Twisted cables to improve cWPS

In the LHC, the measurement chain, as described in Fig. 2, is implemented. Measurement cables between each cWPS and its remote electronics have a maximum length of 30 m. Cables linking the cWPS remote electronics to the survey acquisition system have a maximum length of 300 m [6].

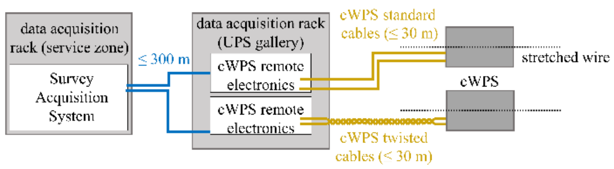

Figure 2: cWPS measurement chain in the LHC

The manipulation of the data acquisition chassis can translate to non-repeatable offsets of 50 mV in the cWPS remote electronics. This corresponds to 50 µm of the sensors' readings. These offsets are due to the mechanical construction of the cWPS cables [7]. Each cWPS sensor performs two radial and two vertical offset measurements w.r.t. a reference wire. The single cables carrying the measurement signal of each axis are not in the same cable. In the case of non-twisted pairs of cables, the cross-talk effect of a single cable is not cancelled. By twisting the two cables containing the active single cables of both axes, the offset effect is cancelled. Additionally, the noise on cWPS signals increases when several non-twisted cWPS cables are tied together.

Table 1: impact of standard and twisted cables on signal

configuration	standard cable		twisted cable	
	offset	noise	offset	noise
Rolled up	0	2	0	2
laid out	27	3	8	2
tied together	34	30	11	2

Measurements given in µm.

Table 1 shows the differences between rolled up, laid out and tied together cables. The result of the comparison confirms that the noise level of the signal does not change with the twisted cables in various configurations. The offset can be significantly reduced to approximately one third of the standard cable solution.

Using unstacked and twisted cables in UPS gallery racks will considerably reduce undesirable cross-talk effects on the measurements [8, 9, 10].

A new solution for the installation and maintenance of stretched wires

For HL-LHC, permanent alignment wires measured by WPS sensors will be stretched over a length of 200 m. Such an installation length, located in a high radioactive area, makes the maintenance of the wire and its replacement in case of break very challenging. To tackle this issue, we studied methods to install and stretch a wire whilst limiting human intervention to its minimum. Two proposals are under investigation:

- Under-pressure wire replacement – based on a vacuum pipe, which takes at the same time the role of the wire shield. In this case, the under-pressure applied on one end of the tube will vacuum-clean the residuals of the old damaged wire and will allow transferring the new wire through 200 m of WPS installation. In this configuration, the WPS sensor is part of the vacuum pipe and its aperture needs to be circular;
- Automatized wire replacement – based on a small vehicle moving on a special rail below the WPS sensors installation. The vehicle's role is to stretch the new wire and to place it inside the WPS sensor. The WPS sensors need to be open for the wire insertion.

The development work on both solutions started at the beginning of 2018 by building prototypes of the wire replacement systems. A 140 m test setup with a vacuum tube was built in a tunnel at CERN. Initial tests confirmed the interest of such a concept. Cleaning the old wire and transferring the new wire is working well. Operational parameters such as pressure values and pipe diameters were defined with the installation. Further tests are planned to validate this technique, e.g. an evaluation of the wire and sensors damage during pulling, irradiation tests of vacuum pipe material and wire stretching within the pipe.

The automatized wire replacement system was also validated on a short 5 m setup. The test showed good pulling performance, with issues concerning the vehicle powering. A new prototype solving this issue is currently under construction.

DEVELOPMENT OF LOW COST SENSORS

Interferometric HLS sensors

The development of iHLS is in the scope of providing sensors for HL-LHC that have an attractive price and at the same time allows the increase of the distance between active elements, e.g. the sensor's electronics, and the passive elements such as the sensor's collimator. The prototype of the relative iHLS has been installed at CERN in 2016. Stability and linearity tests between capacitive HLS and iHLS have shown concordant results [12]. During these tests, an oil layer was used to avoid evaporation of the water and to damp waves that could be introduced into the system by external vibrations in the tunnel environment.

The system development has continued in two directions: first, with the improvement of a relative measurement by removing the oil surface and second, with the development of an absolute measurement.

The observed scale factor during sensor comparison has been investigated by replacing the oil with a water surface. A temperature stabilisation of the collimator allows measurements on the water surface without facing humidity condensation. With these measures, the scale factor reduces to less than 0.2% of the test range of 400 µm.

As the water surface has less damping capacities compared to oil, the system becomes more sensitive to vibrations and high-frequency waves that result in a loss of a return signal. The emphasis has been put on the development of an absolute solution using frequency scanning in the reference gas cell. The system provides an absolute measurement every 15 s. This signal resets the relative signal in case of signal loss and provides a control measurement for the relative evolution of the signal. Thus, in case of signal loss of the relative system, the system can be set back within 30 s. The first test on an oil surface provided a linearity of 0.4% throughout a range of 8 mm and a repeatability of 20 µm.

The relative system meets the technical specifications in terms of sensor range, resolution, data acquisition frequency, inclination tolerance, drift and remote data acquisition. The interchangeability and repeatability are under improvement with the absolute system. An industrial prototype assembly of the relative system is being manufactured to allow connecting up to ten sensors to the electronics.

The choice on the measurement system for HL-LHC will be decided by the end of 2018.

Kapton-electrodes WPS

The WPS sensors foreseen for HL-LHC represent a non-negligible part of the general alignment budget. Moreover, the current solution, based on WPS from Fogale Nanotech, does not allow simple and fast replacement of the wire. The development of kWPS is an answer to cost optimization and operation ergonomics needs.

The kWPS sensor is based on the cheap technology of flexible Kapton polyamide printed circuit boards, with electrodes printed on the surface and covered with a layer of gold. The sensor includes two half-blocks (see Fig. 3 and 4) with one Kapton electrode foil bonded inside each blocks.

This technology allows a big reduction of the sensor's cost, as the sensor assembly consists of a minimum amount of parts with two sensor blocks including connectors, screws, and a Kapton foil, together with a simple assembly procedure. Moreover, using such an approach, the electrodes' aperture can be easily adapted according to the shape or aperture needed for the wire replacement system. The sensor prototype was preliminary tested on a CERN WPS calibration bench, showing a micrometric repeatability within the wire displacement range of ± 5 mm.

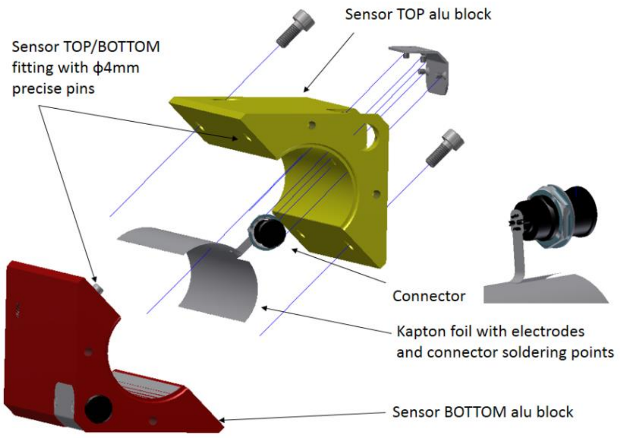

Figure 3: kWPS sensor assembly

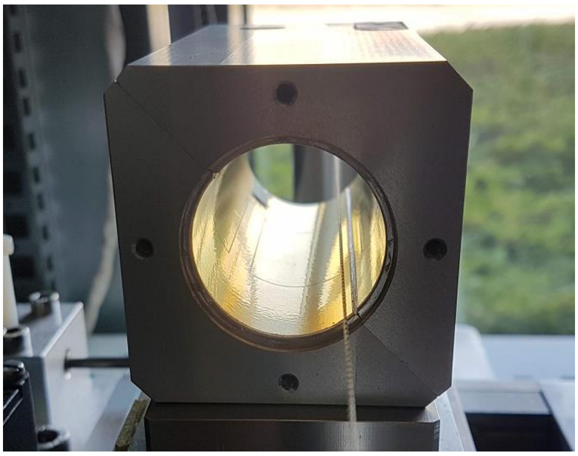

Figure 4: kWPS sensor prototype

In parallel to the tests on the kWPS prototype, irradiation tests on the sensor materials and bonding technology were undertaken. The samples of the capacitive sensors with electrodes bonded to the aluminium body were sent to the Fraunhofer Institute for Technological Trend Analysis INT for gamma irradiation. The test is used to validate the material's behaviour in high radiation conditions, similarly to the expected ones in the future HL-LHC installations. The long term and the extended calibration tests of the sensor prototype are planned before the end of 2018, to confirm if the new sensors can be implemented for HL-LHC.

Development of new sensor electronics

For HL-LHC, the higher number of capacitive sensors deployed over longer distances in the tunnel triggered a new approach on the systems' availability to decrease the time between failures and to get remote diagnostics. As shown in Fig. 2, the current measurement architecture of capacitive sensors is dispersed and is strongly affected by industrial Electro-Magnetic Interference (EMI). To minimize the overall cables' length and increase the maintainability of the systems, we propose a new design for the sensors electronics. This new approach integrates analogue signal conditioners and data acquisition electronics in the same electronic cards. The new conditioner cards are designed to be compatible with HLS and WPS sensors (minimization of equipment versions), equipped with maintenance features allowing operators to perform remote diagnostics. They are designed to resist at least 200 Gy of Total Ionizing Dose and to be compatible with the CERN WordFIP fieldbus used to transfer the data from the conditioner sub-racks to the front end computers, performing sensors data processing, located in non-radiation areas.

The first electronic conditioner prototype card was available at the beginning of 2018. The tests showed a good immunity to noise and a resolution similar to the current analogue conditioners.

In June 2018, the first sub-rack with three prototype capacitive conditioner cards connected to a local WPS test setup were deployed in a UPS gallery of the LHC. The aim of the test is to verify the stability of the equipment in real operation conditions: in a low radiation and industrial noise environment. Currently the equipment has now been operating without failure for four months, showing good long-term stability without visible effects of radiation or EMI.

DEVELOPMENT OF A 5 DOF ADJUSTMENT PLATFORM

In the accelerator domain, one emerging problem is the alignment of components located in radioactive areas, where the issue of a total ionizing dose taken by personnel during adjustment operations is critical. Moreover, each type of components has a unique set of different parameters and requirements, like weight, desired position accuracy or support stiffness. Currently, the usual approach is either a manual adjustment, using regulating screws and shims, or using precise and expensive positioning stages and tables. Both options are very time consuming and not very ergonomic, in particular taking into account the exposure time of personnel in the radioactive area. In 2013, Compact Linear Collider (CLIC) studies investigated the possibilities of an adjustable support allowing the manual and intuitive adjustment of the CLIC Drive Beam Quadrupoles (DBQ) within a micrometric accuracy [13]. The DBQ support mechanism is based on the Stewart platform principle, with modified joints orientation to allow space reduction and intuitive operation (see Fig. 5).

The proposed concept is a standardized platform for the adjustment of small components of the HL-LHC project with the following requirements: being low-cost, intuitive and tailor-made to the user's needs. We offer the users tested and validated actuators/joints; they can integrate them in their various supporting plates [13].

The location of regulation knobs only on one platform side opens the way for different applications: manual, semi-automatic and automatic (see Fig. 6).

The functional prototype of the platform was built at CERN in mid-2018. The goal of the tests is to verify the overall platform performance. In particular, the performance for backlash, directional stiffness, operation ergonomics and behaviour under different loads are tested.

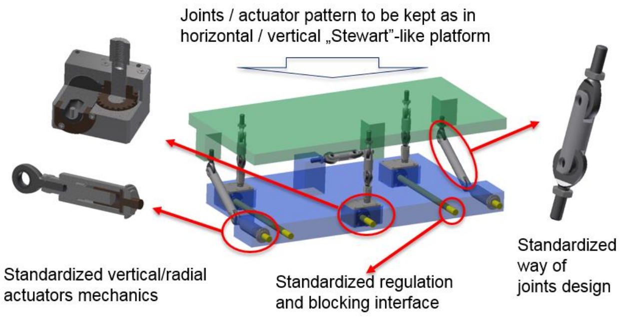

Figure 5: concept of standardized platform

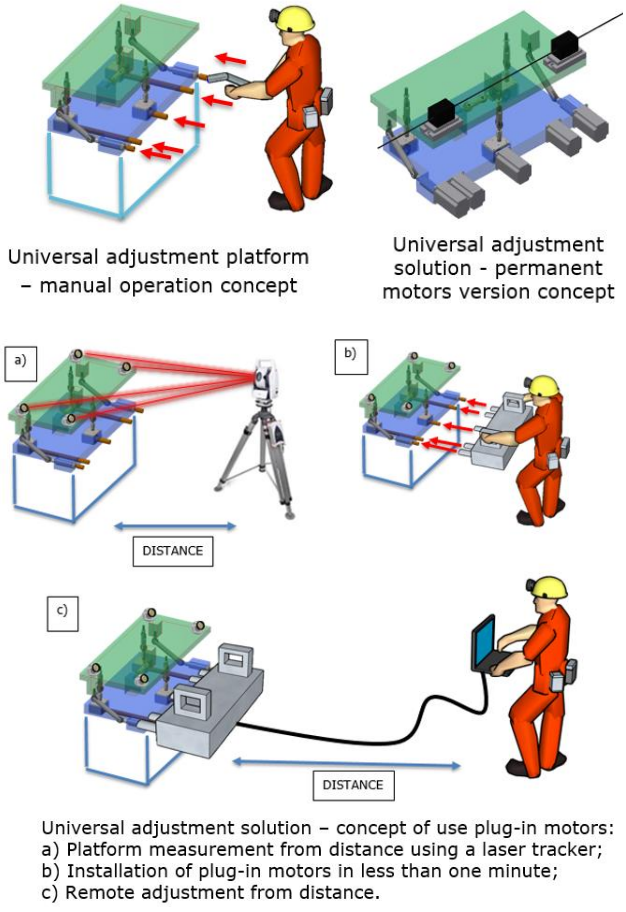

Figure 6: platform applications

FULL REMOTE ALIGNMENT STUDY

The HL-LHC alignment baseline foresees to monitor permanently the main components of the LSS around ATLAS and CMS and to install these components on motorized supports. The inner triplet magnets, dipoles and quadrupoles, crab cavities and the absorber TAXN are designed to be remotely aligned.

In the scope of improving the functionality of the machine and optimizing the costs, this baseline is under review in terms of extending monitoring and alignment concepts to other components, allowing optimization for the HL-LHC operation. The study is based on the idea that a full remote alignment approach will decrease the relative movements needed between components, and thus can result in the use of standard components for vacuum and in the suppression of corrector magnet package.

With the possibility of a full remote alignment of the LSS, the alignment scenarios can be redefined. In the first year of operation, a motorized alignment range of ± 2.5 mm is foreseen, allowing the use of ± 0.5 mm for possible ground motions and relative movements between the components. The remaining ± 2.0 mm are reserved for a possible shift of Q1 to Q4 due to a potential Interaction Point (IP) offset caused by the incertitude of the experiment and machine assembly. This shift could be applied remotely, within a couple of days after the results of the initial luminosity run. After the first year of operation, only a minor activation of the components in the LSS is expected. Therefore, the IP offset will be eliminated by adjusting the motorized range of the alignment systems, gaining the full ± 2.5 mm remote alignment stroke for HL-LHC operations, allowing compensation for expected ground motions over the HL-LHC's lifetime.

The components to be optimized in the alignment process by standardization and motorization are the collimators, protection masks for the Q4 and Q5 magnets, beam position monitors (BPM) and vacuum sector valves. The Full Remote Alignment Study proposes three approaches:

- Passive components like a warm beam pipe are designed large enough in order to cope with ground motions over the HL-LHC's lifetime and the IP offset in the first year.
- BPMs and sector valves are either embarked on adjacent components that are already monitored and motorized or can be hosted on a standardized platform that can be either permanently motorized, operated with plug-in motors or manually operated.
- Combine components that have to follow a rigid alignment scheme on a common girder in order to reduce the costs for monitoring sensors and motorization. The aspects of component interchangeability have to be taken into account particularly for these assemblies.

The Full Remote Alignment Study investigated possibilities to allow a design improvement of the HL-LHC LSS. The proposals are currently being discussed with the corresponding work package leaders and will be submitted for evaluation and approval of a baseline change to the HL-LHC Technical Coordination Committee in October 2018.

CONCLUSION

To answer alignment requirements for HL-LHC and take into account lessons learnt from LHC, we propose innovative alignment solutions. New alignment sensors have been developed (interferometric based HLS sensors and low cost capacitive based WPS), the measurement chain quality of sensors has been improved (design of new remote electronics for capacitive sensors and twisted cables implemented between each WPS sensor and its remote electronics); new solutions to stretch and install a wire remotely are also under development. In parallel, new five DoF standardized adjustable platforms, extrapolated from the CLIC project, are under validation, offering new possibilities for a full remote alignment of all the LSS components from CERN control room.

The final decision between solutions will be taken at the beginning of 2019, endorsed by a review on alignment systems in June 2019. The chosen solutions will be implemented, tested and validated on a string test in 2021, before their installation in the LHC tunnel planned in 2024.

This string test will consist of four low beta quadrupoles, one corrector package and one dipole.

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